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Remote Sensing of Wetland Area Loss and Gain in the Western Barataria Basin (Louisiana, U.S.A.) since Hurricane Katrina

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ABSTRACT

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The goal of this study was to analyze the recent record of Landsat satellite imagery to better understand spatial patterns and infer processes of change in marshland vegetation cover in coastal Louisiana wetlands. The study area covered subbasins of the western Barataria Basin near the Bayou Lafourche in southeastern Louisiana. Bayou Lafourche's estuaries have seen some of the highest rates of wetland conversion to open water of any coastal zone in the United States. The Landsat Normalized Difference Water Index (NDWI) was used in this study to map changes in land/water fractions at a 30-m pixel resolution between October 2005 (post-Katrina) and October 2018. Validation boat surveys were conducted in July 2020 to visually verify the presence or absence of (>1 m) emergent vegetation growing on marshlands across several subbasins, with photographs collected at more than 150 target locations along the route. Based on NDWI change, a total of 42.3 km^2 was estimated to fall into the category of wetland loss since 2005. The leading subbasins for these recent wetland-to-water conversions made up most of the southwestern portion of the study area just north of Port Fourchon. The consistently low distance detected between the majority of wetland loss cells and locations of historical oil and gas wells implies that effects of well drilling and extraction have had a continuing negative impact on marshland degradation in the basin. Conversely, a total of 34 km^2 was estimated to fall into the category of recent wetland gain, with much of the new vegetation growth verified to have been restored within several shoreline protection and dredging projects. It was concluded that the positive contributions made by such shoreline enhancement and marshland nourishment projects in Lafourche Parish to offset wetland losses over the past 15 years should not be underestimated.

ADDITIONAL INDEX WORDS: *Marshlands,* ~~*Subsidence, Disturbance, Sediment.*~~

INTRODUCTION

Bayou Lafourche makes up the western margins of the Barataria Basin, a vast estuary on the Gulf of Mexico located about 40 km southwest of New Orleans, Louisiana. The bayou was once a main distributary of the Mississippi River, which flowed over 100 miles long into the Gulf. Port Fourchon at the terminus of Bayou Lafourche is Louisiana's southern-most port. It is a major seaport that services petroleum industry transport from offshore oil platforms and drilling rigs, as well as the Louisiana Offshore Oil Port pipeline.

It has been estimated that since the 1970s, Lafourche Parish has lost 50% of its wetland area to open water, part of Louisiana's declining wetland coverage that could be disappearing at a rate of up to 75 km^2 y–^{1} (Britsch and Dunbar, 1993; Couvillion *et al*., 2017; Williams, Penland, and Roberts, 1994). The long-term driver of this potentially catastrophic wetland loss in the region has been the reduction of freshwater and sediment inputs from the Mississippi River, through flood control measures such as the construction of levees and dikes (Day *et al*., 2007, Kolker, Allison, and Hameed, 2011), and more locally by the damming of Bayou Lafourche as an outlet of the Mississippi River at Donaldsonville in 1905. The bayou was partially reconnected to the Mississippi River in the 1950s with the installation of a pump/siphon station. However, more recent drivers of southern Louisiana marshland loss have been from gas and oil well drilling, canal and levee construction, hurricanes, wave-driven erosion, saltwater intrusion, eutrophication, invasive species, and sea-level rise (Day *et al*., 2020; Day *et al*., 2019).

The loss of wetlands from canal building, dredging, and spoil placement for oil and gas extraction in the Mississippi River Delta area has been well documented since the early 1970s (Day *et al*., 2020; Day *et al*., 2019). Expansive networks of interconnected canals have led to greater saltwater intrusion from the Gulf (Kolker, Allison, and Hameed, 2011). The analyses conducted by Morton, Buster, and Krohn (2002) and Chang, Mallman, and Zoback (2014) demonstrated that among the factors causing accelerated interior wetland loss in Terrebonne and Lafourche Parishes of southcentral Louisiana between the 1950s and 1970s was induced subsidence and fault reactivation induced by rapid, large-volume production of hydrocarbons (primarily gas) and formation water. These geologic perturbations can cause a variety of direct and indirect damage to plants and soils, often leading to wetland loss to open water (Day *et al*., 2020).

