

Review

Life Cycle of Oil and Gas Fields in the Mississippi River Delta: A Review

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Received: 20 April 2020; Accepted: 20 May 2020; Published: 23 May 2020

Abstract: Oil and gas (O&G) activity has been pervasive in the Mississippi River Delta (MRD). Here we review the life cycle of O&G fields in the MRD focusing on the production history and resulting environmental impacts and show how cumulative impacts affect coastal ecosystems. Individual fields can last 40–60 years and most wells are in the final stages of production. Production increased rapidly reaching a peak around 1970 and then declined. Produced water lagged O&G and was generally higher during declining O&G production, making up about 70% of total liquids. Much of the wetland loss in the delta is associated with O&G activities. These have contributed in three major ways to wetland loss including alteration of surface hydrology, induced subsidence due to fluids removal and fault activation, and toxic stress due to spilled oil and produced water. Changes in surface hydrology are related to canal dredging and spoil placement. As canal density increases, the density of natural channels decreases. Interconnected canal networks often lead to saltwater intrusion. Spoil banks block natural overland flow affecting exchange of water, sediments, chemicals, and organisms. Lower wetland productivity and reduced sediment input leads to enhanced surficial subsidence. Spoil banks are not permanent but subside and compact over time and many spoil banks no longer have subaerial expression. Fluid withdrawal from O&G formations leads to induced subsidence and fault activation. Formation pore pressure decreases, which lowers the lateral confining stress acting in the formation due to poroelastic coupling between pore pressure and stress. This promotes normal faulting in an extensional geological environment like the MRD, which causes surface subsidence in the vicinity of the faults. Induced reservoir compaction results in a reduction of reservoir thickness. Induced subsidence occurs in two phases especially when production rate is high. The first phase is compaction of the reservoir itself while the second phase is caused by a slow drainage of pore pressure in bounding shales that induces time-delayed subsidence associated with shale compaction. This second phase can continue for decades, even after most O&G has been produced, resulting in subsidence over much of an oil field that can be greater than surface subsidence due to altered hydrology. Produced water is water brought to the surface during O&G extraction and an estimated 2 million barrels per day were discharged into Louisiana coastal wetlands and waters from nearly 700 sites. This water is a mixture of either liquid or gaseous hydrocarbons, high salinity (up to 300 ppt) water, dissolved and suspended solids such as sand or silt, and injected fluids and additives associated with exploration and production activities and it is toxic to many estuarine organisms including vegetation and fauna. Spilled oil has lethal and sub-lethal effects on a wide range of estuarine organisms. The cumulative effect of alterations in surface hydrology, induced subsidence, and toxins interact such that overall impacts are enhanced. Restoration of coastal wetlands degraded by O&G activities should be informed by these impacts.

Keywords: oil and gas production; produced water; oil and gas wetland impacts; induced subsidence; wetland restoration

1. Introduction

The first successful oil well was drilled in Louisiana in 1901 in southwestern Louisiana, in the Jennings field and marked the beginning of oil and gas (O&G) production in Louisiana that, by the mid-20th century, was the state's primary industry [1]. Production of petroleum has been widespread in the Mississippi River Delta (MRD) and there is a dense network of pipelines both inshore and offshore (Figure 1). Hydrocarbon extraction in the MRD necessitated the dredging of canals through wetlands and waterbodies for navigation, pipelines, and O&G extraction. As canals were dredged, spoil material from canals was placed on the side of canals partially impounding wetlands; altering natural hydrology and salinity; decreasing nutrient, organic matter, and sediment exchange; changing vegetation composition and reducing vegetation productivity (e.g., [2–5]).

To understand the impacts of O&G activity on MRD wetlands, it is important to recognize that wetland degradation in O&G fields occurred much more rapidly (decades) than the natural deltaic cycle, which took place over centuries to millennia [5–10]. Naturally-occurring geologic faulting, sediment compaction, the delta lobe cycle, variability in river discharge, global sea-level change, tidal exchange, wave erosion, and storms such as hurricanes and frontal passages have shaped the MRD landscape for thousands of years [5–15]. However, in less than a century, more than 30,000 km of canals were dredged in the MRD [16–18], causing dramatic wetland loss (e.g., [9]) due to cumulative effects [4,19] of altered surface hydrology, induced subsidence and fault activation [20], and toxicity of produced water and spilled oil [21–23].

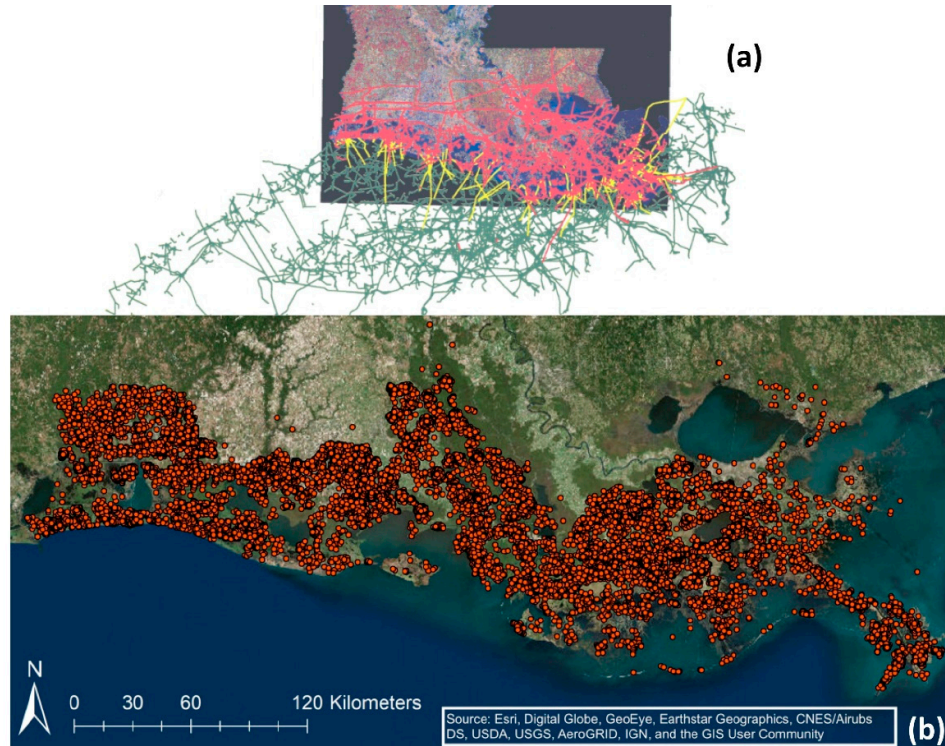


Figure 1. (a) Map of oil and gas pipelines in coastal Louisiana (http://www.dnr.louisiana.gov/assets/docs/oilgas/data/SLA_Pipelines.pdf) and (b) the distribution of oil and gas well permits issued between 1900 and 2017 that were 'plugged' or 'abandoned' as of 2017 in the 14 coastal parishes [18].

Our objective in this paper is to review the literature on the life cycle of O&G fields in the MRD by (1) describing the production history of hydrocarbons and produced water and (2) reviewing the impacts of surface alterations, induced subsidence, and toxic materials. Although, these impacts have been well documented, their interacting affects have been less well addressed. Thus, an important objective is to consider their cumulative and indirect impacts on coastal ecosystems, especially wetlands, in the MRD and to show how this information informs restoration.

2. Production History of Oil and Gas Fields

Hydrocarbon extraction has occurred in the MRD for over a century. Production increased rapidly and then declined as reserves were depleted and fluid output was dominated by produced water (Figures 2 and 3). This is true for the overall production history and for individual fields that were active for 30–50 years or more.

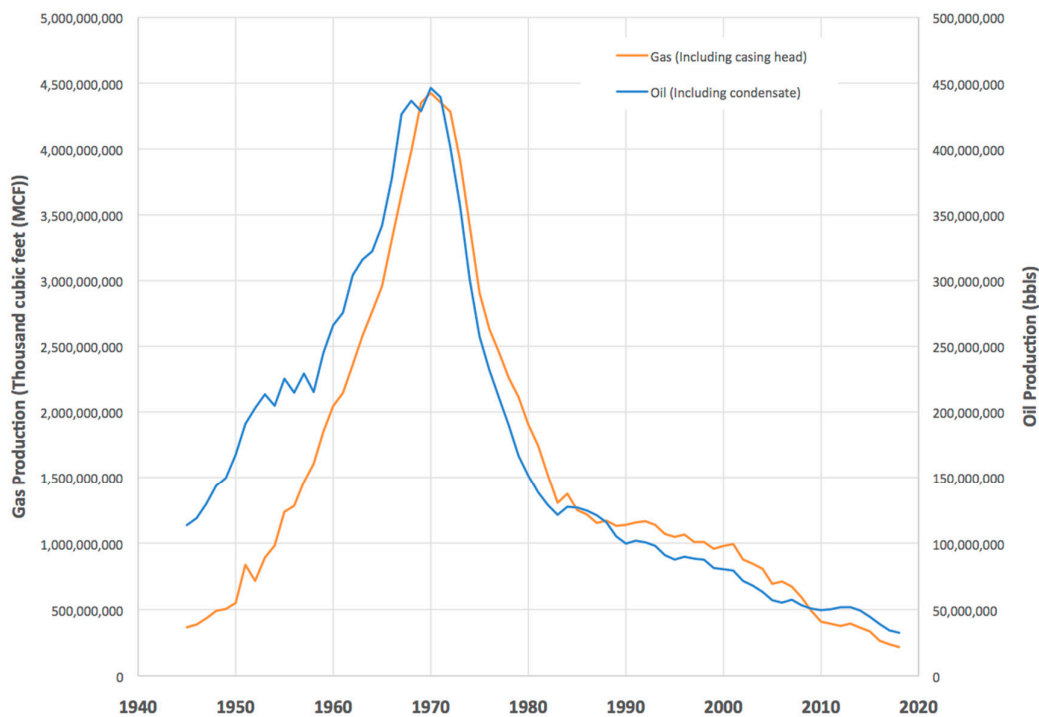


Figure 2. Annual oil and gas production in southern Louisiana between 1945 and 2019. Data source: (<http://www.dnr.louisiana.gov/assets/TAD/OGTables/Table03.pdf>).

