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A review of issues related to formation, deterioration and restoration of the Chenier Plain, Mississippi River Delta, LA - Combining nature based and engineered approaches

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ABSTRACT

Sand and mud reaching the Mississippi River Delta (MRD) via distributary channels created the delta lobes that, in aggregate, make up the current Deltaic Plain (DP). Sediments transported to the west in the coastal boundary current, in turn, have built the "downstream" Chenier Plain (CP). We review options for restoring the CP coast between the beach dune system and the first series of Cheniers that fronts the Gulf of Mexico (GOM) for ~200 km to the west of the DP, and contributes 30% to total area of the MRD. The CP was built by marine rather than fluvial processes that have resulted in episodic westward and onshore transport of fine-grained sediments delivered to the inner shelf by the Atchafalaya River distributary. Long-term restoration of the MRD is currently proceeding under the Louisiana Coastal Protection and Restoration Authority (CPRA). Projects to stabilize the CP coast are being proposed and built to test whether coastal defense structures like breakwaters and groins designed to retard erosion on sandy coasts can be adapted for use on muddy shores where cohesive sediments predominate. An estimated 30 to 50 Mt y^{-1} of resuspended mud is moved past the CP coast by the coastal boundary current in a feature described as the "Atchafalaya Mud Stream." Mid- to late-Holocene MRD lobes on the west side of the DP similarly contributed mud to the same part of the inner shelf. Then, as now, a portion of this near-shore suspended sediment flux was diverted into shore-welded mudflats that were colonized by marsh vegetation that offset local shoreline retreat. The CP is a regressive coastal feature, formed since sea level rise and marine transgression slowed, and it has experienced a 19% wetland loss since the early 1930s. Coastal retreat, up to more than 10 m y^{-1}, prevails along more than half of the CP shore. Most structures built on the CP coast are constructed of lightweight materials to reduce settlement and lower deployment costs. If the generally positive results to date are validated, then designs can be optimized to increase transmissivity of high-density "fluid mud" (>10 g l^{-1}) during low-frequency swell, while reducing energy transmission in the higher frequency band occupied by locally generated seas that seem to be most destructive to newly created mudflats and marshes. We show that restoration in the CP can be enhanced by taking advantage of the land building capabilities of mud stored in the nearshore and delivered to the coast during storms. The goal is to use engineered structures to increase the rate at which mud is deposited and retained at the shore, thereby harnessing natural processes to reinforce the coast. The use of dredged sediments for wetland creation augments coastal shoreline enhancement.

1. Introduction

The greater Mississippi River Delta (MRD) is divided into two readily distinguished physiographic provinces (Fig. 1a). On the east is the deeply embayed Delta Plain (DP), while the smoother, arcuate Chenier Plain (CP) coast to the west has few openings or passes connecting to the

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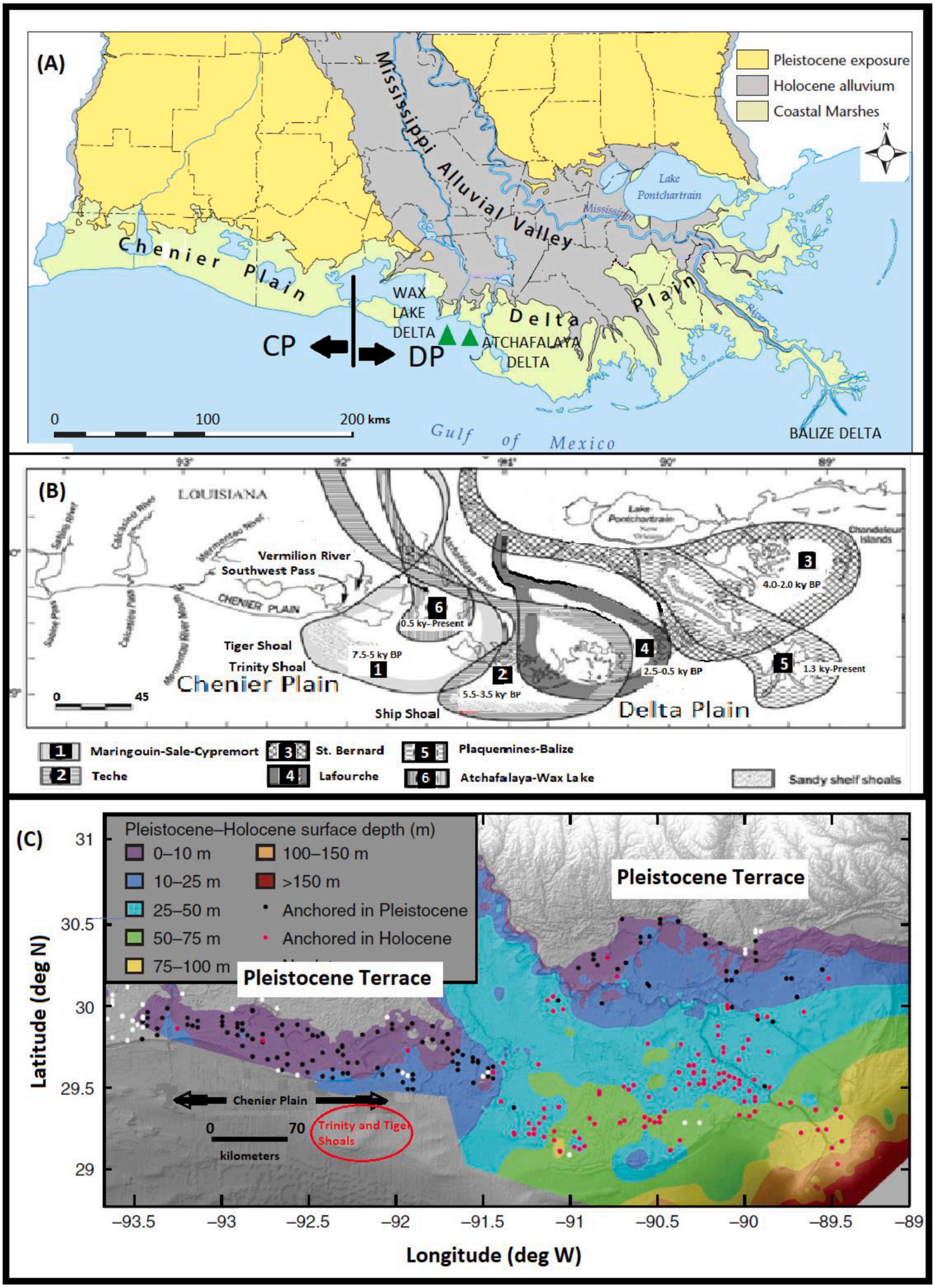

Fig. 1. (A) Mississippi River Delta (MRD) showing Delta Plain (DP) at the seaward end of the alluvial valley, and Chenier Plain (CP) as a downdrift wetland band extending west along the coast. Modified from [9]. (B) Approximate location and extent of Mid-to Late-Holocene delta lobes adapted from McBride et al. [4] with activity intervals for each lobe from Blum and Roberts [10]. (C) Depth to Pleistocene in the MRD. or a Holocene isopach with locations of marsh monitoring stations (CRMS) maintained by the CPRA from Jankowski et al. [11].

Gulf of Mexico (GOM) [1,2,3,4,5,6]. CP wetlands make up 30% of MRD wetlands today, though 20% of CP land present in the early 1930s converted to open water by 2015 [7,8], in part due to rapid shoreline retreat on this muddy coast, which has averaged up to -10 m-y^{-1} in some places [2].

The CP is a ~200-km long microtidal coast composed of long, narrow wooded interior beach ridges dominated by live oaks (the Chenier ridges), tidal mudflats, and fresh to saline marshes extending from Southwest Pass at Vermillion Bay to west of the Sabine River on the Texas-Louisiana border [3,12,4],2015, [13,14]. The CP ranges between 20 and 35 km wide with elevations of more than 2 m on the Chenier ridges [13]. From west to east, the CP is divided by the Sabine, Calcasieu, Mermentau, and Vermilion Rivers and their estuaries [14]. The drainage basins of these rivers are connected at the landward margin of the CP by the Gulf Intracoastal Waterway (GIWW), an important east-west navigation channel.

Coastal deposition and erosion on the shoreline of the CP is affected by near-bottom layers of highly concentrated fine-grained sediment (> 10 g l^{-1}), or “fluid mud,” derived from Atchafalaya River inner-shelf pro-delta deposits [15,16,17–19,20]. The presence of these thixotropic suspensions in the littoral zone are known to prevent wave breaking in the surf zone and promote rapid deposition of shore-welded mudflats [21]. A number of shore protection projects have been built along the CP coast to slow shoreline retreat, and more are proposed by the Louisiana Coastal Protection and Restoration Authority (CPRA) as part of a multi-billion dollar program to restore MRD wetlands and reduce hurricane surge flood risk to communities [22]. These structures are jetties, revetments and breakwaters of varying designs.

In this paper we review processes affecting the seaward fringe of the CP, from the discontinuous beaches, berms and exposed marshes adjacent to the GOM inland to the first major Chenier ridges. By combining new information with existing information, we extend what is known of wave-mediated onshore mud transport to include both overwash through the beach-dune system and through inlets into back-barrier wetlands. We propose integrated nature based techniques that combine natural processes with engineered structures for shoreline protection and land building designed to capture sediment from the nearshore “mudstream” via three mechanisms: (1) capturing sediments advected to marshes through inlets; (2) retaining sediment on the shoreface using engineered structures; and (3) capturing sediments delivered to the back barrier marshes via overwash during tropical storms. Beneficial use of dredged sediments is also an important component of CP restoration. We also review completed projects and examine the potential for such structures to shift the equilibrium state from transgression toward regression on the muddy CP coast by accelerating mud deposition, including littoral mudflat formation and longevity. We also review inlet management to enhance suspended sediment input to marshes between the beach-dune system and the use of dredged material for wetland creation.

1.1. Chenier Plain formation

Cycles of coastal deposition and erosion have created the alternating beach ridges separated by marshlands that characterize the CP coast (Fig. 2). Prior to reactivation of the Red/Atchafalaya route, and infilling of the Atchafalaya Basin, the Mississippi River last discharged to the west of the deltaic plain about 4000 y BP. Then, large quantities of river-derived mud were moved by longshore currents and deposited in nearshore mud banks that could be resuspended and moved onshore by low-frequency storm waves along the CP shore, resulting in shoreline regression [4,21]. When the Mississippi River flow discharged to the east, the mud supply was reduced and the CP shoreline generally retreated, but also became sandier, allowing the formation of shore-parallel carbonate (shelly) Chenier beach ridges. The most continuous Chenier trend, which is 5 to 10 km from the coast, has been dated to 2800 yBP when the St. Bernard sub-delta was building south and east of Lake Pontchartrain [3].

1.2. Chenier Plain geology

The DP formed over the past 6–8 ky by deposition of fluvial sediments into a sequence of deltaic lobes (Fig. 1b) in shallow nearshore

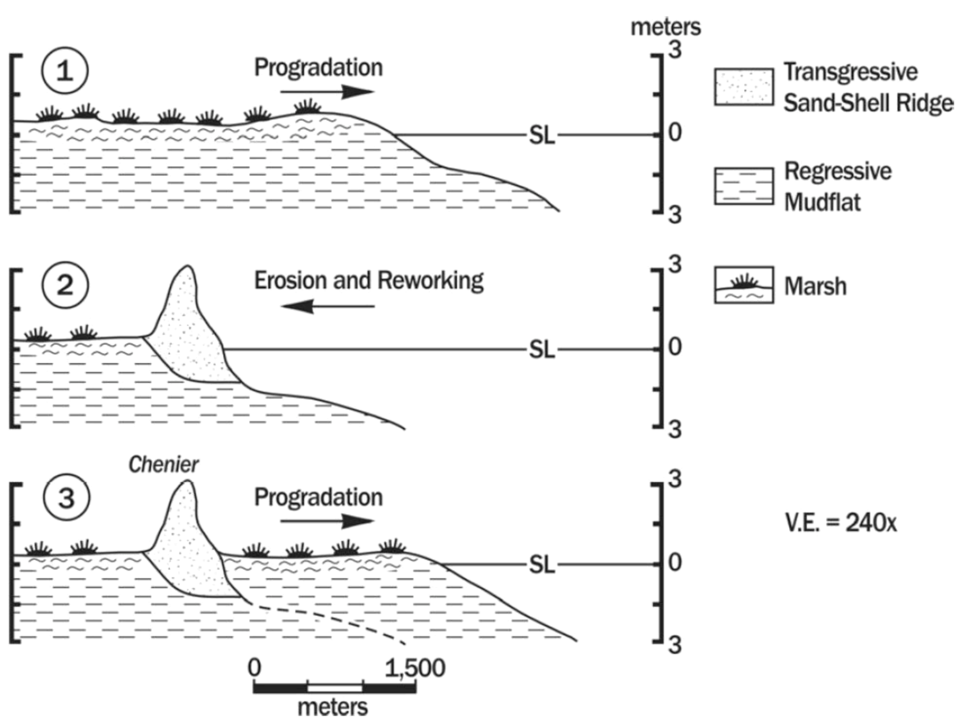

Fig. 2. Depositional model illustrating chenier plain development through mudflat progradation (1), wave erosion and reworking to create a transgressive ridge (2), and then mudflat progradation, which completes chenier genesis (3). SL = sea level [4].