Tropical storms are annual and often destructive events on the Louisiana Gulf Coast. Among the most damaging regional impacts of Hurricane Katrina in August 2005 was the storm surge on the southeastern Louisiana Deltaic Plain that formed new water bodies and expanded existing canal networks

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(Barras, 2007; Potter and Amer, 2020). Lafourche Parish suffered damage to its seaports, to LA Highway 1, and to approximately 5000 homes from flooding and high winds during landfall of Hurricanes Katrina and Rita (LRA, 2006). However, since 2005, there have been very few published studies on the overall loss or gain of wetland area in the subbasins of the western Barataria Basin. The conventional thinking is that notable wetland losses have continued unabated on the Mississippi Deltaic Plain over the past 20 years. Nonetheless, there have been several marshland restoration projects undertaken in the past decade in Lafourche Parish that were intended to recover vegetated wetland through engineering of new shorelines and terraces, as well as dredging of sediment (CPRA, 2019). The near-term effects of these restoration projects on net land cover changes have yet to be assessed.

Consequently, the objective of this study was to analyze a time series of satellite remote sensing images to determine the overall losses and gains since 2005 (post-Hurricane Katrina) in wetland cover on the drainages that make up western Barataria Basin. More specifically, the Landsat Normalized Difference Water Index ([NDWI] Amer, Kolker, and Muscietta, 2017) was used to map changes in land/water fractions at a 30-m pixel resolution between 2005 (post-Katrina) and 2018. Potter and Amer (2020) have validated this Landsat NDWI as being a highly accurate mapping index of water-to-land changes over the past 30 years in the Breton Sound basins of southern Louisiana just east of the Mississippi River. The results of this new study in Lafourche Parish should aid in the assessment of management and engineering efforts to restore and preserve wetlands on the Louisiana Deltaic Plain in the face of unprecedented natural disasters and historical human disturbances that have made this region one of the fastest in terms of land cover change in the world (Giosan *et al*., 2014).

METHODS

The sources and processing methods for remote-sensing images used in this study are described in this section. Satellite image analysis methods are described for scenes obtained in the years 2005 and 2018, followed by the approach followed for validation of the land gain mapping results.

Landsat Land/Water Index

For the cloud-free Landsat 4–5 Thematic Mapper (TM) imagery acquired from the U.S. Geological Survey (USGS) EarthExplorer for 25 October 2005, 30-m resolution surface reflectance data were generated from the Landsat Ecosystem Disturbance Adaptive Processing System (Masek *et al*., 2006). Moderate resolution imaging spectroradiometer atmospheric correction routines were applied to level 1 TM data products. Water vapor, ozone, geopotential height, aerosol optical thickness, and digital elevation are input with Landsat data to the Second Simulation of a Satellite Signal in the Solar Spectrum (6S) radiative transfer models to generate top-of-atmosphere reflectance, surface reflectance, brightness temperature, and masks for clouds, cloud shadows, adjacent clouds, land, snow, ice, and water. Landsat 8 (after 2012) surface reflectance products were generated from a method that uses the scene center for the sun angle calculation and then hard codes the view zenith angle to 0. The solar zenith and view zenith angles are used for calculations as part of the atmospheric correction.

The NDWI (Amer, Kolker, and Muscietta, 2017; Potter and Amer, 2020) for wetland loss and gain detection was calculated from two Landsat surface reflectance bands using the equation:

$$(\text{Blue} - \text{SWIR})/(\text{Blue} + \text{SWIR})$$

Blue is the reflectance band from 0.45 to 0.51 μm, and SWIR is the shortwave infrared reflectance band from 1.55 to 1.75 μm. The most cloud-free image from October of every year was mapped by NDWI to control for the seasonality of vegetation growth.

The NDWI values are a ratio that ranges from –1 to 1, with negative values indicating land that includes soil and live vegetation cover and positive values indicating water coverage. If NDWI ranges from –1.0 to –0.2, then the pixel is 100% land, and if NDWI ranges from –0.2 to 0.0, then the pixel is majority land and minority water. If NDWI ranges from 0.0 to 0.49, then the pixel is majority water and minority land, and if NDWI ranges from 0.5 to 1.0, then the pixel is 100% water. Although it is possible that sediment in river water could result in some water-dominated pixels being classified as land, Amer, Kolker, and Muscietta (2017) noted that the surface reflectance indicted that the maximum difference between land and water occurs in the blue band and that this error was not manifest in the NDWI results for their study area in the nearby Mississippi Delta.