Wetland loss in coastal Louisiana has been quantified [19,24,25]. Researchers have used different proxies of field development to correlate this land loss with specific oil and gas activities [26–29]. The authors of [30] reported the highest rates of wetland loss in the MRD correlated with peak hydrocarbon production (Figure 3). In [18] it was reported that the annual number of well drilling permits, a proxy for production, correlated with wetland loss rates (Figure 4). In this paper we investigate the factors contributing to these relationships.

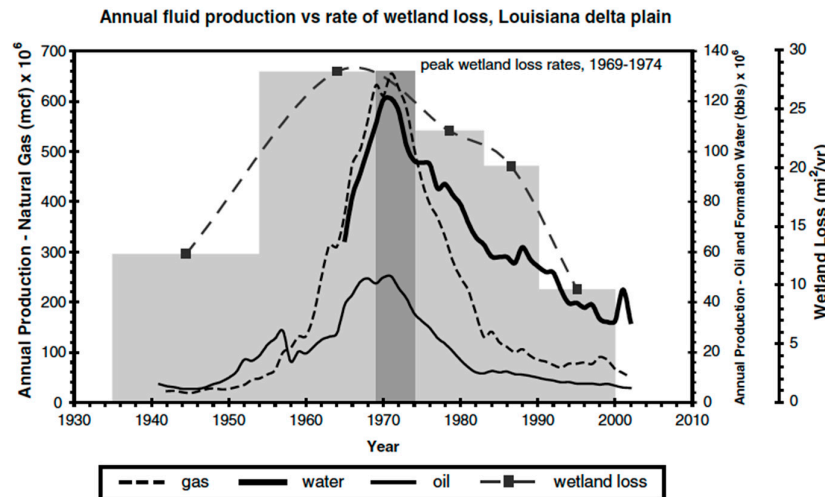


Figure 3. Composite histories of fluid production from oil and gas fields and wetland loss in south Louisiana. Production data from the Louisiana Department of Natural Resources and the PI/Dwights PLUS database [31]. Wetland loss values were determined by [32] and John Barras (unpublished data). These historical data, integrated across the delta plain, show close temporal and spatial correlations between rates of wetland loss and rates of fluid production [30]. Note that “water” in the legend refers to produced water.

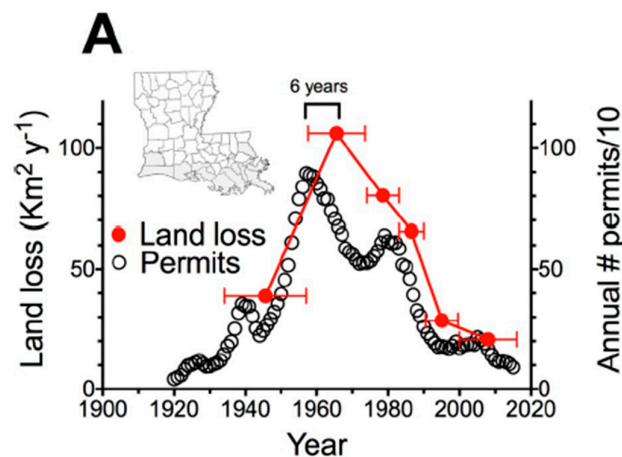


Figure 4. The number of oil and gas permits issued annually and land loss rates [18].

Although individual fields show a similar pattern of production history and wetland loss, they differ in some details as illustrated for four different field complexes (Figure 5) that produced O&G over 4–6 decades. The Bully Camp and Madison Bay area had increased produced water development in the second half of their production history. Peak water production in the Bayou Rambio and DuLarge fields coincided with peak gas in this region that had relatively low oil capture. Water production was also high in the second half of the production history of this area. The pattern of water production in the Pointe au Chien study area was similar to gas production in the second half of the oil field life. In each example though, the production of oil, gas, and produced water varied over the field life-cycle, each field began, peaked, then gradually depleted over decades. All fields combine to yield the overall history of the coastal zone (Figures 2 and 3). All four fields illustrate the concept of a development cycle that includes a run-up to peak production followed by a gradual decrease to total abandonment. Individual fields and the aggregate of all fields follow a similar life

cycle. These patterns have important implications for the impacts of hydrocarbon extraction on coastal ecosystems, especially wetlands, for three main reasons. First, dredging of canals leads to severe alteration of surface hydrology that impacts coastal wetlands. Second, extraction of fluids (oil, gas, and water) leads to changes in pore pressure that result in induced subsidence and fault activation. Third, accidental spills and intentional releases of oil and produced water cause toxicity stresses that degrade coastal ecosystems. These factors are discussed in more detail below, after which we show how cumulative and interacting impacts multiply the individual impacts.

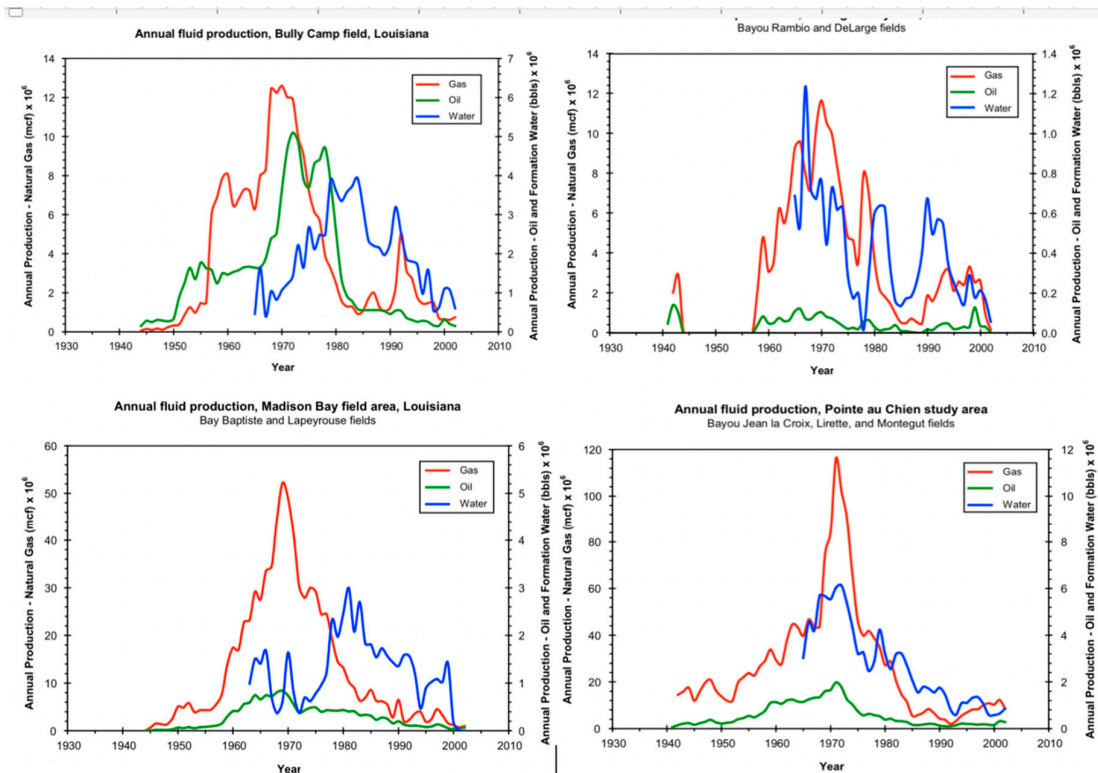


Figure 5. Production history of selected oil and gas fields in the Mississippi delta. Upper left—Bully Camp; upper right—Bayou Rambio and DeLarge fields; lower left—Madison Bay field area; lower right—Pointe au Chien study area [30]. Note that “water” in the legends refers to produced water.

3. Patterns of Wetland Loss and Oil and Gas Activities

From 1930 to 2010 about a quarter (about 5000 km²) of MRD coastal marshes were lost, mostly by conversion to open water [33,34] with two general patterns (Figure 6). Wetland loss has been pervasive across the coast with high loss near the mouth of the Mississippi River, in the Barataria and Terrebonne basins, and in the Chenier Plain. Two areas stand out with much less loss. One is the central coast that receives input from the Atchafalaya River, which carries about a third of total Mississippi River discharge, that flows into shallow bays and wetlands over a wide arc along the central Louisiana coast. The other zone is on the northeastern flank of the delta in the seaward reaches of the Pontchartrain estuary.

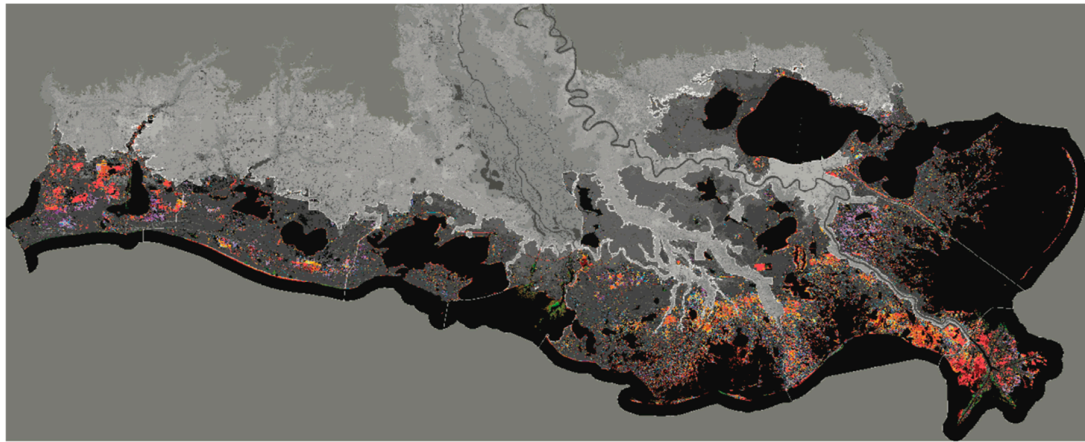


Figure 6. Wetland loss in coastal Louisiana from 1932 to 2016. Red and yellow areas have high land loss rates. Note that land loss is low in the central coast and in the northeastern flank of the delta. (Source: [33,34] The map can be downloaded at <https://pubs.usgs.gov/sim/3381/sim3381.pdf> for detailed examination of specific areas of change. See also <https://pubs.er.usgs.gov/publication/sim3381>).