GOM waters [10,4,23]. A linked land-building cycle began in the downdrift CP about 5.6 ky BP when mean sea level (MSL) was about 2 m lower than it is now, but high enough to shift the GOM shore 25 to 30 km inland of its current position [24], Anderson et al. 2012. The landward limit of this shift is marked by the Ingleside Barrier , a shoreline deposit formed during the previous interglacial highstand of sea level (127 ky BP). This feature marks the southern edge of Pleistocene Terrace exposure today near the Gulf-Intracoastal Waterway (GIWW) right-of-way (Fig. 1c; [25]). An erosional discontinuity separates the Pleistocene alloformation (Beaumont) from the less consolidated and weathered Holocene sediments above (Heinrich et al. 2017). The top of the Beaumont gently slopes seaward under the marshes into the GOM. Nowhere in the CP is the Pleistocene more than 10 m below the marsh surface (Fig. 1c).

Rising water levels in the GOM submerged the abandoned Maringouin/Sale/Cypremort Delta while the Teche Lobe was building seaward (Fig. 1b). This created a source of prodelta mud in much the same inner-shelf location as the Atchafalaya mud stream today [26]. Erosion of the old lobe and creation of the new one provided reworked sediment to the CP north of the extant chenier ridges where a tier of large, shallow lakes, including Sabine, Calcasieu, Grand and White Lakes, have since displaced 1300 km^2 of the northern CP marsh. The relict Trinity and Tiger Shoals complex 30 to 40 km offshore (Fig. 1c) has remained a continuing influence on the waves and currents that affect the CP coast, and the geometry of the mud stream that connects the DP to the CP [26].

The end of the regressive phase of the Teche delta initiated a period of shoreline retreat in the CP, as well as creation of the first shore-parallel CP beach trends. These ridges were named “cheniers” for the massive live oak trees that flourished 2-3 m above the marsh and made the ridges visible from the GOM [6]. Gould and McFarlan [3] used radiocarbon dates from shells retrieved from beneath cheniers to calibrate the linkage between delta lobe building on the eastern side of the DP (Fig. 1b) and the timeline for chenier formation. Little Chenier, the most inland – and therefore oldest – extant chenier returned a radiocarbon date of 2.9 ky BP, which corresponds to the end of the regressive phase of the Teche Delta, when the Mississippi River avulsed into the east facing St. Bernard Lobe (Fig. 1a). Hijma et al. [27] used the

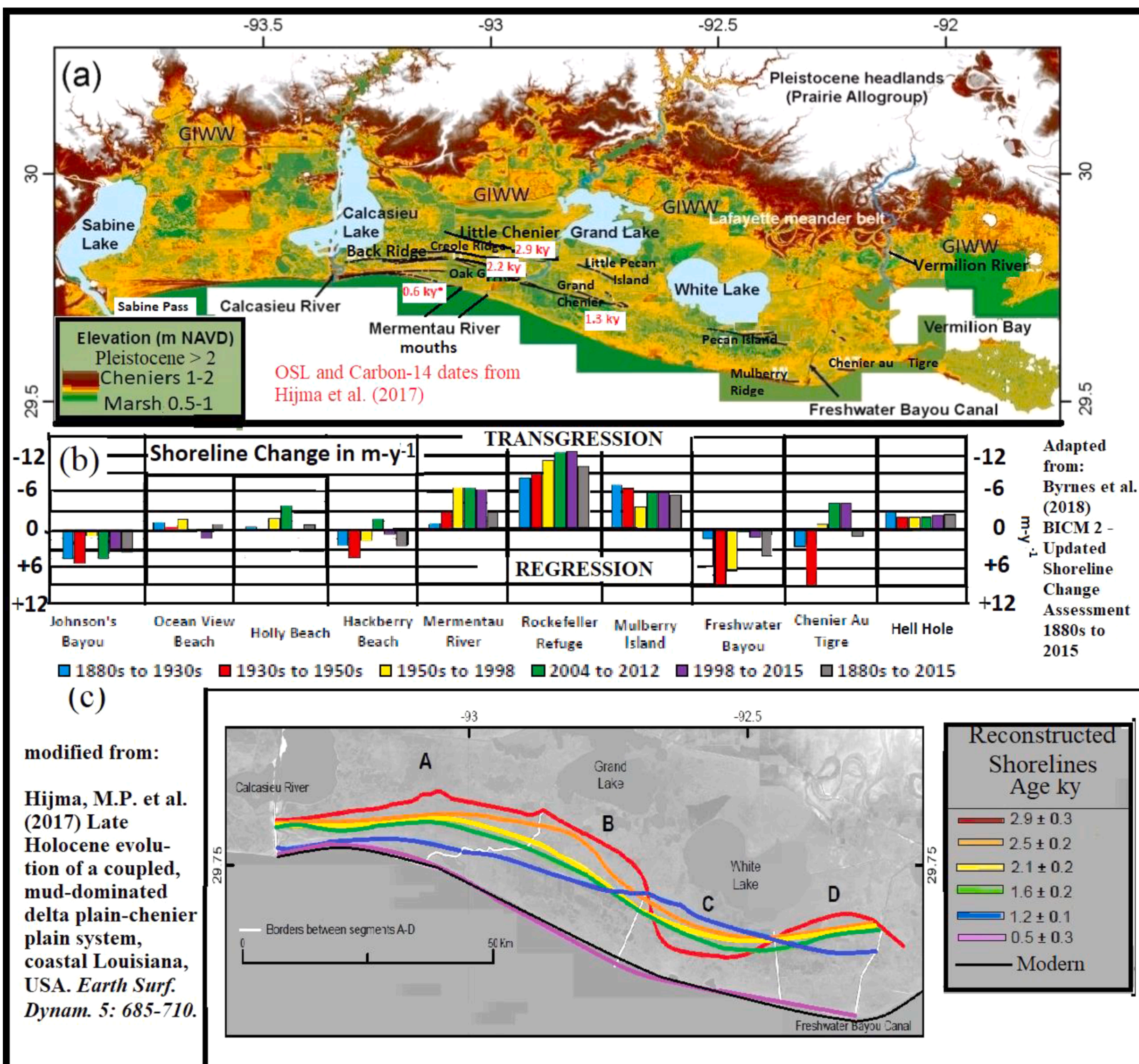

Fig. 3. (A) Chenier Plain (CP) digital elevation model modified from Hijma et al. [27]. (B) Rates of shoreline change over a range of intervals from 1880 to 2015 for 10 shoreline reaches monitored by Byrnes et al. (2018). (C) Shoreline positions mapped by Hijma et al. [27] at times when beaches formed along the Chenier Plain coast.

Optically Stimulated Luminescence (OSL) technique to date burial of quartz grains in the Cheniers. These results supported and augmented the earlier radiocarbon dates, and more broadly, permitted reconstruction of a range of older CP shorelines (Fig. 3a). After abandonment of the Teche Delta, coastwise mud transport to the CP did not resume until 1.2 ky BP. This was when the prograding Lafourche Delta reached the shelf, when Grand Chenier was at the GOM interface (Fig. 3a).

Many kilometers of relict barrier beaches, spits, and inlet gaps are embedded in the CP marsh today within a 10 km band that includes the modern coast. They were formed during the 2000-year hiatus between the end of the Teche and beginning of the Lafourche mud streams. Hijma et al. [27] obtained dates of 500 to 600 y BP from discontinuous Chenier ridges that are now being truncated by retreat of the modern shoreline. These dates are consistent with another Mississippi River avulsion, in this case from the Lafourche to the modern shelf-edge Plaquemines/Balize Lobe (Fig. 1b), which again cut off, or significantly reduced conveyance of fine-grained sediment to the CP in a nearshore mud stream (McBride and Suter 2008). The mapped chenier sytems from the Sabine to the Calcasieu and then easternmost sub-plains vary markedly, suggesting that MRD lobe switching may have been convolved with a combination of river sediment supply events and/or major storm impacts to produce the complex record here [28]. The Hijma et al. [27] reconstruction of past GOM shorelines indicates that the eastern CP marsh built 12 km seaward during the relatively brief 500 years it received mud from the Lafourche Delta (24 m-y^{-1}). This rate was essentially zero 100 km to the west at Calcasieu Pass (Fig. 3c). Such a pattern is consistent with an inner-shelf prodelta mud source east of the earlier Teche source. As is true today, however, coastal retreat and advance may occur simultaneously on different portions of the CP shore (Fig. 3b).

Hijma et al. [27] place the CP shoreline at 500 y BP very close to the modern shoreline despite all the changes in Mississippi River sediment supply documented above (Fig. 3c). Activation of the Atchafalaya as a significant Red/Mississippi River distributary occurred at about the same time as the abandonment of the Lafourche Delta [29,30]. A reactivated mud stream from an inner-shelf source close to the CP curtailed the CP transgression that might otherwise have accompanied a major delta lobe shift to the east.

1.3. Historic CP marsh loss processes

Interior CP wetland loss over the past century is largely due to anthropogenic alteration of wetland hydrology by canals, construction of leveed impoundments for waterfowl management, and salinity intrusion caused by enlargement of the Sabine, Calcasieu and Mermentau River navigation entrances [31].

In the CP, shore-normal deep-draft navigation channels constructed in the 1910s, and enlarged many times since then at the outlets of the Calcasieu and Sabine Rivers, exposed low-salinity interior wetlands between shore-parallel beach ridges to saltwater intrusion, while dredging of oil and gas access and pipeline canals created new connections that allowed salinity changes to spread as well as increasing subsidence [31], Yu et al. 2012, [32]. The opposite occurred north of the main Chenier ridge where a number of small communities and LA Highway 82 are located. There, locks were built to restrict tidal exchange and store freshwater for rice irrigation, developed in seasonally flooded freshwater wetlands to the north. Throughout the region, at a smaller scale, owners of tidal marshes constructed low levees with weirs at water exchange points to control water levels and salinity in marsh impoundments managed for waterfowl [33–35,36,37]. These activities have fundamentally altered the hydrology, vegetation and ecology of this region, and have led to wetland losses in the CP (Fig. 6a). However, as can be seen in Fig. 6b, land loss rates in the three sub-basins of the CP have slowed over time. Coastal retreat – which prevails along much of the eastern 120 km CP shore - can be as high as 10 m/yr. Mudflats that can prograde the shoreline subaerially more than 500 m in a few days can occur anywhere along this coast, but are typically ephemeral and generally last less than a year.

In the DP, much historical loss has been attributed to tidal marsh submergence as a consequence of Relative Sea Level (RSL) rise, which is determined at more than 300 Coastal Reference Monitoring System (CRMS) stations [38]. Jankowski et al. [11] compared Surface Elevation Change (SEC) as well as Shallow Subsidence (SS) and Vertical Accretion (VA) at 89 CP and 185 DP stations with 6 to 10 years of record (Fig. 1c). The only statistically significant difference found between the two MRD regions was for SEC. Like all of the values acquired at CRMS stations, SEC is a trend (mm y^{-1}) determined by measurements made during repeated visits to a benchmark rod driven to refusal, typically more than 15 m, that serves as the base and datum for a removable Sediment-Erosion Table (SET; Fig. 4).