Overlay of the resulting NDWI maps generated for 25 October 2005 and 13 October 2018 was used to determine the study area locations where majority land cover had converted to majority water cover and where majority water cover had converted to majority land cover. Due to extensive cloud cover over the study area during all of October 2019, Landsat image data from that year were not available for this comparison.

Spatial Data Layers

The drainages that make up western Barataria Basin have been previously delineated by the USGS into subbasins at the level-12 hydrologic unit classification ([HUC12] Seaber, Kapinos, and Knapp, 1987). Fourteen HUC12 subbasins, covering roughly 1600 km^2 (600 square miles), were delineated for these studies of wetland cover change (Figure 1).

Oil and gas well locations were obtained as a spatial data layer that was developed from historical records held by the State of Louisiana's Department of Natural Resources (DNR, 2007). This layer consisted of all wells permitted since the industry was first regulated in the early 1900s.

Marshland vegetation types of southern Louisiana have been mapped and described by Visser *et al*. (2000), based on the following plant associations.

Freshwater marsh—Dominated by *Panicum hemitomon, Sagittaria lancifolia, Eleocharis baldwinii,* or *Cladium jamaicense*. Other than these dominant plants, the following species primarily occur in fresh marshes: *Boehmeria cylindrica, Cephalanthus occidentalis, Colocasia esculenta, Decodon verticillatus, Nymphaea odorata, Sagittaria latifolia, Sagittaria platyphylla, Schoenoplectus deltarum,* and *Triadenum virginicum*.

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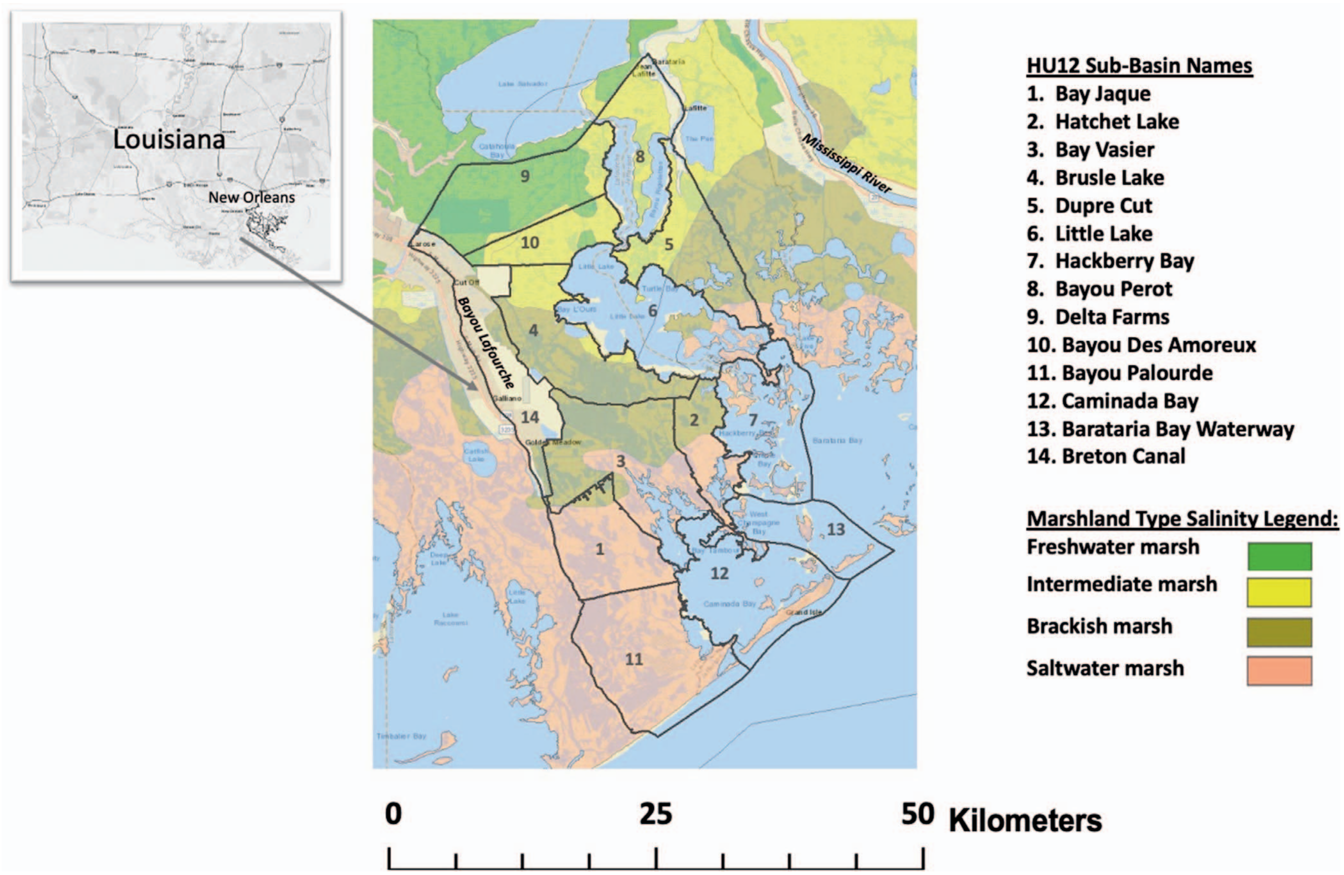