A number of studies have discussed the causes of wetland loss and addressed the role of O&G activities in this loss (Table 1). O&G activities reduce forces leading to wetland sustainability (e.g., sedimentation, accretion, vegetation biomass production) and enhance forces leading to deterioration (e.g., increased subsidence, saltwater intrusion, vegetation decline, toxicity stresses). O&G impacts on wetlands are both direct and indirect. Direct loss is due both to canal dredging and spoil placement, while indirect impacts include alteration of surface hydrology, induced subsidence, and introduction of toxic substances. Direct impacts are reported to have caused between 6% and 70% or more land loss while indirect impacts have caused between 20% and 80% or more of wetland loss (Table 1).

Table 1. Estimates of the percentage of wetland loss caused by all oil and gas activities (overall) or by direct or indirect impacts of oil and gas activities.

Location	Time Period	Overall Impacts (% Wetland Loss)	Direct Impacts (% Wetland Loss)	Indirect Impacts (% Wetland Loss)	Source
Coastal Louisiana	1931–1967		69		[35]
Coastal Louisiana		45			[36]
Coastal Louisiana			10–69		[37]
Coastal Louisiana			10	up to 80	[38]
Coastal Louisiana	1955–1978		10	48–97	[39]
Mississippi River Deltaic Plain	1955/56–1978		25–39		[40]
Coastal Louisiana	1932–1990	Majority of losses due to canals			[18,26,27]

Coastal Louisiana	1955–1978	20–60	14–16	20–60	[16]
Coastal Louisiana	1955–1978		16		[41]
Coastal Louisiana	1955–1978		6.6		[42]
Coastal Louisiana	1955–1978		16	30–59	[43]
Breton Sound	1933–1990	68			[9]
Barataria Basin	1933–1990	72			[9]
Mermentau Basin	1933–1990	35			[9]
Mississippi River Deltaic Plain	1930–1990	33.2	10.8	22.4	[24,25]

Wetland loss patterns are generally similar to temporal patterns of production (Figure 7). The different studies were done using different methods and represent different conceptualizations of the delta and sub-areas sampled. Regardless of the proxy used to describe the oil and gas life-cycle, the relation to land loss is unmistakable. The rates of land loss differ because they are for different areas (e.g., total coast vs. deltaic and Chenier plains) and for different time periods and the study methods, though similar, are not the same [32,34,44]. Peak loss occurred generally between 1960 and 1980. The curve for total O&G production is sharper than that of land loss likely because of delayed impacts of O&G as well as other causes of land loss (e.g., isolation from riverine input, edge erosion, hurricane impacts).

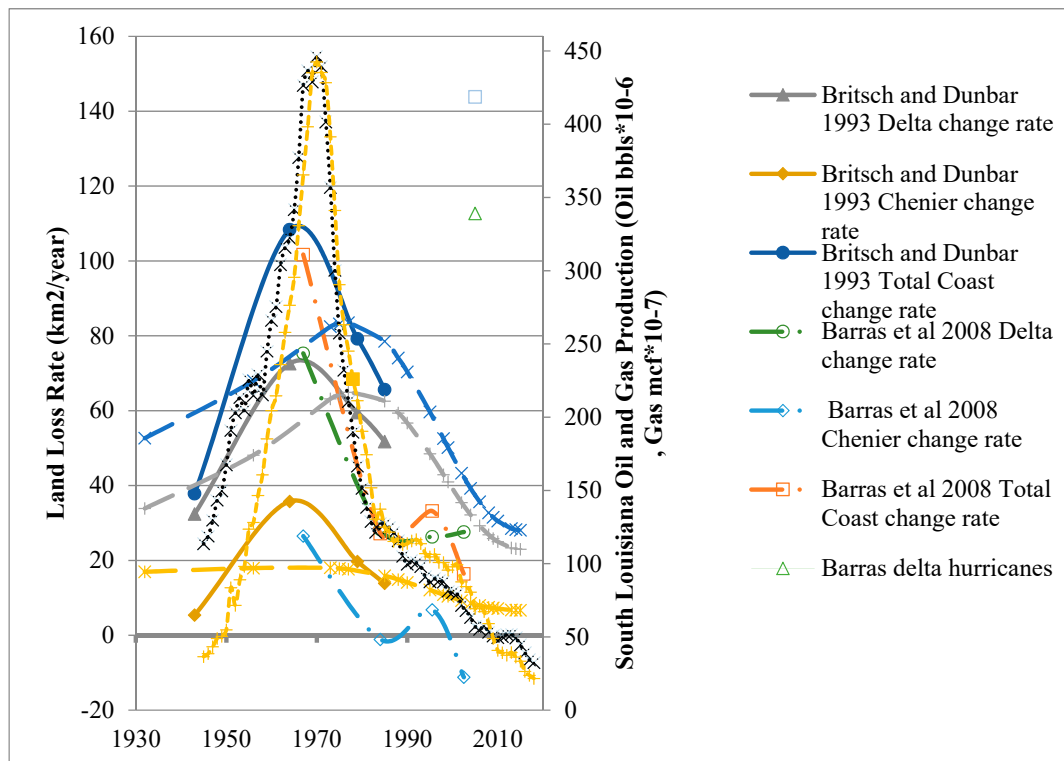


Figure 7. Oil and gas production and land loss studies for coastal Louisiana. Loss values are from [32,34,44] where rate values represent an average over the time interval shown. Production data are from Louisiana Department of Natural Resources. These historical data show close temporal and spatial correlations between rates of wetland loss and rates of hydrocarbon production.

4. Indirect Impacts of Oil and Gas Exploration and Production on Coastal Louisiana Wetlands

4.1. Alteration of Surface Hydrology Due to Canal Dredging and Spoil Placement

MRD wetlands are dependent on sheet flow for exchange of water, sediments, and nutrients to sustain wetland health. Unimpeded wetland hydrology facilitates alternating flooding and draining of wetlands. Canals and spoil banks are linear and intersecting, and spoil banks are higher in elevation than surrounding wetlands and normal high tides [4,9,15,45]. Placement of dredge spoil impounds wetlands, reducing or eliminating surface water exchange and tidal influence, reducing sediment deposition onto wetlands, impeding the exchange of materials (e.g., nutrients, sediments, organisms) between semi-impounded marshes and the surrounding marsh, and increasing inundation duration while decreasing inundation frequency [2,4,16,46–50]. Spoil banks trap water, increasing water logging and decreasing drainage, sediment accretion, and vegetation productivity (Figure 8) [4,15,16,19,46,48,51–63]. As surface flow is minimized by spoil banks, water may only be introduced into impounded wetlands when water levels are elevated during frontal passages or major storms.

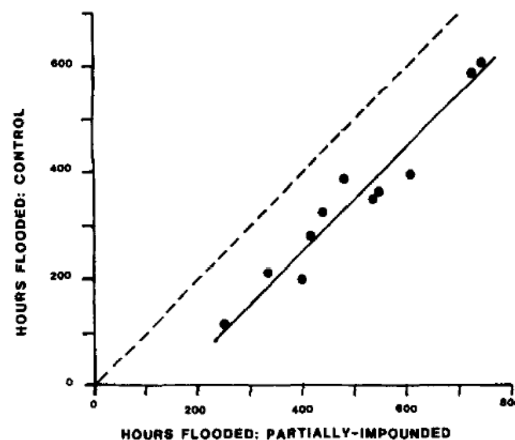


Figure 8. Total hours flooded, for one month, at a reference marsh with a natural berm and a partially impounded area where about 75% of the natural berm had been replaced by a dredged canal spoil bank, Golden Meadow oil and gas field south of New Orleans, LA [52]. The dashed line shows what the relationship would be if there were no partial impoundment.

Due to spoil banks, accretion in un-impounded marshes may be up to five times higher than that in impounded marshes [3,57,61,64–67]. Canals also promote saltwater intrusion into wetlands previously isolated from direct exchange with higher salinity waters [2,4,27,47,48,68–71]. Increases in salinity cause changes in vegetation composition and reduced productivity and/or death of fresh and low salinity marsh species and lead to formation of open water [53,71–73]. Introduction of saltwater increases sulfate concentrations, which can be reduced to sulfides in anaerobic soils, that stresses and causes mortality to low salinity wetland vegetation [73] and rapid decomposition and collapse of soil organic matter and soil structure peats [74]. Reduced vegetation productivity and vegetation death exacerbate land loss because plant roots bind soils and increase soil strength. When roots die, the wetland rapidly loses elevation and is more vulnerable to erosion [74,75].

Over time, canals widen as a result of spoil bank undercutting, erosion, and collapse causing additional wetland loss [45,46]. Localized subsidence along pipeline canals occurs along the flanks of spoil banks when the weight of the spoil depresses the surface of the marsh and leads to the formation

of linear ponds behind the spoil banks due to subsidence from the weight of the spoil, trapping of water at the base of spoil banks and blocking of sediment input [76]. The authors of [77] documented soil compaction beneath spoil banks created more impenetrable soils that reduced ground water movement. These processes isolate the wetland behind the spoil bank from both above- and belowground water exchange.

O&G canals are deep, straight channels while natural waterways are primarily shallow and sinuous tidal channels [4]. As canal density increases in an area, the density of natural channels decreases because canals preferentially capture water flow from natural channels (Figure 9) [37,52] in a process termed ‘channel theft’, because deep, straight canals transport water more efficiently than natural shallow and sinuous channels [50].

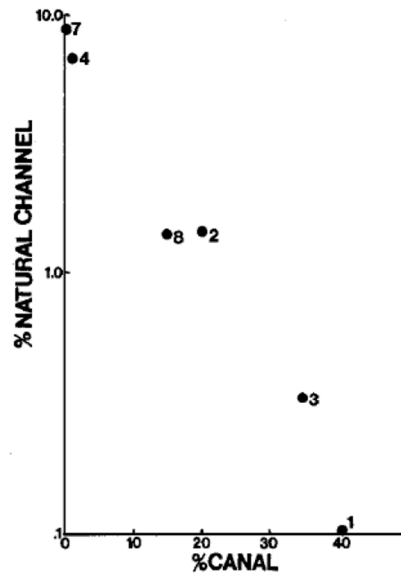


Figure 9. The relationship between canal density and the density of natural channels. The data are averages of replicate 1-km² grids (numbers shown by symbol) in the region of Leeville, LA, a saline marsh area [37].