Because the Pleistocene is less than 10 m deep in the CP, the SET rod at each CRMS station penetrates the entire Holocene and is anchored in the Pleistocene (Fig. 1c). The mean SEC trend for DP sites was 5.7 mm y^{-1} (SD 7.2 mm y^{-1}), while the mean in the CP was -0.2 mm y^{-1} (SD 6.3 mm y^{-1}), essentially nil. The mean VA trend (12.8 mm y^{-1}) was twice that of SS in the DP, but the two trends were equal and offsetting at 6.5 mm y^{-1} in the CP ([11] Sup.). We interpret these findings to mean that SEC station trends in the CP marsh reflect maintenance of a static distance between the base of the rod (anchored in the Pleistocene) and the marsh soil surface. The thickness of the Holocene stratum in both CP and DP wetlands is reduced, on average, by 6 to 7 mm y^{-1} through subsidence due to gravity-driven dewatering and compaction (SS) in the top meter. This accommodation space is replaced in the CP by an equal increment of VA. Though the marsh vegetation in the CP includes the same tidal species as in the DP, diurnal and semi-diurnal tides are almost non-existent in the interior of the CP though seasonal water level fluctuations are at least as great as in the DP, up to 1 m.

So, if tidal deposition of sediment is less active in the CP marsh but is not leading to a lowering of marsh elevation, what is causing localized marsh submergence and lake formation other than anthropogenic activities? A recent 3D seismic investigation from southwest of Grand Lake near Little Chenier has shown that the Pleistocene formation underlying the CP marsh is fractured by many active down to the coast and and up to the coast normal faults that are resolved at depths greater than about 600 m below and can be projected to the surface (Fig. 5), the surface manifested in LiDAR data by elevation changes that in some cases have led to lake formation [5]. SET outliers in the CP that range from +22.5 to -17.3 mm y^{-1} could be measuring fault movement in the Pleistocene SET frame anchor that is reflected in the elevation of the marsh surface. If this is so, a fault-induced downthrown block that includes the Pleistocene will be read as a decrease in marsh surface elevation because it will lower the rod supporting the SET. On the other hand, if the thickness of the Holocene stratum above the Pleistocene will give results similar to what is commonly reported as shallow subsidence at DP stations lacking the Pleistocene anchor. It is possible that SET trends in the CP may be recording different processes than in the DP.

1.4. Littoral processes on the CP coast

Progradation of the CP shore is mediated by the addition of mud mobilized from temporary deposits on the inner shelf. Some of the vast flux is diverted to mudflats that weld to the shoreface under the influence of waves that are themselves modified by the very high concentrations of sediment entrained [39,4,13,40,41,42,21].

Despite an increase in the average volume of the Mississippi and Red rivers' sediment reaching the inner continental shelf offshore of the growing Atchafalaya River distributary, survival of the CP is challenged by the intermittency of mud delivery during high-energy events to an otherwise transgressive shoreline on the downdrift coast [16,40]. Persistent seaward regression occurs on the western end of the CP both east and west of the Calcasieu and Sabine River outlets, and on the eastern CP margin near Freshwater Bayou Canal [16,4]. These areas and

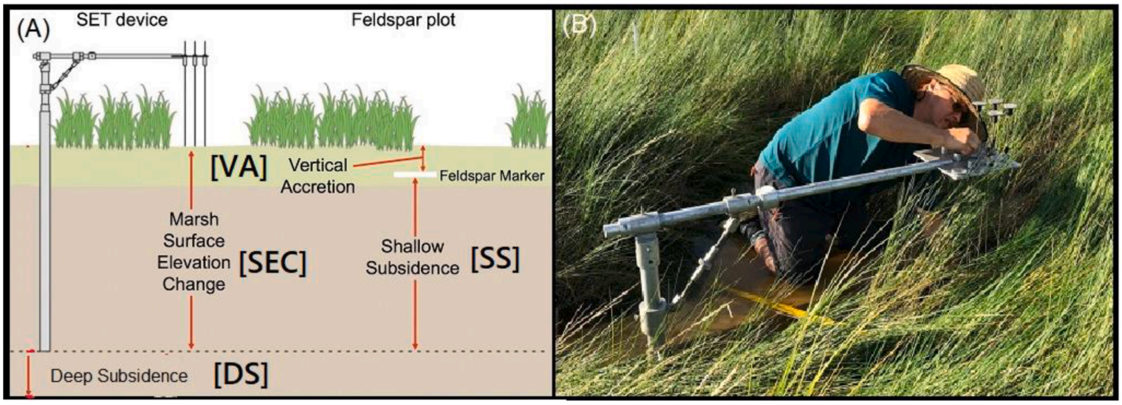

Fig. 4. (A) Measurements made at a CRMS station in the CPRA long-term marsh monitoring program focusing on how Surface Elevation Change (SEC) is determined using a Sediment Erosion Table (SET) modified from Jankowski et al. [11]. (B) Deploying a Sediment Erosion Table (SET) as described in Lane et al. (2020).

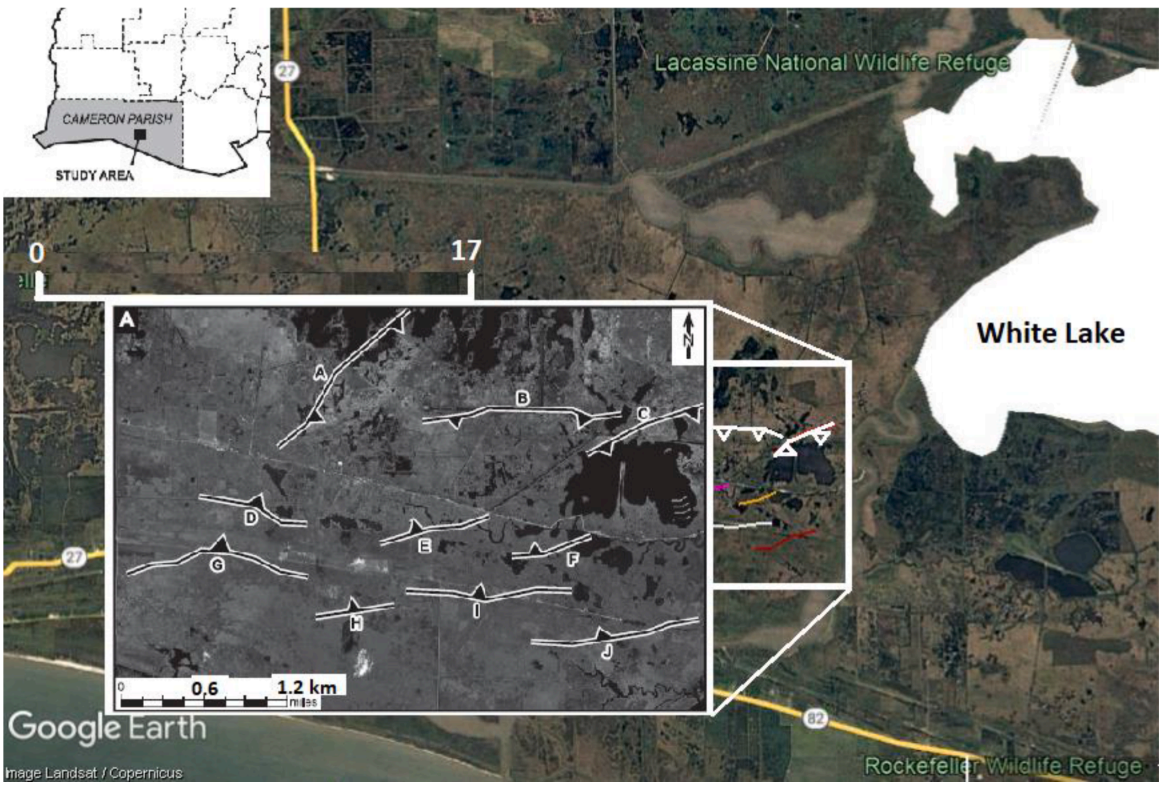

Fig. 5. Little Chenier area with detail inset showing active faults [62]. Tick marks are on the fault downtrown side. Note the presence of water bodies and their relationship to some of the faults.

others could be enhanced by considering sediment sources such as the Atchafalaya complex in combination with additional shoreline structures of the types built over the past 30 years as part of a major coastal restoration program (Coastal Protection and Restoration Authority 2017, [43]).

Input of sediment on the CP coast typically occurs in deposits up to 2 m thick lain down over a few days and consist almost exclusively of silt and clay with very little shell or organic matter [22]. These mudflats are rapidly colonized on the landward margin by salt marsh vegetation that is very productive. This chenier development sequence was first reported on the western Louisiana coast by Russell and Howe [6], but it was Morgan et al. [44] who noted the association of mudflat deposition with high-energy events. They measured 0.5 m of “gelatinous clay” blanketing a previously surveyed foreshore 3 days after a minor storm. They also observed subaerial “mud arcs” extending a kilometer offshore and for 4 km alongshore after Hurricane Audrey in 1958. Repetition of this process over the past 4 ky led to a building out the coast by many kilometers as long as erosion was overwhelmed by deposition.

With the exception of the prograding Atchafalaya and Wax Lake deltas, the present Louisiana coast is being shaped largely by erosive processes [45,46,4,13,47]. Along the CP shore, however, segments of mudflat progradation and accretion alternate with erosional segments, though erosion predominates, especially in the eastern CP [48,49,42]. Shoreline change is a function of incident wave energy, shoreline orientation to dominant wave processes, sea level rise, sediment supply, and the presence of engineered structures [48]. High winds associated with frontal passages and hurricanes also cause changes to the shoreline, generally flattening beach berms, but also causing regression in spots as arcuate mudflats several hundred meters wide form seaward and over the pre-storm beach face [16,4,40].

Because the Mississippi River discharge is divided between the east Mississippi distributary and the west Atchafalaya distributary, the CP coast has experienced persistent mudflat progradation for about 10 km west of Freshwater Bayou on the eastern flank, but shoreline retreat continues for 60 km to the west (Figs. 6c and 3c), until a reversal in the coastal buildout associated with the Calcasieu River jetties. While mudflats can form today anywhere along the central CP coast, they are ephemeral, rarely lasting a year, and have little influence on the long-term erosion rate.

2. Causes of land gain and loss in the Chenier Plain

2.1. Sediment delivery

The discharge of both the Mississippi River and the Atchafalaya River has increased over time. Since around 1930, the mean discharge of the Mississippi and Atchafalaya rivers have increased by about 25% and 70%, respectively due to rising temperatures and increased precipitation in the upper Mississippi and Ohio River watersheds (Fig. 7; [50], NOAA 2020). The discharge of the Atchafalaya River has increased more than the Mississippi because of the shorter distance to the GOM (187 km vs about 500 km for the Mississippi River). The water and sediment discharge from the basin reaches Atchafalaya Bay through two outlets,

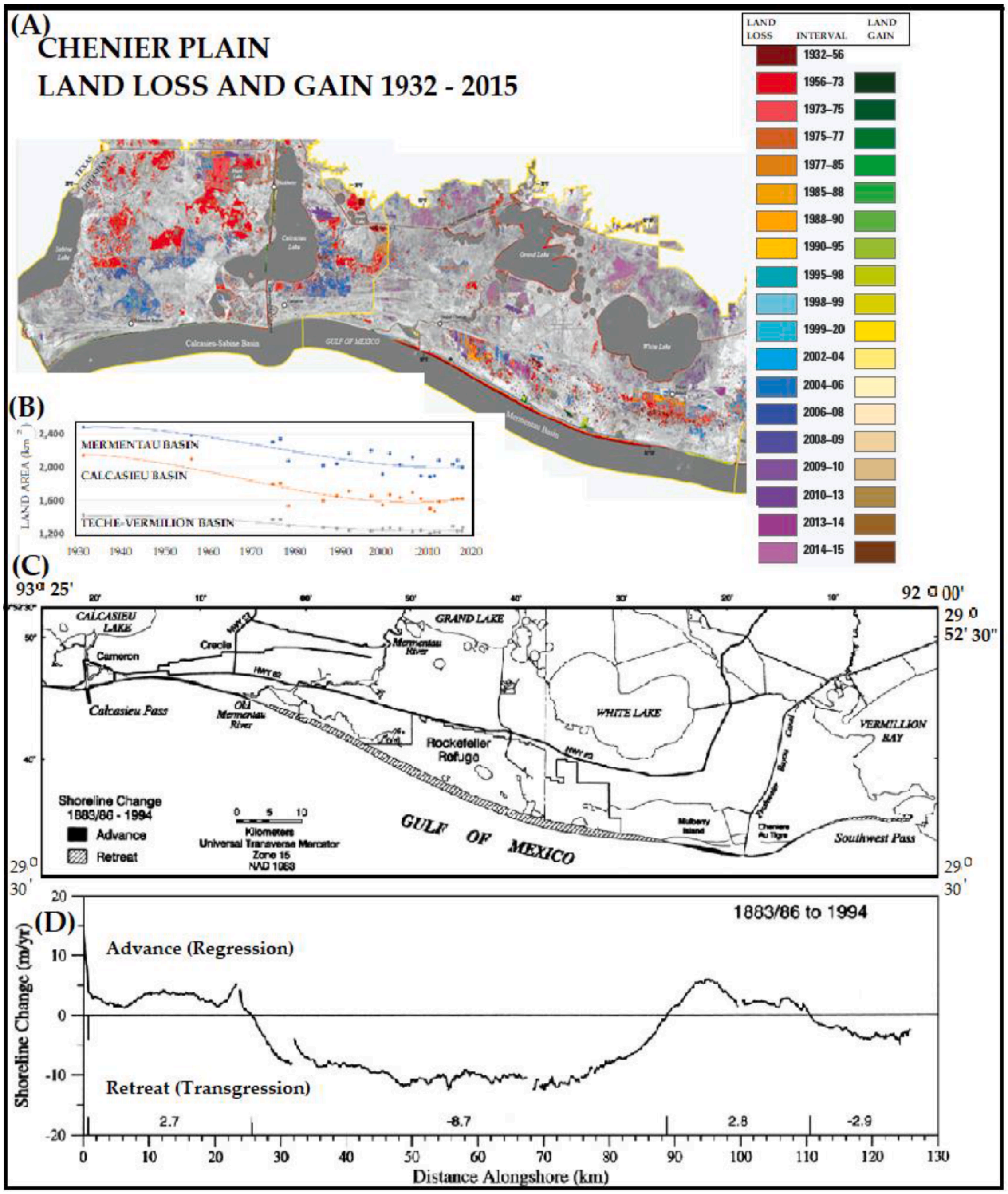

Fig. 6. (A) Map showing land loss and gain during time intervals shown, and (B) land area change over time in the three different basins of the Chenier Plain between 1932 and 2015 [8]. (C) Map showing zones of net shoreline regression (advance) at the eastern and western ends, and transgression (retreat) in the central zone adjacent to the Rockefeller Refuge, with (D) showing variation of shoreline change along the Chenier Plain coast between 1883/86 and 1994 [4].

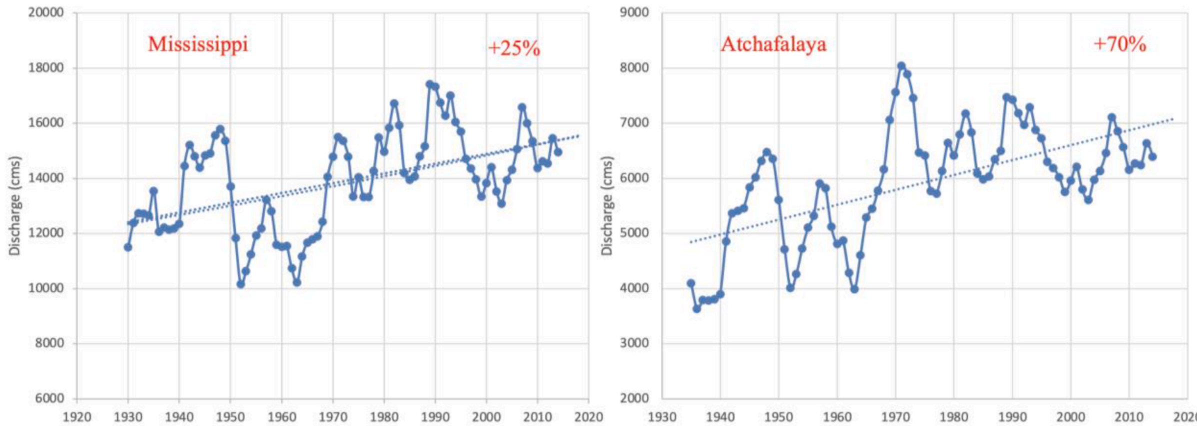

Fig. 7. Discharge of the Mississippi and Atchafalaya rivers from 1930 to the present (modified from [50]).

the natural Atchafalaya and the artificial Wax Lake Outlet dredged in 1942, that carry 70% and 30% of the discharge, respectively. Atchafalaya Bay is a shallow (2-3 m deep), mud-floored bay composed of several sub-bays (Atchafalaya, Cote Blanche, and Vermilion), whose exchange with the Continental shelf is partially obstructed in the eastern sector by oyster shell reefs. Some of the sediment is retained in the coastal bays but a considerable quantity enters the nearshore GOM.

Wells and Kemp [42] refer to the turbid (100-280mg/L) plume exiting Atchafalaya Bay as the Atchafalaya mud stream. The mud stream is generally confined landward of the 10m isobath along the southwest Louisiana coast except during frontal passages, and at most times is moving westward entrained in a residual current flow of about 10 cm/s. Wells and Kemp calculated that this mud stream carried 53×10^6 m^3/yr of suspended sediment, almost half the volume of sediment exiting Atchafalaya Bay at that time. The re-initiation of mudflat accretion along the downdrift chenier coast west of Atchafalaya Bay has resulted in shoreline mudflat accretion along the CP coast [51,52,44,40,42]. Sediment supply to the CP shoreface occurs mainly during the late winter and early spring, when high Atchafalaya River discharge coincides with the main period of cold front passage (Mossa and Roberts 1990). Near-surface current speeds of 10-50 cm/s have been observed on the inner shelf and are strongly influenced by the passage of cold fronts.

The behavior of Beryllium-7 (^{7}Be), which serves as a tracer of short-term deposition (or mixing), in shelf sediments is an indicator of the relative influence of atmospheric flux, sediment supply from adjacent rivers, and lateral marine transport [53]. Allison et al. [15] collected sediment cores and water column measurements of suspended sediment and flow conditions on the continental shelf off the Atchafalaya River to examine the development and reworking of a seabed flood layer with seasonal variations in river discharge and hydrodynamics. Downcore profiles of the short half-life (53 d) of ^{7}Be showed a three to twelvefold increase in seabed inventory and an increase in depth of penetration during the high Atchafalaya discharge period (April) at two inshore stations (5-7 m depth). There was an absence of biological mixing at these sites where there is deposition of a 1-3 cm thick annual flood deposit. The organic carbon contents and stable carbon isotopic compositions of the flood deposit reflect the terrestrial influence of riverine sediment flux and this seasonal deposit is two to six times the long-term (e.g., decadal) accumulation at these sites. Passage of cold fronts on 7-10 day timescales interrupts the formation of these flood deposits, particularly during the rising to early high discharge period (December--March). The depth of sediment resuspension landward of 10 m during these events may reach several cm and decreases offshore. Offshore stations (<20 m water depth) show only a small increase in deposition during high discharge period. Redistribution of sediment from shallower parts of the shelf during the remainder of the year is likely a major supplier to these areas.

Neill and Allison [54] analyzed sediment cores and seismic profiles to examine the development and impact on land accretion of the early-stage subaqueous Atchafalaya Delta accumulating on the shallow (<25 m depth) continental shelf. The subaqueous clinoform is muddy (70–100% finer than 63 um) and extends approximately 21–26 km seaward of the shell reef (to 8 m water depth) across the mouth of the Atchafalaya Bay. The sigmoidal clinoform has a topset surface that steepens from east to west (1:2500 to 1:1600), a foreset with maximum slopes of about 1:550, and a limited bottomset region (~0.5 km wide). ^{210}Pb and ^{137}Cs geochronology showed maximum sediment accumulation rates (~3 cm/year) correspond to the foreset and bottomset region, with rates decreasing to as low as 0.9 cm/year on the shelf topset region and its extension inside Atchafalaya Bay. There is a marked alongshore sediment dispersal pattern observed by the progressive winnowing of sand and coarse silt to the west. The resulting sigmoidal clinoform deposit (~3 m thick) more closely resembles strata geometries of subaqueous mud deltas associated with energetic systems (e.g., Amazon, Ganges–Brahmaputra, Fly), than it does the mature Mississippi delta 180 km to the east, but on a smaller scale and in shallow water.

Siadamousavi and Jose [55] studied winter storm-induced hydrodynamics and morphological on the response of the Trinity and Tiger shoal complex located south of Marsh Island and the eastern CP in 3-8 m water depth (see Fig. 1 for location). The surface and bottom current speeds exceeded 0.5 m/s and 0.3 m/s, respectively, in the direction of the prevailing winds and water level variability was 0.6-0.7 m. During frontal passages, the nearer to shore Tiger shoal bed sediment texture changed from mud to shell hash-shell assemblage. Further offshore, the Trinity shoal was dominated by fine sand and mud and experienced a few cm of ephemeral sediment deposition. Energetic high frequency waves propagating from the north were the dominant wave component during frontal passages; while during pre- and post-frontal conditions, the southerly waves had lower frequency. The passage of energetic cold fronts resulted in large-scale resuspension of bed sediment where sediment is pushed offshore and to the west along the CP. The westward decrease of sand and coarse silt is evidence of preferential sorting alongshore in the dispersal system on the shelf.

Hijma et al. [27] used a refined chronology based on 22 new optically stimulated luminescence and 22 new radiocarbon ages to test the hypothesis that cyclic Mississippi sub-delta shifting has influenced the evolution of the CP. They found that over the past 3,000 years, when the Mississippi River was discharging to the eastern portion of the MRD, accumulation rates in the CP were generally 0 – 1 Mt/yr. However, when the Mississippi River shifted west and began discharging closer to the CP, these rates increased to 2.9 + 1.1 Mt/yr. Thus, CP evolution is a direct consequence of shifting subdeltas (Fig. 3c), along with changing regional sediment sources and modest rates of sea-level rise.

2.2. Shoreline erosion

Byrnes et al. [48] measured shoreline changes along the CP between 1883 and 1994 and found that shoreline retreat was dominant over much of the area. The average change rate for the period of record was -2.6 m/yr, despite net shoreline advance (regression) between Sabine and Calcasieu Passes (0.7 m/yr). East of the bulge associated with the Calcasieu Pass jetties, shoreline change has ranged from 5 m/y regression to -10 m/y transgression, with a spatially averaged shoreline retreat of -3.8 m/yr since 1883, but the only persistent area of advance through mud deposition is about 10 km just to the west of the outlet of Freshwater Bayou Canal. Similarly, Martinez et al. [56] measured shoreline changes of the CP between 1855 and 2005 and found a net gain in the Western CP and a net retreat in the Eastern CP. In the Western CP, accretion rates were 0.73, -0.49, 0.70, and 13.29 m/yr for historical (1855-2005), long term (1904-2005), short term (1996-2005), and near term (2004-2005) shoreline changes in the CP. In the Eastern CP, changes for the same time periods were -4.09, -4.76, -7.25, and 0.77 m/yr [56].

2.3. Subsidence

Subsidence may be caused by natural geologic processes [57] (e.g., sediment compaction, sediment load isostatic adjustment, continental glacial melt isostatic adjustment, faulting) or human activities (e.g., subsurface fluid withdrawal for oil, gas, groundwater and consequent compaction translated to the surface), mineral extraction or a combination of several processes [58,59, 60,32]. The downthrown side of active faults on the CP often appears as a "D" shaped water body [61]. A number of these faults have been mapped (e.g. [62], Heinrich 2005) and there are doubtless many more. Active faults on the CP and across the Louisiana coast are often related to depleted oil and gas fields where a differential stress created by a difference in pressure across the fault plane at the depleted reservoir depth served to re-activate an existing fault involved with the oil and gas field structure [58].