Once dredged, spoil banks are not permanent features and have a life cycle of their own. They disappear over time due to compaction, subsidence, sea-level rise, and erosion. Spoil banks protect remnant marsh from wave erosion and as spoil banks disappear remnant marsh can be lost due to wave attack, leading to further wetlands loss. In Figure 10, subaerial land that disappeared between the two mapping dates (center panel in Figure 10) in the Leeville Field includes both spoil banks and marsh.

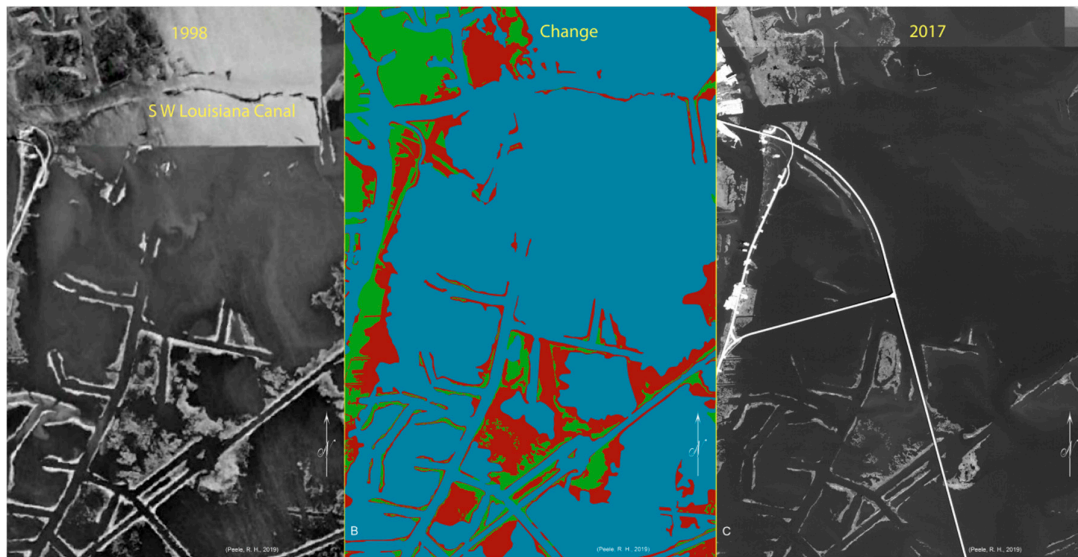


Figure 10. Aerial imagery of a portion of the Leeville oil and gas field in southern Louisiana showing the disappearance of spoil banks and marsh between 1998 and 2017. Bayou Lafourche is in the upper left in each of the images [5]. Areas depicted in red in image B disappeared between the two dates. Red linear strips are spoil banks that disappeared. Green shows subaerial land, both spoil banks and marsh, that was still present in 2017. The Southwest Louisiana Canal at the top of image A was dredged in the late 19th century. In 1998, some spoil banks along the canal were still present, but by 2017 they had disappeared. Louisiana highway 1 is shown at the upper left in image A. By 2017, a new, elevated highway was constructed (white lines in Image C). The width of images is approximately 2.8 km.

As O&G canals are so pervasive, it has been suggested that canals are responsible for practically all wetlands loss. For example, the authors of [18,27] plotted land loss from 15-min quadrangles against canal density and concluded that land loss was directly related to the percent of canals in each map, indicating that almost all land loss was related to canals (Figure 11). However, in [5] and [9] the authors showed that this approach is flawed because it statistically relates all land loss in 15-min quadrangles (which cover about 66,000 ha) to canal density in the quadrangle even when it is neither spatially or functionally related to land loss patterns. Additionally, as we discuss below, induced subsidence causes land loss but is not functionally related to surface alterations in hydrology. In addition, toxic stress due to spilled oil and produced water cause vegetation stress and mortality. However, altered hydrology, induced subsidence, and toxic compounds interact synergistically and cause wetland loss as indicated by the interactions demonstrated in the Leeville field (Figure 10).

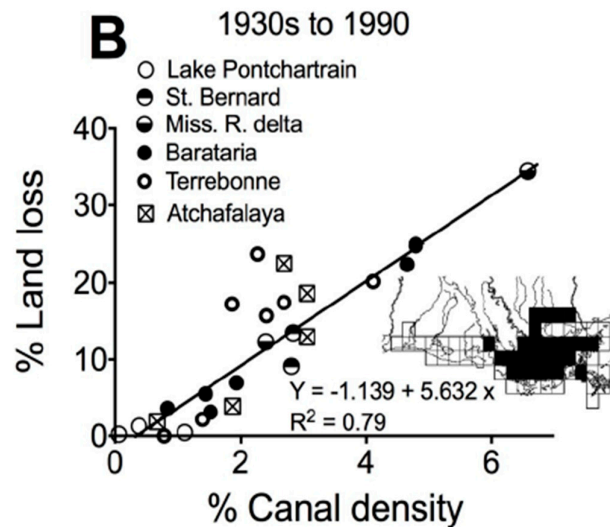


Figure 11. The land loss rate from the 1930s to 1990 and canal density in 15-min quadrangle maps. The authors of [18] concluded that this demonstrates that most wetlands loss is due to canals. This is incorrect, however, because of the large size of 15-min quadrangle maps and other causes of land loss due to induced subsidence and toxic stress.

4.2. Oil and Gas Production Induced Subsidence

Oil, gas, and brine extraction depletes the hydrocarbon reservoir, often precipitously, resulting in pressure drop, compaction, and fault activation (usually reactivation); and this change at depth translates upward, manifesting at the surface as subsidence and faulting. That is, without pressure support the depleted reservoir collapses, and the pressure difference at the nearby associated fault plane nucleates slippage there [4,20,28,30], leading to a subtle, and sometimes dramatic, overprint integrated with other O&G related processes. Observations generally confirm the relationship between fluid production and subsidence in coastal Louisiana: for example, wetland loss is typically higher in the vicinity of oil and gas fields [9,20,29,78–83]. On the coastal Chenier Plain, the authors of [83] suggested that paleo-sea level elevations, vertically offset by 0.5–1 m on a transect near the area of maximum oil and gas production, were influenced by this production. Local rates of measured subsidence in oil and gas fields in south central Louisiana (often more than 20 mm/year) were much higher than regional rates in the Mississippi River Delta (about 10 mm/year) [84]. In [30] the authors analyzed releveled surveys, remote images, subsurface maps, stratigraphic sections, and hydrocarbon production data in relation to wetland loss for the Terrebonne-Lafourche basins and found that the highest rates of subsidence coincided with the location of oil and gas fields (Figure 12) [30]. This study also showed that subsidence rates were greater in the later epoch (1982–1993) than the earlier (1965–1982); that is, subsidence accelerated late in the cycle of O&G production. In [20,30,84] it was concluded that these rapid changes were likely caused by induced subsidence and fault reactivation due to oil and gas activity.

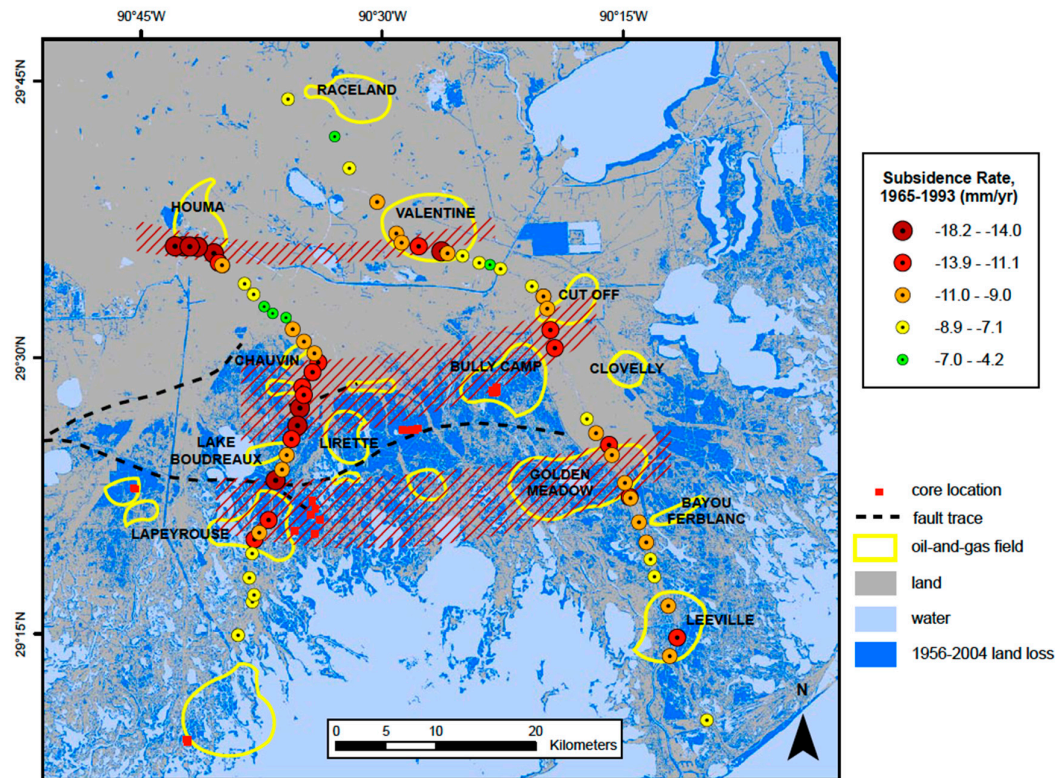


Figure 12. Map showing average subsidence rates between 1965 and 1993 in south Louisiana. Areas of highest subsidence rates (>12 mm/year; hatched pattern) correlate closely with locations of oil and gas fields. Lowest average subsidence rates are located between major producing fields [30].

Elevation change related to faulting in the MRD is often marked by an arcuate scarp separating marsh and water [85], while subsidence related to a reservoir's compaction is spread over and beyond the production area (up to kilometers away from the producing wells) [20]. Subsidence involved with O&G fields typically begins around the time of peak production [84], and continues for an extended time as the field is depleted, often decades after peak production [29,79,86], though it too reaches an ultimate limit [79,84].

The Mississippi Delta is particularly susceptible to subsidence and faulting since rapid deposition of sands and clays has created a weak, metastable situation that responded from early in its geologic history with “landslide-like” faulting (down to the coast listric normal faulting) parallel to the coast, and that faulting has progressed upward as deposition continued—that is, growth faulting [14,87–89]. The sedimentary section developed so rapidly that there was little time for consolidation, cementation, or in many cases, normal pressure equilibration. At the same time, these faults and related rollover anticlines on their downthrown side, formed hydrocarbon traps, the basis for many of the present-day O&G fields on the delta (Figure 13). To add complexity, the low density, easily deformed Louann salt layer that began near the base of the geologic section flowed upward in various geometries, creating salt domes dragging up steeply tilted beds, faults, and anticlinal features that became hydrocarbon traps as well. Growth faults in the delta move episodically over their lifetime, and along segments a few kilometers in length (e.g., [90]). Over the cycle of MRD petroleum development, a number of these growth faults related to oil and gas fields have been reactivated, with consequent displacement and surface subsidence on the fault downthrown side. The mechanism of reactivation along these growth faults is expedited by a poroelastic reduction of horizontal confining stress, which occurs as a result of the fluid withdrawal and consequent pore pressure decrease [91,92]. That is, faults related to MRD O&G fields that break the surface today are mostly

reactivated growth faults involved with the reservoirs below—reservoirs that these faults created in the first place.

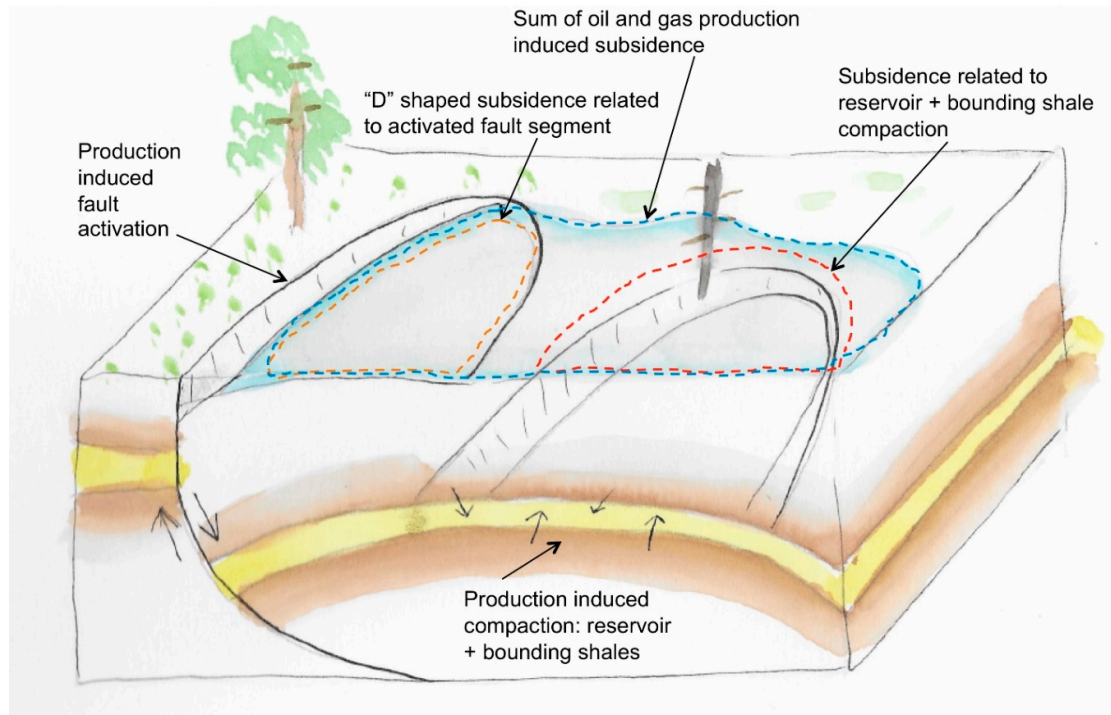


Figure 13. Typical Mississippi River Delta oil and gas reservoir, a rollover anticline on the downthrown side of a down-to-the-coast normal fault. Oil, gas, and water production affects the subsurface in and around the producing reservoir. The depletion process leads to production induced fault activation, reservoir compaction with additional compaction of bounding shales as shown in the subsurface. The surface manifestation of these subsurface changes is shown as a composite of land loss on the downthrown side the activated fault plus subsidence over the compacted oil, gas, and water producing reservoir.

The mechanism of O&G subsidence is involved with the collapse of the reservoir itself. Subsidence happens when production of oil, gas, and water (and sometimes sand) reduces reservoir sand pore pressure to the point where it can no longer support the overburden [93]. Thus, the delta's young, often poorly consolidated reservoir sands, sandwiched between shales, often undergo compaction with production drainage and this deformation is transferred to the surface as a subsidence bowl form. The authors of [94] modeled this reservoir compaction and surface deformation process using the concept of a nucleus-of-strain (the impacted reservoir), together with an elastically deforming half-space (the geologic section above), spreading the effect and reducing the displacement to produce a halo-like effect in and around the O&G field. In [79] the authors used this concept along with 1982–1993 epoch releveing at the Leeville, Golden Meadow, Cut Off, and Valentine fields and the authors of [95] modeled the Lapeyrouse field (Figure 12). At Lapeyrouse, modeling matched the measured releveing when a reactivated down-to-the-coast growth fault was added to the deformation of the compacted disc reservoir sand. This reservoir compaction subsidence process is found in fields along the Louisiana coast and often acts in concert with O&G field related faulting.

In [29] the authors considered the extended timeframe of subsidence where displacement related to depleted O&G fields did not stop as the production cycle ended, but accelerated significantly for decades. As shown in Figure 14, this study indicates (a) greater subsidence over traversed O&G fields

for each epoch (panels A and B), (b) increased subsidence rates (accelerated subsidence) in the later epoch (panel C), and (c) areas of greatest subsidence and rates likely related to fault displacement.

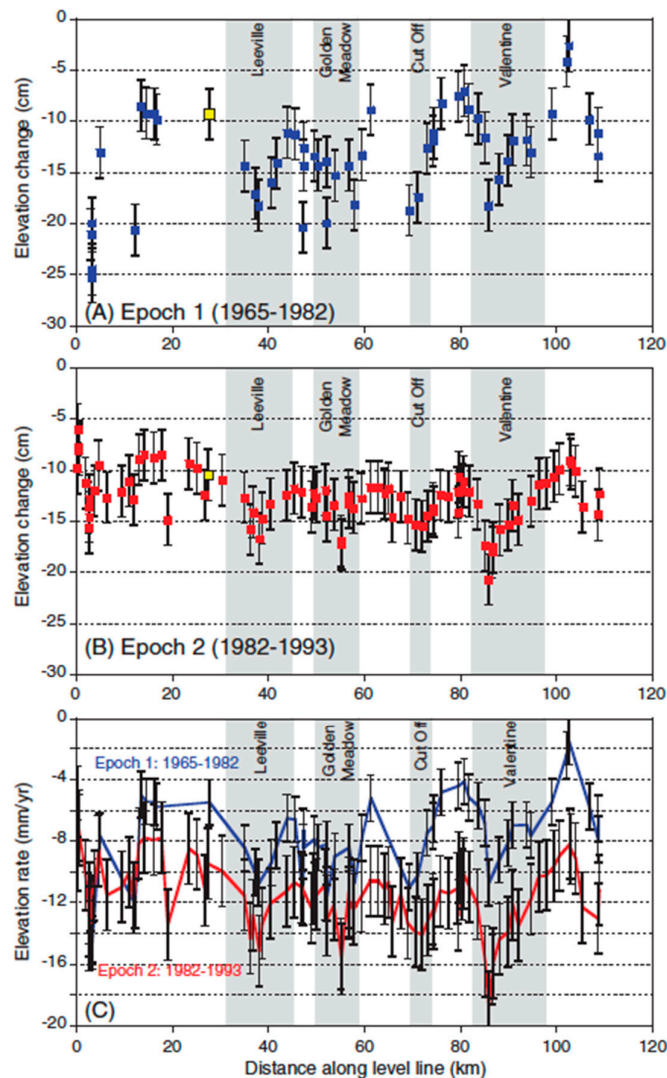


Figure 14. Elevation changes during epoch 1 (1965–1982; A) and epoch 2 (1983–1993; B), and the rates of subsidence in the two epochs (C). Over the entire transect, subsidence rates were greater in epoch 2 than in epoch 1. The yellow squares in (A) and (B) indicate an arbitrarily selected reference station approximately 8 km south and outside of the projected Leeville (see Figure 10) to estimate the magnitudes of local production-related subsidence signals [29].

While post production time-dependent subsidence is intuitively expected due to factors such as slow dissipation of pore pressure in the reservoir (e.g., [96]), and time-dependent creep in the reservoir [97], this subsidence typically happens over only a few years, not decades after and not with acceleration. The authors of [29] considered the role of the bounding shale above and below the sand reservoir itself (Figure 15), and modeled compaction in the Valentine field (Figures 12 and 14) in two stages, the first being poroelastic compaction of the reservoir sand during active production, followed by the time-delayed compaction resulting from slow poroelastic and viscoplastic compaction of the low-permeable bounding shale as included pore water slowly drained into the depleted sand.

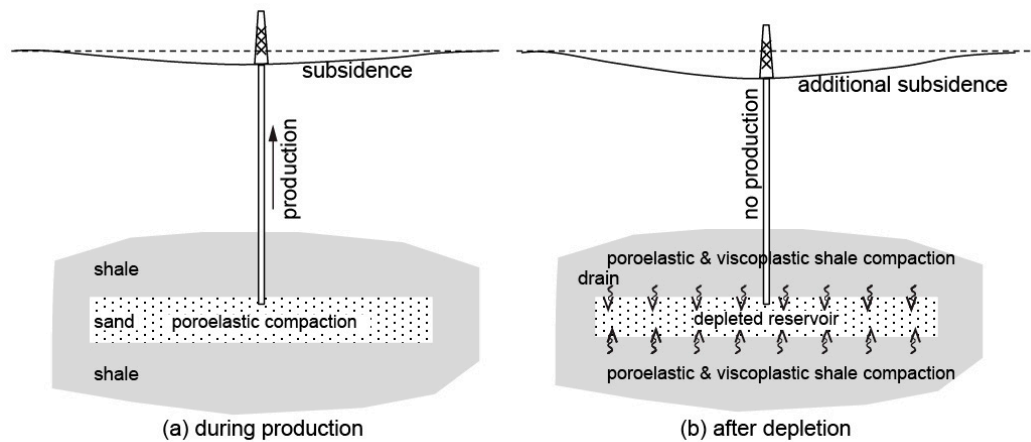


Figure 15. A simple compaction model of sand reservoir embedded with surrounding shale. It is assumed that during production stage, pore pressure depletion in a sand reservoir induces poroelastic compaction, and after depletion, a slow decrease in pore pressure in the bounding shale induces shale compaction in two independent rheological modes (poroelastic and viscoplastic) (modified from [29]).