Jankowski et al [11] analyzed rod surface-elevation table-marker horizon data from 274 Coastwide Reference Monitoring System (CRMS) study sites to examine surface elevation changes along coastal Louisiana, including shallow subsidence and vertical accretion. Their results showed a high spatial variability of shallow subsidence rates with similar median rates for the MDP (6.0 mm/yr) and CP (5.8 mm/yr; Fig. 8), but the frequency of both surface elevation change and vertical accretion is higher in the CP. In general, subsidence is lower in the CP compared to the MDP.

2.4. Accretion

We compiled accretion rate and surface elevation change rate data at approximately 65 CRMS stations along the CP coast to determine how these mechanisms were affecting the CP [63]. These stations are part of the coastal network developed to measure changing wetland conditions over an extended time. Rates at which sediment accumulates, or accretes, over the CP are an indicator of the potential for land building, and persistence of those rates over time would suggest that sedimentation mechanisms here are reliable over time. Accretion rates are determined by measuring the thickness of sediment deposited over feldspar clay marker layers placed on the marsh surface [64]. The result is a series of accretion values over different lengths of time, from a few months to

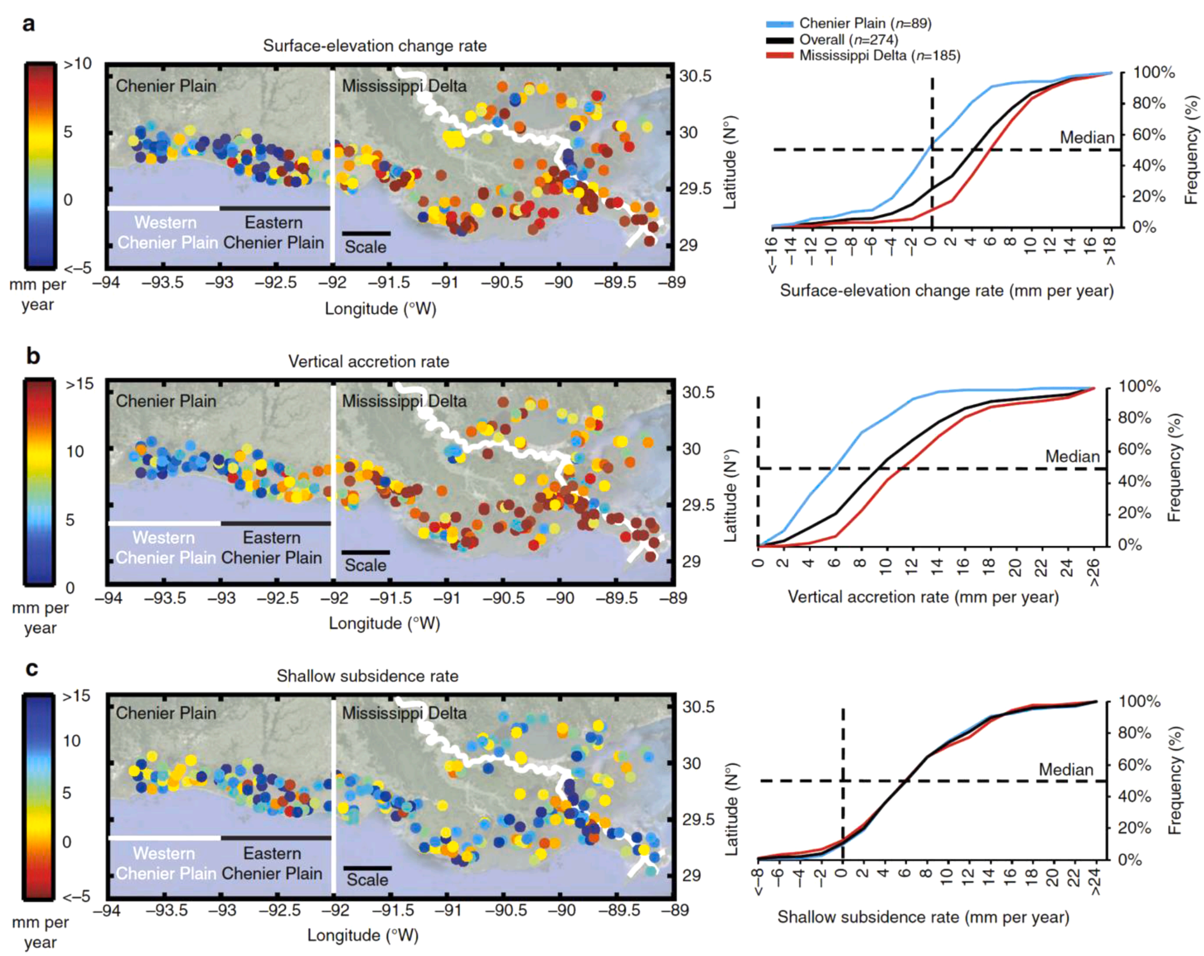

Fig. 8. Rates of surface elevation change (a), vertical accretion (b), and shallow subsidence (c) in coastal Louisiana [11].

several years that show positive and significant accretion (Fig. 9). Moreover, where accretion rates related to winter fronts and tides develop persistent sedimentation, hurricanes may distribute massive sediment loads across the CP as shown by the measurements made following Hurricanes Delta and Laura.

2.5. Surface elevation change rate

While accretion rate is a measure of the sedimentation process, an evaluation of the land surface provides information about persistent contribution of this process to land building, surface elevation change rate provides information about the ability of a marsh develop sustainably. A marsh surface is not a uniform horizontal plane, and the CRMS stations measure the surface and its change at stations along the CP (Yu et al 2012). The rods at the CP CRMS stations are generally anchored in the underlying Pleistocene and that surface reflects the long-term coastal subsidence. Using the same 65 previously discussed CRMS stations, we plotted the surface elevation change rate against station longitude, ranging from the Sabine to Freshwater Bayou. A generally positive surface elevation change rate can be seen, though there are several negative rates, particularly in the western part of the CP (Fig. 10). The surface elevation change rate trends positively from west to east and closer to the Mississippi and Atchafalaya sediment sources, indicating increasing sediment availability moving east and closer to Atchafalaya River and MRD sources. This suggests that measures to more efficiently capture sediment along the coastline have the potential to reverse shoreline retreat in that area.

3. Management of sediment in the Chenier Plain

Despite a reduction in the sediment load of the Mississippi River and levees isolating much of the MDP from direct riverine input [65,66], westward sediment transport to the CP coast has increased due to higher Atchafalaya River discharge [50]. Based on restoration projects in the 2023 Coastal Master Plan, 11 to 34 billion tons of sediment are needed to offset past and future land losses (https://coastal.la.gov/our-plan/2023-coastal-master-plan/). The land loss cannot be offset using only dredged sediment, both because of limited sediment resources and the high costs associated with dredging. Therefore, it is important to incorporate longer-term, sustainable solutions such as those that include capturing and reusing that sediment by means of beneficial use dredging, freshwater river diversion, sediment trapping, and coastal engineering [67]. Integrated techniques for CP shoreline protection and land building designed to capture sediment from the nearshore “mud-stream” include three mechanisms: (1) capturing sediments advected to marshes through inlets; (2) retaining sediment on the shoreface using engineered structures, and (3) capturing sediments delivered to the back barrier marshes via overwash during tropical storms. Beneficial use of dredged sediments is also an important component of CP restoration.

3.1. Capturing sediments advected to marshes through inlets

One method for enhancing sediment accretion in coastal marshes is the transport of suspended sediments in through dredged or natural inlets. This method utilizes natural system processes for sediment delivery through a channel or other type of inlet typically dredged for another purpose, primarily navigation. One example of this is the delivery of sediment into the Hog Bayou oil and gas field through the Mermentau River Gulf Navigation Channel, a previously undocumented phenomenon involving enhanced sediment delivery and capture. Despite impacts associated with oil and gas activity [32], the Hog Bayou field has not had the same rate of wetland loss as most other oil and gas fields in coastal Louisiana. There are several reasons for this positive land building, and we conclude that, with proper engineered

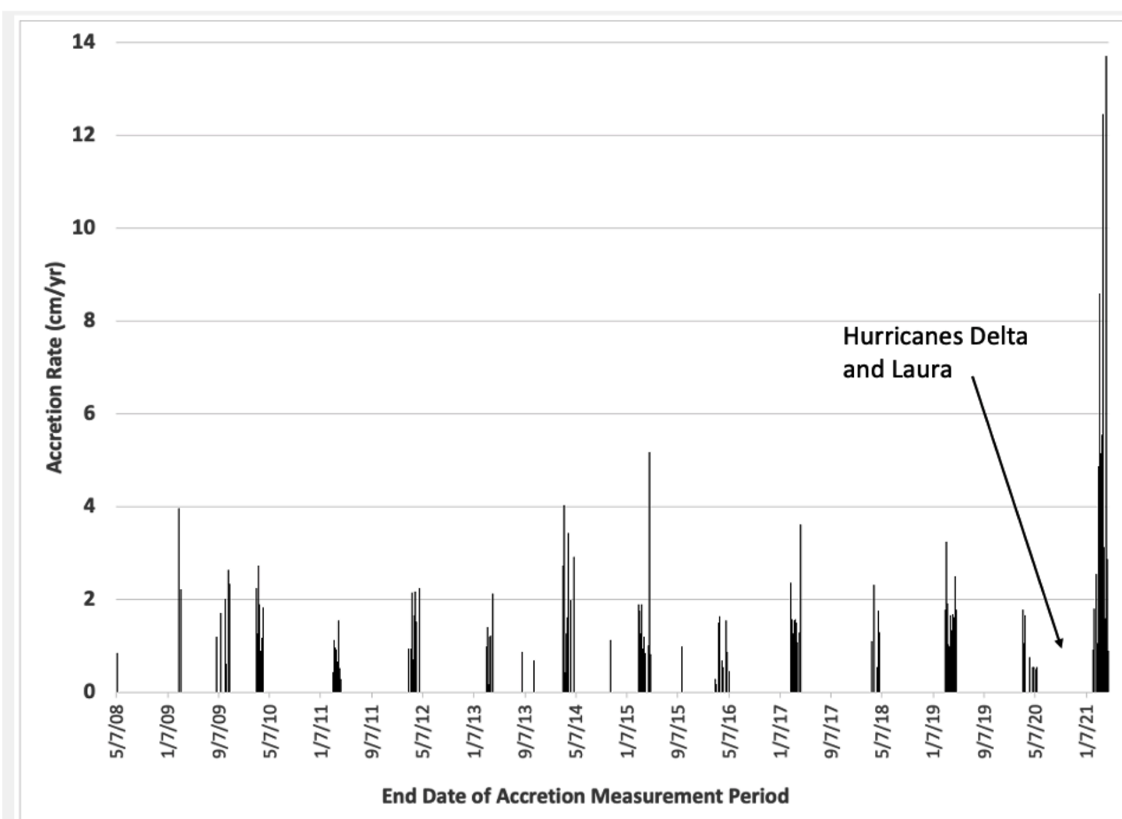

Fig. 9. Temporal patterns of short-term accretion at 65 CRMS stations in the Chenier Plains (CRMS 2021). Note high accretion rates resulting from Hurricanes Delta and Laura.

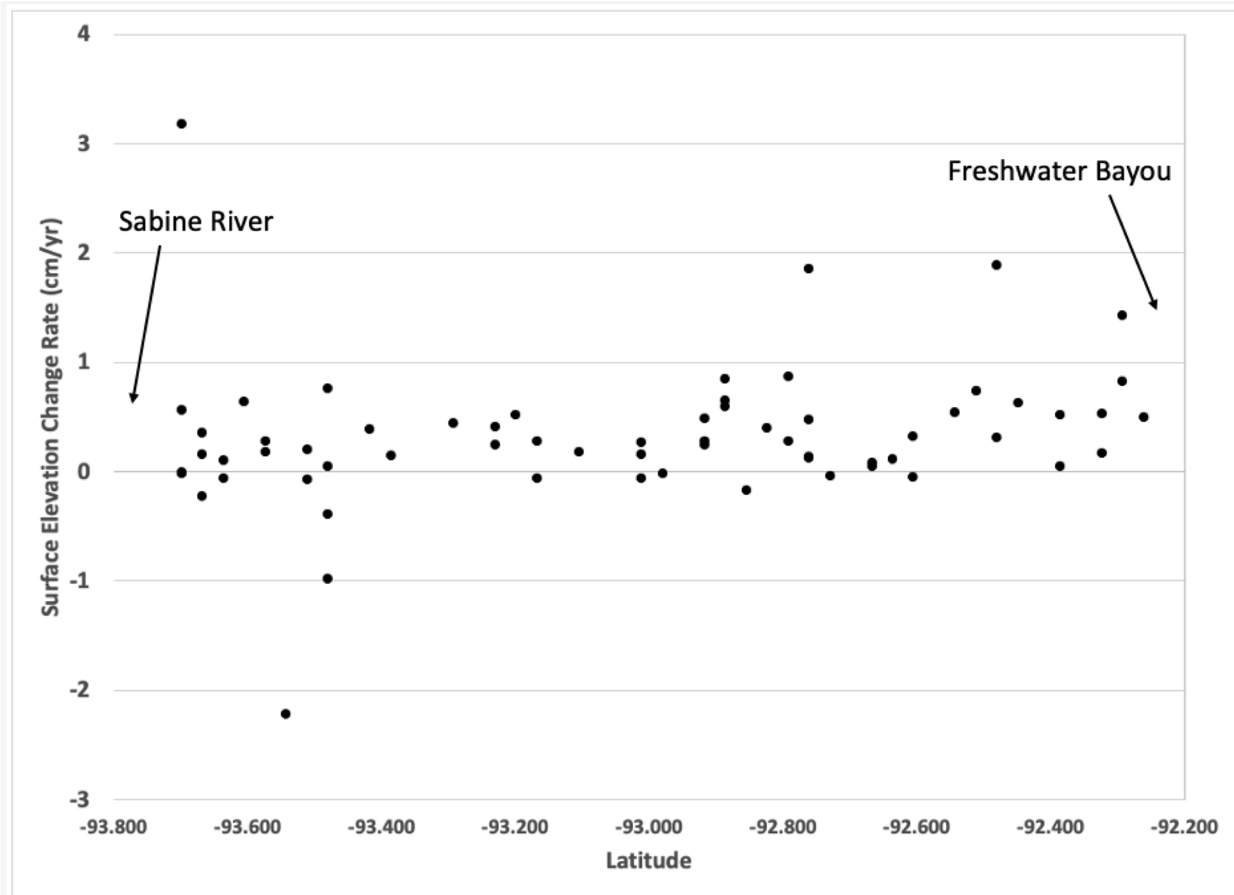

Fig. 10. Surface elevation change rate at CRMS stations measured in early 2021 between the Sabine River and Freshwater Bayou, southwestern Louisiana. For both accretion and surface elevation change rates, the trends and scatter are expected in that the chenier and coastline patterns dominate, there is an overprint of streams, canals, water bodies, and land loss that affect individual measurements.

enhancements, the processes at work here could be extended to a number of depleted oil and gas fields along the Chenier Plain.

The Hog Bayou oil and gas field is located adjacent to the Gulf of Mexico and east of the Mermentau River Navigation Channel (Fig. 11). Dredging of the Mermentau River Navigation Channel and its widening over time, along with eustatic sea level rise, has increased the tidal prism and thus increased the amount of sediment advected through this inlet into back barrier wetlands . Unlike frontal passages and hurricanes, which are episodic events, wave resuspension of sediments in the nearshore zone is a quasi-continuous process. The increased

Fig. 11. Location of the Mermentau River Navigation Channel and the Hog Bayou Oil and Gas field.

hydrodynamic energy feeding the Hog Bayou system initiated the formation of new tidal channel networks in the wetlands of the area as it adjusted to the increased tidal prism. These channels flowing into the Hog Bayou area bring in large amounts of sediment that are filling in dredged canals and other open water areas. For example, a rig access canal in the northern part of the Hog Bayou field has narrowed considerably as the canal filled with sediment and was colonized by marsh (Fig. 12). This has also been the case at other, older rig access canals as well as a subsided area likely due to oil and gas withdrawal in the field. Tidal creeks that formed in impounded and semi-impounded wetlands provided sediments that nourished the marshes and reversed and/or prevented conversion to open water. In addition, when storms are large enough to drive sediment laden water through the Hog Bayou system and out and through breaches in the spoil banks, the avulsions added to the marsh and created new tidal creeks. Hurricanes Delta and Laura resulted in avulsions at the Hog Bayou field, notably adding to previous micro-delta fans.

Because of the increased tidal prism, the tidal network has expanded as the number and length of tidal channels increased to come into equilibrium with the new tidal prism (Fig. 13). The number of separate tidal channel networks increased from 15 in 1983 to 24 in 2018. The total length of tidal channels increased from 4,265 m in 1983 to 15,384 m in 2018 (Table 1). Stream order (i.e., the number of successive bifurcations) also increased from 1983 to 2018 (Table 1).

This example demonstrates that a reliable sediment source, along with a mechanism to deliver sediments to the back barrier marshes via inlets, can counteract land loss in these back barrier marshes. Thus, without the sediment subsidy provided by the proximity to the Mermentau River Navigation Channel, the wetland loss due to oil and gas exploration and production would have been much higher, as seen throughout oil and gas fields in coastal Louisiana [32,68,69]. Thus, judicious placement of shoreline protection features in conjunction with natural or artificial inlets can lead to restoration and sustaining of marshes landward of the dune beach system.

3.2. Retaining sediment on the shoreface

Shoreline stabilization techniques such as groins and breakwaters are designed to reduce wave energy and/or to restrict longshore sediment transport. Maintaining the coastline of the CP is essential because of extensive shoreline erosion that has taken place. The Holly Beach Breakwaters Project (CS-01) is a shoreline protection project located

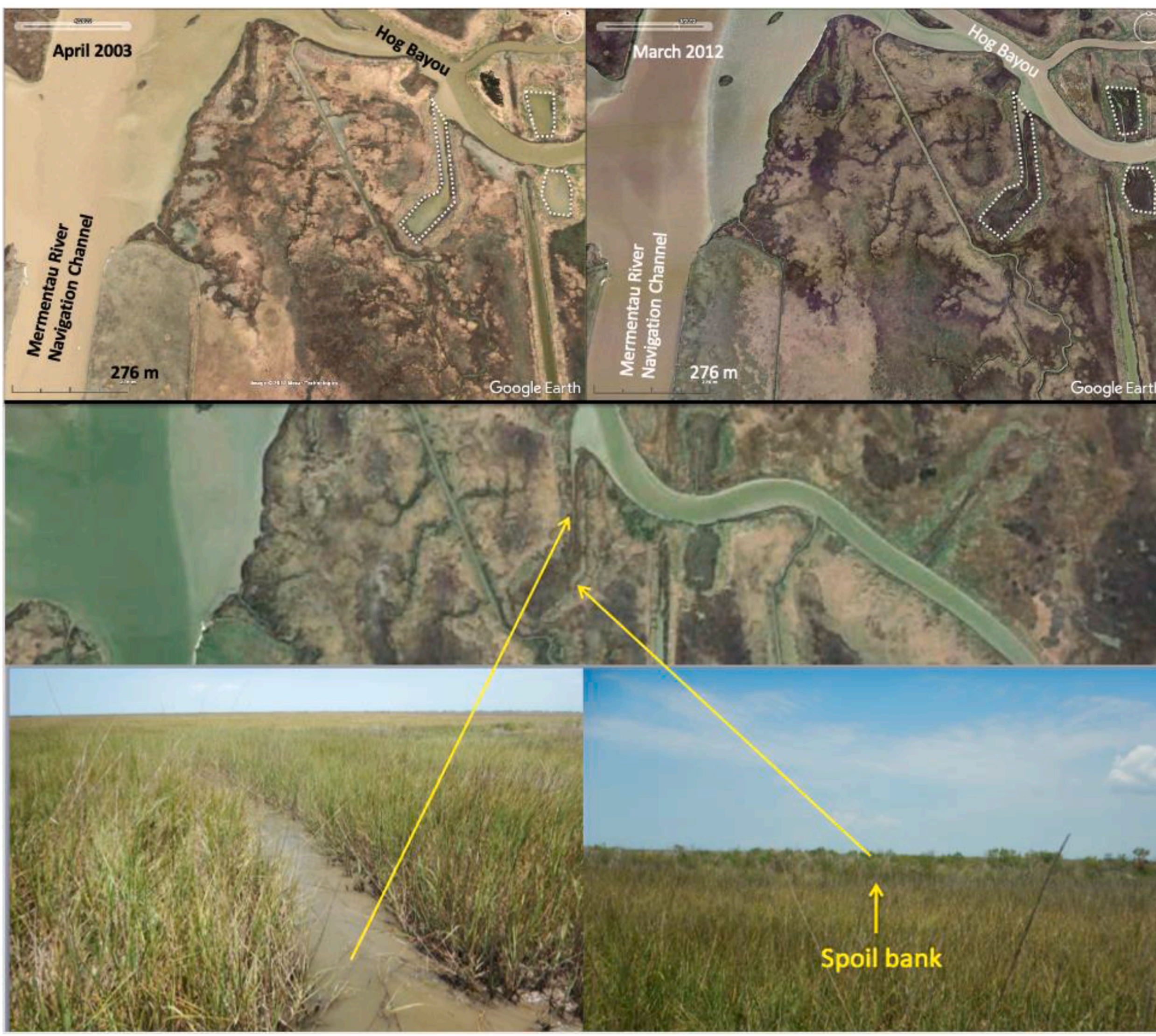

Fig. 12. Top: Infilling of a canal at the Hog Bayou oil and gas field (note outline). In 2003 the canal was unvegetated and by 2012 the canal has almost filled in with sediment (Google Earth). Bottom: The same canal has narrowed considerably and now supports marsh vegetation (Photos: Day and Hunter 2020). In 2020 the canal was less than 2 m in width although it had an initial width of about 30 m.

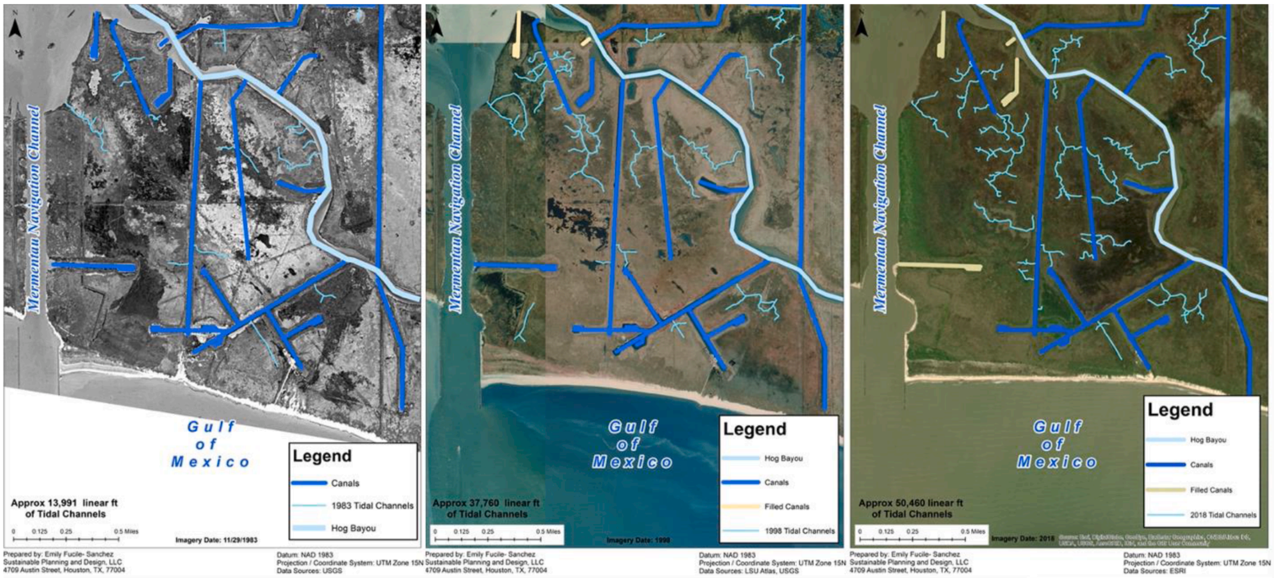

Fig. 13. Tidal creek development at the Hog Bayou oil and gas field over time: left – 1983, center – 1998, and right – 2018 (Photos Google Earth).