Compaction that occurs in reservoir-bounding shales is often evidenced by wellbore problems in overburden formations during and after production, such as casing damage and even shear (e.g., [98]). These studies and others matching displacement measurements and mathematical modeling of causality mechanisms, confirm the importance of oil and gas field induced subsidence and faulting. In summary, fault reactivation and reservoir compaction lead to induced subsidence at the surface that reflects both. The interaction of these elevation change mechanisms with oil and gas field development is an important part of land loss in the MRD.

5. Toxic Impacts of Produced Water and Spilled Oil

Produced water from O&G fields is brought to the surface during crude oil and natural gas extraction and, prior to the USEPA banning surface discharge of produced water in 1992, an estimated 2 million barrels per day were discharged into Louisiana coastal wetlands from nearly 700 sites [99]. It is by far the largest volume byproduct or waste stream associated with O&G extraction and is about 10 times more toxic than oil [100]. The fluid generally includes a mixture of either liquid or gaseous hydrocarbons, high salinity water, radioactive materials, dissolved or suspended solids, solids such as sand or silt, and injected fluids and additives associated with exploration, drilling, and production activities (Table 2) [101,102].

Table 2. Common components of produced water resulting from oil and gas production [103].

Category	Constituent
Metals	Aluminum, antimony, arsenic, barium, boron, cadmium, gold, iron, mercury, chromium, copper, lead, zinc, nickel, platinum, silver, strontium, tin, magnesium, molybdenum, titanium, thallium, vanadium
Naturally occurring radioactive materials	Radium-226, radium-228
Monocyclic aromatic hydrocarbons	Benzene, benzoic acid, chlorobenzene, di-n-butyl phthalate, toluene, ethylbenzene, isopropylbenzene, n-Propylbenzene, p-chloro-m-cresol, xylenes
Polycyclic aromatic hydrocarbons	Acenaphthene, anthracene, benzo(a)anthracene, cyrsene, dibenzothiophenes, fluoranthene, flourene, naphthalene, benzo(a)pyrene

Miscellaneous organic chemicals	Phenols, bis(2-ethylhexyl)phthalate, oil and grease
Miscellaneous other components	Calcium, potassium, radon, sodium chloride, total dissolved solids, ammonia, bromides, sulfates, sulfides

Several factors determine the fate and effects of produced waters in coastal environments including the volume and composition of the discharge and the hydrologic and physical characteristics of the receiving environment [22,104]. In many cases, oil field brine was discharged directly to wetlands and surface waters [105]. Energetic storms can mix the water column and advect produced water into marshes where it can significantly damage vegetation. Spills may also impact wetlands. In [106] accidental brine spills between 1990 and 1998 were studied, and a total of 567 brine spills were reported to LDEQ. In sites where produced water was spilled, acute and chronic exposure affected the vegetation. The study author documented ecological impacts ranging from minor vegetation damage to the destruction of hundreds of ha of wetlands. Many wetlands where a single spill had occurred had not recovered up to 10 years later and most of the wetlands with chronic exposure were no longer vegetated and some had converted to open water. In [105] the formation of new ponds where produced water was being discharged was documented and the authors of [23] reported that half of the *Spartina alterniflora* exposed to 120 mg/L of oil and grease, which is the norm for produced water, died within 30 days.

Salinity of produced water ranges from a few psu to up to 300 psu [21,22,102,103]. High salinity leads to the death of most plants and has been linked to wetland loss [105]. In Cameron Parish, Louisiana, north of Black Lake and the Hackberry O&G fields, thousands of ha of sawgrass marsh were killed due to discharge of produced water and the area subsequently converted to open water [107,108]. Naturally occurring radioactive material (NORM), primarily radium-226 and radium-228, is present in much of the produced water in the Gulf of Mexico [109,110]. The authors of [104] reported total radium activities ranged from 304 to 2312 dpm/L.

Hydrocarbons are also present in produced water, both in dissolved and dispersed (oil droplets) form that can interact with the benthic community [103]. Dispersed oils can also rise to the surface and interfere with the transfer of oxygen from the atmosphere into the water, coat marine mammals, birds and fish, and have direct toxic action on some organisms [111]. Whole effluent toxicity assessments have reported high toxicity levels of produced water [21,112]. Produced water has been shown to reduce abundance of benthic macroinfaunal communities in wetlands receiving discharge [21,99,104,112] often at distances of hundreds of m from discharge sources. [112]. The presence of high concentrations of hydrocarbons in sediments near discharge sites indicates long-term accumulation and resistance to degradation [21,22].

In [4] the authors reviewed the ecological impacts of O&G development on coastal ecosystems in the Mississippi delta. Oil spills have generated significant impacts due to the toxicity of spilled oil. Effects on plant communities include disruption of plant–water relationships, direct impacts to plant metabolism, toxicity to living cells, and reduced oxygen exchange between the atmosphere and the soil. Effects on consumers include growth inhibition, reduced production, altered metabolic systems, and biomagnification of hydrocarbon compounds. The combination of these factors increases plant stress and plant death.

6. Interactive, Cumulative, and Indirect Impacts of Oil and Gas Impacts

Each of the three types of oil and gas activity (alteration of surface hydrology, induced subsidence, and production of toxic contaminants) causes significant impacts. However, when the effects of all three activities interact in cumulative and indirect ways, the impacts are much greater.

In Figure 16, the impacts of each type of activity are shown separately. The direct effect of induced subsidence is a loss of surface elevation due fault activation and/or compaction of subsurface sediments due to fluid removal. Loss of surface elevation leads in turn to stressed wetland vegetation, lower productivity, and ultimately vegetation death and wetland loss.

Surface hydrologic alteration due to canals and spoil banks also leads to a loss of surface elevation due to a cascading series of impacts as shown by the relationships in Figure 16. Deep straight canals cause the deterioration of natural tidal channels and changes in regional hydrology and saltwater intrusion. Spoil banks block tidal flooding of marshes and lead to increased inundation of marshes as well as reduced sediment and nutrient input to marshes. These impacts stress marshes so that productivity is lower and organic soil formation is reduced. The combination of lower sediment input and lower organic soil formation causes higher shallow subsidence and ultimately to vegetation death. Saltwater intrusion and vegetation death lead to collapse of the soil column due to rapid decomposition of soil organic matter.

Toxic impacts are due to oil spills and produced water discharge which contains very high salinity brines and a variety of toxic materials. These stress vegetation and cause wetland mortality and collapse of marsh soils leading to loss of elevation.

Thus, all three types of impacts lead to stressed wetland vegetation, loss of elevation, and vegetation death. The cumulative and indirect impacts are much greater than for individual impacts acting independently. These interact with a range of environmental forcings such as lack of riverine input, sea-level rise, and hurricanes to exacerbate wetland loss even further. For example, wetland loss in the region of the central coast impacted by Atchafalaya River discharge is much lower than most of the rest of the coast even in areas impacted by O&G activity [74,113]. The net effect is that O&G activities make wetlands more susceptible to other forcings that negatively affect wetlands.

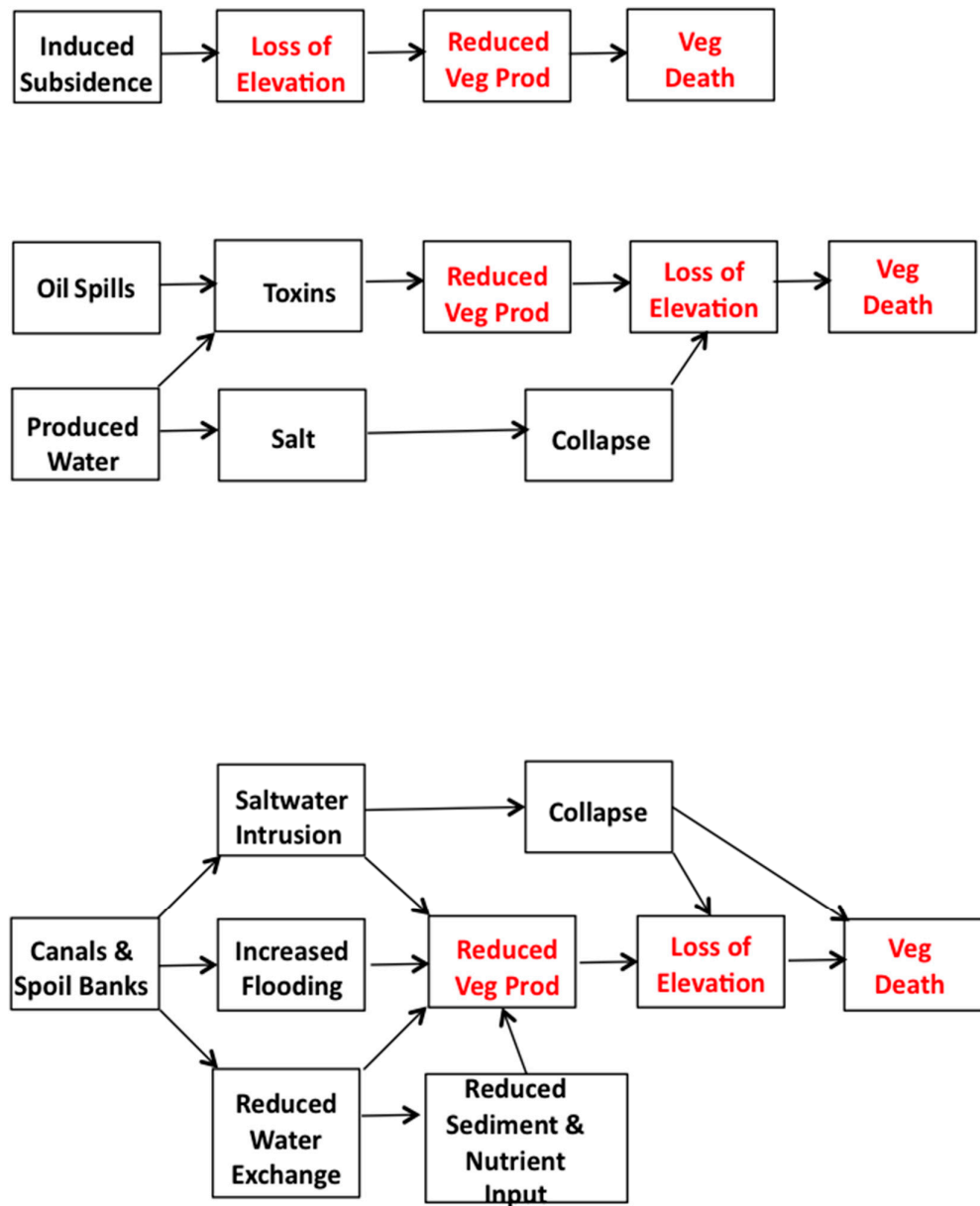


Figure 16. Diagram showing the three general types of impacts from oil and gas activity-induced subsidence, toxicity effects, and altered surface hydrology due to canals and spoil banks. The impacts of these activities are shown separately, and impacts shown in red are common to all three activities. As reduced vegetation productivity, loss of elevation, and vegetation death can result from all three activities, there are pervasive cumulative and indirect impacts that result in overall greater impacts on coastal ecosystems, especially, that would result from the impacts acting separately.