Table 1
Number, length, and number of bifurcations of tidal channels at the Hog Bayou oil and gas field.

Year	# of Tidal Channels	Total Length (m)	# of Bifurcations
1983	15	4,265	15
1998	18	11,512	30
2018	24	15,384	43

along the southwestern shoreline of Cameron Parish. The project protects Louisiana Highway 82 along a 12.8 km reach between Holly Beach and Constance Beach, as well as protecting more than 12,500 ha of coastal marsh from direct wave energy and tidal exchange with the Gulf of Mexico. Highway 82 has been relocated inland several times to accommodate shoreline retreat and is now located on a chenier that also serves as the last barrier between the GOM and approximately 5000 hectares of marsh to the north. In 1985, the Louisiana Department of Transportation and Development constructed six segmented experimental breakwaters. Five of the six structures were timber (tire and pylon) construction with similar design parameters. The sixth was a rock rubble mound structure. After eight months of data collection, a decision was made in favor of a regional rock breakwater system for erosion control along Highway 82 [70].

Construction began in 1991 on 34 rubble mound segmented breakwaters beginning at Constance Beach and extending eastward for 4,400 m. The breakwaters were 45 m long with gap widths of 90 m and placed offshore at distances varying from 26 to 137 m. In 1992, another 21 breakwaters were installed. Eight were constructed on the western end of the existing breakwaters and 13 on the eastern end. Breakwater lengths and gaps remained the same, but the distance offshore ranged about 100 to 160 m. In 1993, an additional 21 structures were added to the eastern end. Structure length was increased to 53 m and gap length decreased to 84 m. The distance offshore varied from 135 to 180 m. In 1994, nine breakwaters were added to the western end of the existing system. This final addition brought the total number of breakwaters to 85. The breakwaters were built to elevation +1.2 m with a 3 m crown and 3 to 1 side slopes. After beach nourishment was conducted at Holly Beach to reduce the distance from the breakwater segments and the shoreline, low tide tombolos/high tide salients formed between the shore and the detached segmented breakwaters in several locations (Fig. 14; [71, 72]). Also, it appears that westerly currents along the shore have moved some of the beach nourishment sand westward. While they have shown some degree of success in causing the deposition of new sand, they are not high enough to adequately protect Highway 82 from overtopping waves [73,74,75].

3.2.1. *Rockefeller refuge gulf shoreline stabilization*

This project is located along the Rockefeller Wildlife Refuge Gulf of Mexico shoreline from Joseph's Harbor canal, westward 4.8 km in Cameron Parish, Louisiana (Fig. 15). Average rate of erosion-driven shoreline retreat in this area was approximately 14.5 m/year between 1998 and 2017, with a subsequent direct loss of emergent saline marsh [22]. A lightweight aggregate core rock breakwater was constructed to reduce shoreline retreat and promote natural vegetation colonization of the overwash material landward of the structure [22]. Gaps in the breakwater facilitate movement of organisms and allow sediment-laden water behind the breakwater. Although the project was initially funded for 4.8 km of breakwaters, the construction bid came in lower than expected, which enabled the project to extend the breakwaters by an additional 1.6 km (Fig. 16). The breakwater consists of encapsulated lightweight aggregate, bedding stone, and large armor stone and has a 20-22-m bottom width and a 5.5 m crown width. Sediment has accumulated behind the completed breakwater segments and, as the sediments and silts have compacted, vegetation has become established (Fig. 17). Prior to hurricanes Laura and Delta, the protected shoreline lost approximately one meter of land while the unprotected shoreline eroded by nearly fourteen meters

During the 2020 hurricane season, Cadigan et al. [22] established two transects along the Rockefeller Wildlife Refuge shoreline; one protected by breakwaters and one that was the natural, unprotected shoreline. Hurricanes Laura (Cat 4) made landfall in this area on August 27, 2020 and Hurricane Delta (Cat 2) made landfall on October 9, 2020. Following Hurricane Laura there was a significant loss of elevation at the shoreline in both the natural and breakwater-protected transects. After Hurricane Delta there was higher inland sediment deposition on the natural shoreline than on the breakwater-protected shoreline. Floodwaters drained from the area with breakwater protection more slowly than the natural shoreline, though topography profiles were similar, indicating a potential dampening or complex hydrodynamic interactions between the sediment-wetland-breakwater system.

3.2.2. *Shoreline accretion at Hog Bayou*

Just to the west of the Hog Bayou field, the construction of the Mermentau River navigation channel included two ~1 km rock jetties

Fig. 14. Low-tide tombolos/high-tide salients at Holly Beach that formed as a result of the detached, segmented breakwaters [72]. Note that the 2022 image was taken after Hurricanes Laura and Delta (2020).

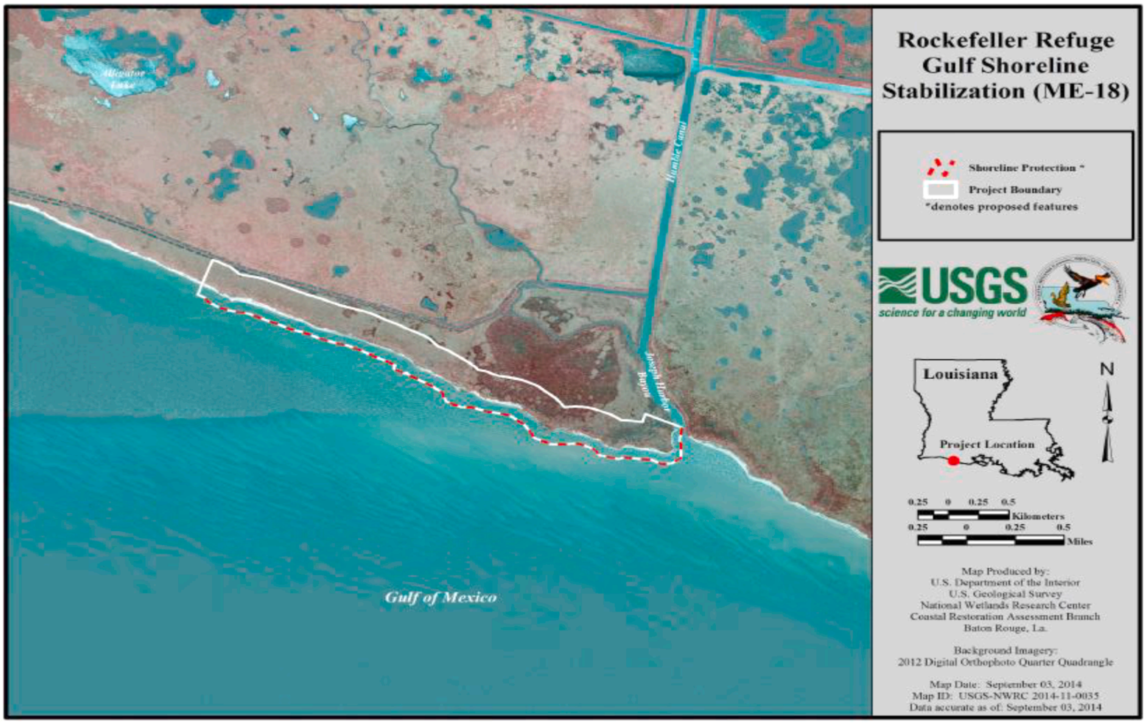

Fig. 15. Location of Rockefeller Refuge Gulf shoreline stabilization project (USGS 2014).

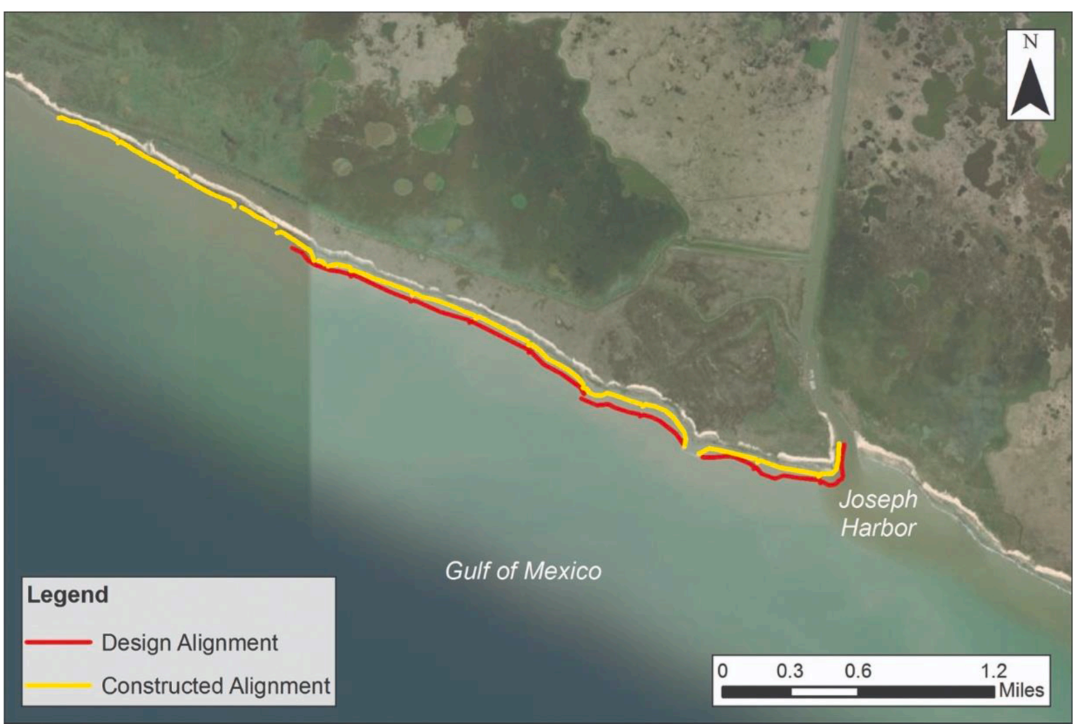

Fig. 16. Location of breakwater locations as designed (red) and as constructed (yellow)(HDR Engineering Inc.).

into the GOM [76,77]. Over time the eastern jetty trapped sediments being transported west by longshore currents resulting in a net gain in the beach-dune system (Fig. 18). As noted earlier, the navigation channel resulted in a greater tidal prism that transported large amounts of sediment into the marshes and filled several oil field canals. The net result was seaward growth of the beach-dune system and wetland rehabilitation along Hog Bayou.

There are jetties associated with both the Calcasieu and Sabine rivers with significant beach accretion. We believe that a carefully planned comprehensive program could stabilize much of the CP shoreline and lead to sustainable marshes between the GOM shoreline and the Chenier Ridge system.

Fig. 17. Breakwater composed of lightweight aggregate, bedding stone, and large armor stone [97].

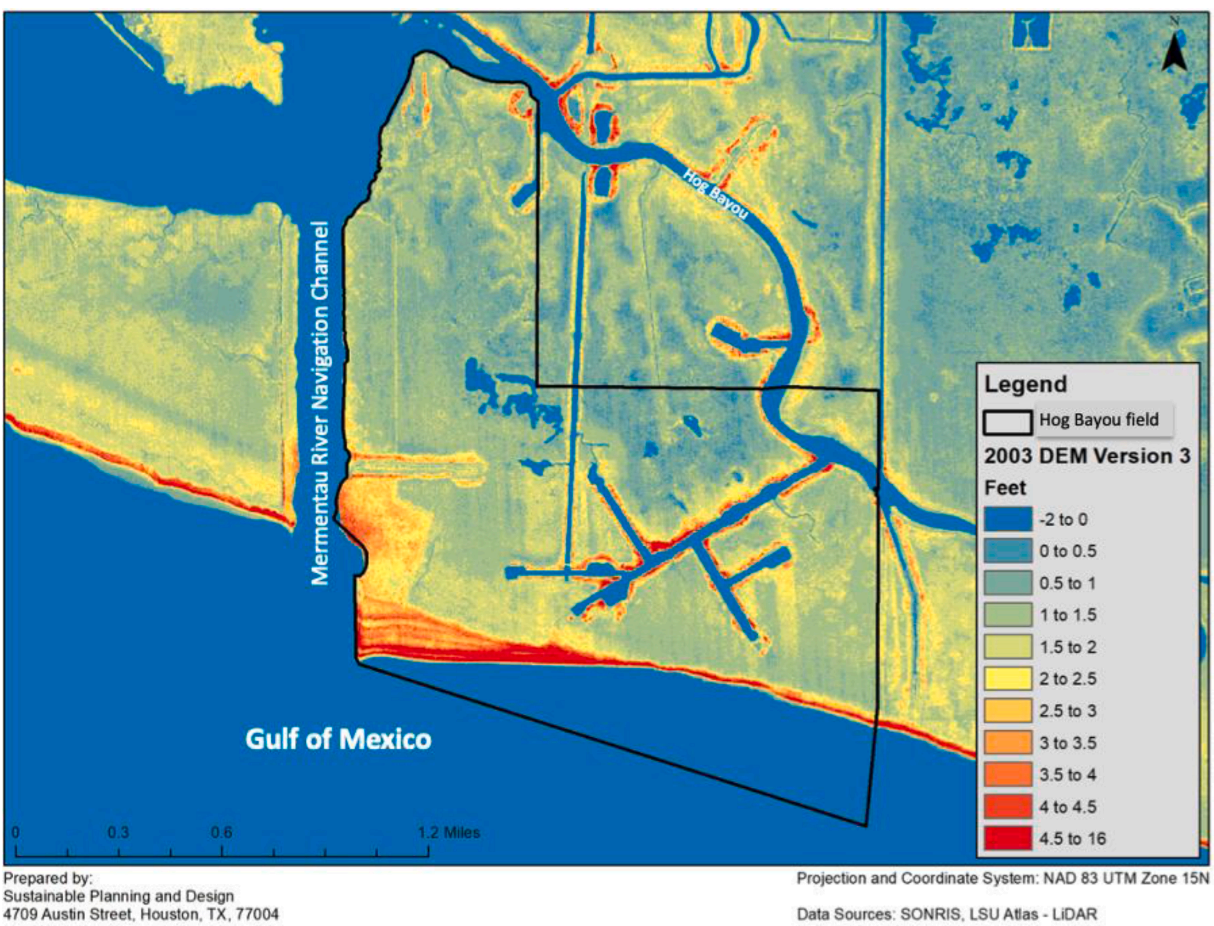

Fig. 18. Effect of navigation channel on Gulfward accretion of the beach-dune system east of the jetty. Elevations at the Hog Bayou area in 2003. The highest elevations are more than 1.2 m while the lowest elevations are at or below sea level. Note that ponds generally occur in wetlands with the lowest elevation.

3.3. Capturing sediments delivered to back barrier marshes during tropical storms

Winter storm fronts generally pass every seven to ten days from November through March in coastal Louisiana, resulting in frequent flooding and draining of marshes. The strong frontal winds resuspend shallow bottom sediments resulting in total suspended solids concentrations often between 400 to 600 mg L^{-1} to as high as 2,000 mg L^{-1} [78, 79] and high deposition of mineral sediments in wetlands [80,81,31]. Hurricanes can lead to enhanced sediment deposition on wetlands [82, 22,83,84,85,86,87,88]. Baustian and Mendelssohn [82] reported that up to 12 cm of sediment was deposited on a coastal Louisiana marsh surface during the 2008 hurricane season. Cadigan et al. [22] reported that a mud mass up to 2 m thick was deposited over a marsh area of several ha in the eastern Chenier Plain during Hurricane Laura. Sediment input to marshes adjacent to the coast during hurricanes occurs primarily by overtopping of the beach-dune system with sediment derived from the beach-dune system and resuspended sediments from the Gulf of Mexico. Although hurricane surge and waves can ravage exposed CP marsh shorelines, these events can also transport mineral sediment far inland, providing another source for tidal marshes to maintain elevation despite sea level rise and subsidence.

The potential for hurricanes and frontal storms to add sediment to coastal marshes has been recognized (for examples, Ike: [89], Rita: Faulkner et al, 2005 [90], Katrina, Rita, Gustav, and Ike: [91]) though extrapolation to broad constructive development [92,93] should be tempered by evaluating the destructive element of these storms [94]. An analysis of source materials [95] together with post storm geomorphic reviews (Barras et al, 2006) would accomplish this differentiation. These studies demonstrate the net positive sediment accretion capability of GOM hurricanes and coastal storms and the challenge is to develop solutions designed to enhance net coastal land building.

3.4. Beneficial use of dredged material

Beneficial use of dredged material involves placing sediment dredged from channels and other water bodies onto coastal areas that have subsided or been subjected to other processes that lower elevation or cause erosion. The Calcasieu Ship Channel (CSC) is a 110 km deep draft navigation channel connecting the Gulf of Mexico to the Port of Lake Charles. The CSC requires dredging one to two times per year. The first beneficial use of dredge material from maintenance of the CSC took place in 1983 during maintenance dredging of the Mile 5.0 to Mile 22.7 reach. In April and May 1983, approximately 150,000 m^3 of dredged material were placed at each of two sites (about 35 ha and 18 ha, respectively) within the Sabine National Wildlife Refuge in an attempt to stabilize the bank and restore eroded wetlands [96] (Fig. 19). The maximum height of the dredged material placed in these disposal areas was +1.2 m Mean Low Gulf (MLG) with an anticipated final elevation, following compaction and dewatering, of about +0.25 m MLG. Since 1983, the use of dredge material from the CSC has created and/or restored nearly 1,620 ha of wetlands (Fig. 20). In addition to beneficial use marsh creation, dredged material has also been used in defined disposal facilities bordering the CSC. These disposal areas provide bank stabilization and additional created wetlands and upland wooded habitat.

Summary and conclusions

Land loss in the CP has been extensive and is the result of a number of interacting factors including changes in salinity, subsidence, ecosystem health, and pervasive hydrological alterations that impacted seasonal inundation patterns and drainage potential. Despite these impacts, there are positive factors that, with engineered enhancements in conjunction with natural elements, can lead to a more sustainable Chenier Plain system.

A key factor in coastal restoration in the CP is management of sediment. There is a quasi-continuous source of suspended sediment in the nearshore zone due to wave resuspension. When there is a pathway for the sediment to move inshore to marshes landward of the beach-dune system, there are high rates of sediment accretion in wetlands, canal filling, and expansion of tidal channel networks by avulsion into shallow ponds. By contrast, in areas with little direct riverine input, sediment input is dominated by re-suspended sources. Local, state, and federal government along with landowners and commercial and industrial enterprises all have vested interest in land loss restoration, including identifying, planning, cost analysis and implementing land restoration.

Restoration approaches should include capturing sediments advected to marshes through inlets, retaining sediment on the shoreface using engineered structures, capturing sediments delivered to the back barrier marshes via overwash during tropical storms, and beneficial use of dredged sediments. There are numerous restoration projects in the CP that demonstrate that these methods can be successful. There are also significant areas with natural resilience that can be engineered to enhance land building, shoreline protection and habitat development processes.

NBS impacts and implications

- Environmental – This paper addresses wetland loss in the Chenier Plain, Louisiana and sustainable wetland restoration solutions.

Fig. 19. Restored areas using dredged sediments at the Sabine National Wildlife Refuge (USACE 1983).

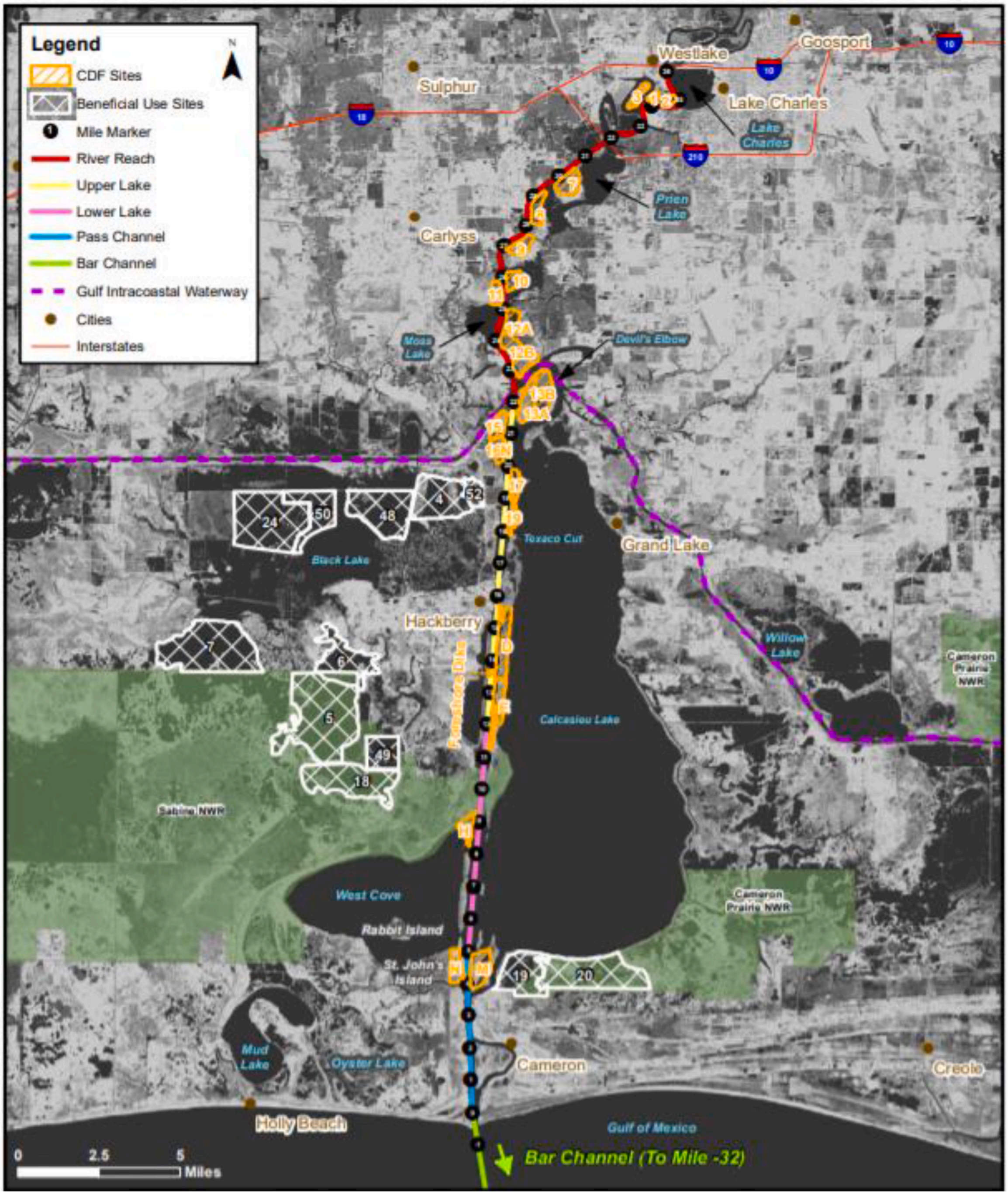

Fig. 20. Calcasieu Shipping Channel dredged materials disposal sites (areas shown in white) [98].

- Economic – This paper discusses how to use natural sediment supplies to build land in the Chenier Plain to reduce costs typically associated with built infrastructure.
- Social – Coastal wetlands are important to reduce hurricane impacts and this paper discusses restoration and land building techniques in the Chenier Plain, Louisiana.

Declaration of Competing Interest

Dr. John W. Day, Dr. Rachael G. Hunter, Dr. H.C. Clark, Charles Norman, and Colton Sanner were paid for their work on a lawsuit involving the Hog Bayou oil and gas field, Cameron Parish, Louisiana.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2022.100037.

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