Such cumulative and indirect impacts due to O&G production are evident when images of oil fields are viewed over time. The Venice Salt Dome in Plaquemines Parish and the Bully Camp oil field in Terrebonne Parish are just two of hundreds of examples of wetland disappearance over time in coastal Louisiana (Figures 17 and 18). In these two fields, pre-oil and gas activity maps show the presence of small natural levee ridges and extensive unbroken marsh. In both fields, the 1950s maps show canals and spoil banks but without significant marsh loss. Over time, marsh loss expands to cover almost the entire area of the field and spoil banks begin to disappear as they subside below

water level. The widespread loss of wetlands is due to such cumulative and interacting effects of surface alterations in hydrology, induced subsidence, and toxic effects.

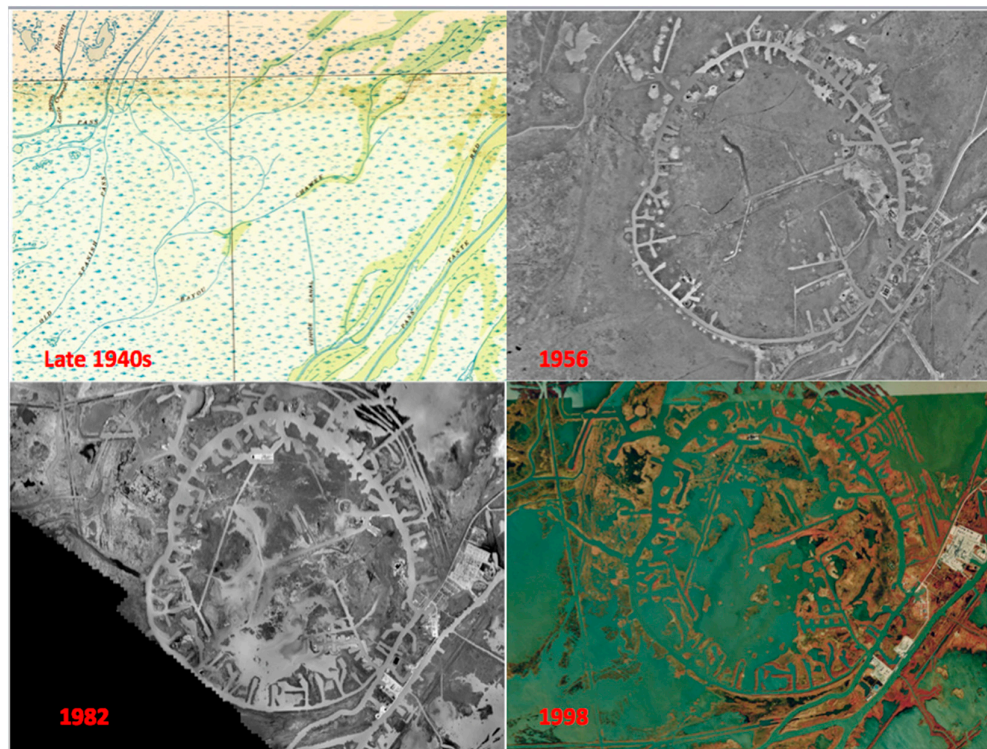


Figure 17. Images of hydrologic changes and wetland loss in the Venice field, Plaquemines Parish, Louisiana over time. This oil and gas field has been termed the “wagon wheel” because of the circular canals and spoil banks that outline the salt dome around which oil and gas containing formations were located. Note that wetland loss occurs both in the vicinity of the canals as well as throughout the area of the field. In addition to wetland loss, many of the spoil banks have subsided below water level and are no longer visible. The green highlighted channels in the 1940s are minor distributary ridges that both conveyed water and were a barrier to horizontal flow perpendicular to these ridges. (Images from USGS topographic maps (late 1940s) and Google Earth).

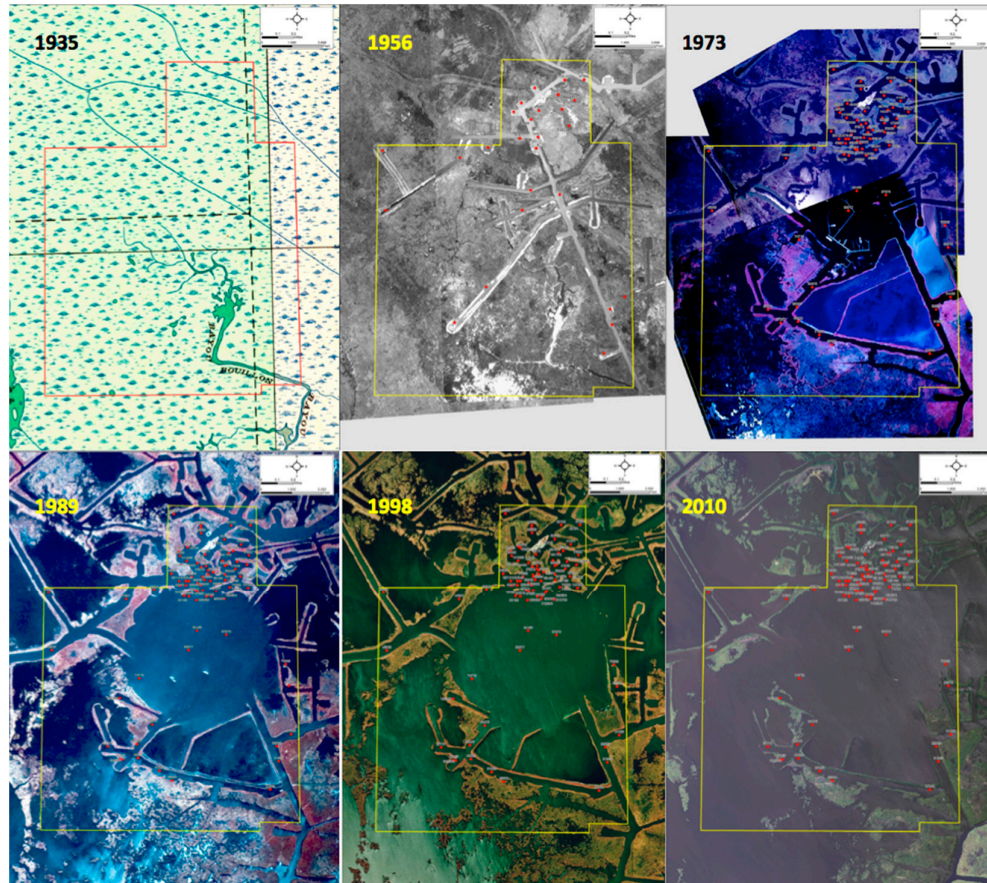


Figure 18. Images of the Bully Camp oil and gas field over time. The yellow line denotes an ownership tract in the field and red dots show locations of oil and gas wells. Note that land loss has been pervasive over the general area of the field. The central water body in the 1989 image is over an area of sulfur production on the top of the salt dome underlying this field. The narrow blue lines in the 1935 map are abandoned minor distributary ridges that were breached by canals (images from [76]).

7. Restoration

A well-designed restoration plan should be based on information about the impacts during the life cycle of O&G fields. Restoration of wetlands lost due to O&G activities will involve a synergistic approach that deals with the damage of O&G impacts and rebuilds a functioning coastal wetland system. A central objective in restoration is rebuilding elevation due to both surface subsidence caused by altered hydrology and subsurface induced subsidence. Subsurface induced subsidence cannot be reversed, so sediment must be added at the surface to offset both subsurface and surface subsidence. Options for restoration include (1) marsh creation and restoration using dredged sediments [114–117]; (2) full use of all available sediment resources including Mississippi River, GIWW, and sediments resuspended during storms [118,119]; and (3) hydrologic restoration such as backfilling canals and spoil bank management, and restoration of hydrologic networks [119–123]. Rebuilding natural levee ridges that have been severed by canals can help restore natural hydrology to prevent saltwater intrusion and reduce increased hydrologic energy caused by more direct connections between interior parts of the delta and the Gulf of Mexico.

Elevation can be built up by adding dredged material to shallow water bodies, some that were previously wetlands, to an elevation that will support marsh vegetation [115,124,125]. Restoration of open water and degraded wetland areas to sustainable marsh are of tremendous importance in coastal Louisiana. The 2017 Coastal Master Plan (CMP) for restoration of the Mississippi delta dedicates nearly \$18 billion to marsh creation (the largest investment in a single type of restoration

project) and many of those projects include both a short-term and a long-term phase [126]. The short-term phase focuses on immediate actions needed to protect vulnerable marshes from the proximal causes of loss (saltwater intrusion, erosion, and other consequences of significant hydrologic modifications) using a combination of restoration techniques (especially hydrologic restoration and marsh creation using dredged sediments). Successful implementation of short-term strategies reduces rates of wetlands loss and provides the foundation for longer-term strategies. The long-term phase focuses on wetlands gains through Mississippi River sediment diversions and capture of sediments advected over the marsh surface, with the intent of encouraging development of a sustainable wetland ecosystem (https://www.lacoast.gov/new/about/Basin_data/te/Default.aspx).

Introduction of sediments, through placement of fill material and/or spray dredging, is a necessary component of marsh restoration in degraded O&G fields and sediment can be pumped long distances, as is the case for many 2017 CMP projects [127–132]. Containment dikes are utilized to confine unconsolidated material until it settles and dewateres [120]. Then these dikes can be degraded or gapped to the same elevation as the marsh platform in order to allow water exchange and marsh drainage, to improve productivity and aeration, and increase capture of suspended sediments that are advected over the marsh surface.

Sediment addition increases marsh surface elevation, thus reducing flood stress to the plant community. The authors of [114] showed that raising the surface of a deteriorating *Spartina alterniflora* salt marsh by 10 cm using dredge spoil resulted in a twofold increase in aboveground biomass production after the second growing season. In [115] it was found that increased elevation through the deposition of a 2 cm layer of dredged material in a deteriorated Louisiana marsh increased percent cover of *S. alterniflora* three-fold within one year. The authors of [125] studied dead marshes near Leeville that were restored using dredged material and found that sediment-slurry addition increased the elevation of the marsh surface and alleviated stress associated with excessive inundation and high salinity. Primary production was highest at elevations ranging from 29 to 36 cm NAVD 88 (12–20 cm above ambient marsh), and decreased at elevations above 36 cm NAVD 88, where primary production was limited by insufficient flooding and low nutrient availability. Sediment subsidy increases soil mineral matter, soil fertility, and marsh elevation, and thereby reduces nutrient deficiency, flooding, and interstitial sulfide stresses, generating a more favorable environment for plant growth and potentially, marsh sustainability [116,117].

After containment dikes are gapped, restored marsh will have connectivity with surrounding ecosystem and plants will naturally recruit to the area or they can be planted. Although the created marsh will be initially higher than surrounding marshes, it will settle and have a higher bulk density. It is likely that these created marshes will have a higher productivity and production of organic matter than surrounding marshes. The plant species richness should be the same as surrounding marshes, which is not very high in brackish and salt marshes of coastal Louisiana compared to fresh marshes. Plant diversity and soil organic matter content are higher in brackish marsh than in salt marsh. Brackish marsh is typically dominated by *Spartina patens* (marshhay cordgrass). Other significant associated species include *Distichlis spicata* (salt grass), *Schoenoplectus olneyi* (three-cornered grass), *S. robustus* (salt marsh bulrush), *Eleocharis parvula* (dwarf spikeweed), *Ruppia maritima* (widgeon grass), *Paspalum vaginatum* (seashore paspalum), *Juncus roemerianus* (black rush), *Bacopa monnieri* (coastal water hyssop), *S. alterniflora* (smooth cordgrass), and *S. cynosuroides* (big cordgrass) [130]. Salt marsh has the least plant diversity of any marsh type. The community is often totally dominated by smooth cordgrass. Significant associate species includes marshhay cordgrass, salt grass, black rush, and *Batis maritima* (salt wort).

A tidal network needs to develop in the restored marsh. All restoration plans need a component that focuses on natural hydrological functioning. A large-scale restoration project on Delaware Bay indicated that if a few primary channels were dredged, the system would naturally then develop a full tidal channel network [130,131]. The project involved restoration of tidal flooding by breaching dikes around formerly diked salt-hay farm and re-excavation of tidal creeks. Hydrologic design occurred in a “self-design” fashion after only initial cuts by construction of the largest (class 1) channels.

Spoil bank and canal management should be part of a restoration plan. Some canals should be backfilled as much as possible by pushing spoil banks back into canals. As spoil banks have settled and organic matter has decomposed, canals cannot be fully filled in using material from spoil banks. Thus, dredged material will have to be used to fully fill canals. In some cases, spoil banks should be left in place to protect remaining marshes from wave attack (see Figure 13).

After the marsh is restored and natural hydrology has been re-established, full use of all available sediments should be incorporated into the restoration design. Important sources of sediments include Mississippi/Atchafalaya Rivers as well as smaller rivers, sediment diversions, the Gulf Intracoastal Waterway, and sediments resuspended by storms [118]. Water sources with appreciable levels of nutrients should be used where possible to enhance marsh production including upland runoff, agricultural drainage, and treated municipal effluent [133,134].

When planning restoration priorities, consideration should be given to the more stable underlying geologic framework choices, and avoidance of those areas still in the actively degrading part of the cycle. Examples include marsh construction on the more stable upthrown side of a fault, rather than the subsidence compaction and fault affected O&G field on the downthrown side. The authors of [14] discussed the role of faulting in wetland loss in the Mississippi delta. In [135] the authors pointed to failed restoration projects where faulting has not been considered. Thus, taking into consideration underlying geology can lead to more successful and sustainable restoration.

Decontamination of restored sites is an integral part of restoration. In many cases, toxins can be buried in place but in some instances the contaminants have to be removed [4]. In addition to environmental impacts associated with land loss from O&G production operations, there often is environmental damage to soil and groundwater contamination that may have occurred from these same types of O&G operations. These damages include contamination to soils, groundwater, and in some cases underground sources of drinking water. These types of damages require extensive testing and the restoration includes soil treatment or removal and the cleanup of contaminated freshwater zones. Dealing with contamination can involve removal of the surface waste, excavation of 'hot spots' of concentrated pollution (chemicals of concern, COC) followed by treatment and disposal, and pumping and treatment of contaminated groundwater followed by treatment or subsurface injection. The goal of the remediation effort is to return the soil and groundwater to agreed-upon standards such as background soil standards contained in the La. DNR/OC regulations known as 29B (the section of the rules) and the La. DEQ RECAP (Risk Evaluation/Corrective Action Program) for both soil and groundwater. A mix of the standards is sometimes used. The term 'agreed upon' is used because cleanup is usually done in the context of a legal action with the involvement of the landowner-plaintiff, the oil companies(s), DNR, DEQ, and the Court. The DNR 29B (Title 43, Part XIX, statewide order 29B) standards were/are heavily influenced by the oil and gas exploration and production industry (E&P) while the DEQ RECAP standards are based on risk science (LAC 33, 2003; <https://www.deq.louisiana.gov/assets/docs/Land/RECAP/RECAPfinal.pdf>). RECAP provides numerical screening standards for many chemicals in soil and groundwater and three management options. In many cases, addressing land loss and environmental cleanup must be done at the same time to fully restore the land.

In planning for restoration of degraded wetlands in O&G fields, there should be coordination with other projects. For example, beneficial use of dredged sediments, where available, can be used to raise elevation. There are numerous wetland restoration projects taking place in the Mississippi Delta. These include marsh creation, river diversions, hydrologic restoration, barrier island restoration, rebuilding of distributary ridges, and shoreline protection [126,136]. Restoration of the impacts of O&G activities involves to a lesser or greater degree all of these activities. For example, where sediment diversions are planned in the vicinity of an O&G field that is being restored, maximum use of diverted sediments should be a goal of the project. As noted above, beneficial use of sediments dredged for other activities such as navigation canal maintenance should be considered for marsh creation in restoring wetlands degraded by O&G activities. Hydrologic restoration and natural levee restoration in the vicinity of a restoration project in an O&G field should be done in a

way that compliments the larger efforts. In this way, the restoration of and O&G field can be done to increase benefits over a larger area.

8. Summary and Conclusions

Oil and gas activity has been pervasive in the Mississippi delta and both production and environmental impacts follow a predictable life cycle. There are hundreds of O&G fields in coastal Louisiana, as well as a dense network of canals associated with drilling access, navigation, and pipelines. The production history for individual fields can last 40–60 years with production rising rapidly to a peak around 1970 and then declining. Since most drilling started in the 1940s and 1950s, most wells are no longer producing or are in the final stages of production and this cycle conclusion holds true for aggregate MRD production. Most fields had very low levels of production by the 2000s. Produced water generally lagged O&G production and was generally higher during declining O&G production.

Oil and gas activities have contributed in three major ways to environmental impacts on coastal ecosystems and specifically to wetland loss. These include alteration of surface hydrology due to canal dredging and spoil placement, induced subsidence and fault re-activation due to fluids withdrawal, and toxic stress due to pollution by spilled oil and produced water. Wetland loss due to O&G gas activity is initially due mainly to direct impacts of canal dredging and spoil placement, but grows over time due to cumulative and interactive effects. This wetland loss then grows over time to encompass much of the field and adjacent areas. Networks of interconnected canals form new patterns of water flow and often lead to saltwater intrusion. Interestingly, spoil banks are not necessarily a permanent landscape feature and have a life cycle of their own. They subside and compact over time and a quarter to a third of spoil banks likely have no subaerial expression.

Fluid withdrawal from O&G formations leads to induced subsidence and fault activation [91]. Induced subsidence occurs in two phases. Withdrawal of O&G and produced water induce reservoir compaction resulting in a reduction of reservoir thickness. A slow drainage of pore pressure in the bounding shale mainly due to water pumping induces time-delayed shale compaction and subsidence can continue for decades after most O&G has been produced. This results in subsidence over much of the oil fields that can be greater than surface subsidence due to altered hydrology.

Produced water from O&G fields is water brought to the surface during O&G extraction and generally includes a mixture of either liquid or gaseous hydrocarbons, high salinity produced water, dissolved or suspended solids, produced solids such as sand or silt, and injected fluids and additives associated with exploration and production activities. Produced water has been shown to be toxic to many estuarine organisms including vegetation and consumers. Spilled oil has been shown to have lethal and sub-lethal effects of a wide range of estuarine organisms. The three main types of impact of O&G activities act in cumulative, synergistic, and indirect ways that lead to greater overall impact. Restoration of wetlands lost due to O&G activities will involve a synergistic approach that deals with the damage of O&G impacts and rebuilds a functioning coastal wetland system.

Restoration should be the final stage in the life cycle of O&G fields. A central objective of restoration is restoring lost elevation. Options for restoration include marsh creation and restoration using dredged sediments, full use of all available sediment resources, and hydrologic restoration. Decontamination of restored sites is an integral part of restoration.

Author Contributions: All authors contributed to the writing of this review manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of Interest: J.W.D., H.C.C., R.G.H., and C.R.N. state that they are engaged as experts in lawsuits regarding the environmental impacts of oil and gas activity on coastal ecosystems. No funding from these activities was used for the preparation of this paper.

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