Figure 1. Study area map of subbasins in the western Barataria Basin, with predominant marshland types (from Visser *et al*., 2000).

Intermediate marsh—Dominated by *Leptochloa fusca, Panicum virgatum, Paspalum vaginatum, Phragmites australis,* or *Schoenoplectus americanus*. Both intermediate and brackish marshes can be dominated by *Spartina patens*, but such areas can have higher species richness, often including *Sagittaria lancifolia, Schoenoplectus americanus, Eleocharis* spp., and (or) *Cyperus* spp.

Brackish marsh—Dominated by *S. patens*, but is occasionally dominated by *Spartina cynosuroides, Spartina spartinae,* or *Bolboschoenus robustus*. Both intermediate and brackish marshes can be dominated by *S. patens*, but brackish marshes typically have a small number of other species present, such as *Spartina alterniflora, Distichlis spicata, Juncus roemerianus,* or *B. robustus*.

Saline (saltwater) marsh—Dominated by *S. alterniflora, D. spicata,* or *Avicennia germinans*.

The breakdown of total marshland cover types for the study area of subbasins shown in Figure 1, according to the classification by Visser *et al*. (2000), was 40% saltwater, 29% brackish, 20% intermediate, and 12% freshwater. The freshwater marshlands of the study area were confined mainly to the Delta Farms and the Bayou Des Amoreux subbasins, whereas the brackish marshlands were confined mainly to the Brusle Lake, Bay Vasier, and Dupre Cut subbasins (Table 1).

Ground-Truth Surveys

A boat survey was conducted on 29 July 2020 to visually verify the presence or absence of (>1 m) emergent vegetation growing on marshlands of the study subbasins. Geo-referenced digital photographs were taken at more than 150 locations along the survey route (shown in Figure 2), mainly to document

Table 1. *Attributes of subbasins in the western Barataria Basin.*

Subbasin Name (USGS HU12)	Area Covered (km^2)	Predominant Marshland Type (Visser *et al*, 2000)
Bay Jaque	92	Saltwater
Hatchet Lake	55	Brackish
Bay Vasier	167	Brackish
Brusle Lake	121	Brackish
Dupre Cut	98	Brackish
Little Lake	158	Saltwater
Hackberry Bay	117	Saltwater
Bayou Perot	103	Intermediate
Delta Farms	126	Fresh
Bayou Des Amoreux	57	Intermediate
Bayou Palourde	165	Saltwater
Caminada Bay	143	Saltwater
Barataria Bay Waterway	72	Saltwater
Breton Canal	109	Brackish
Total	**1584**	

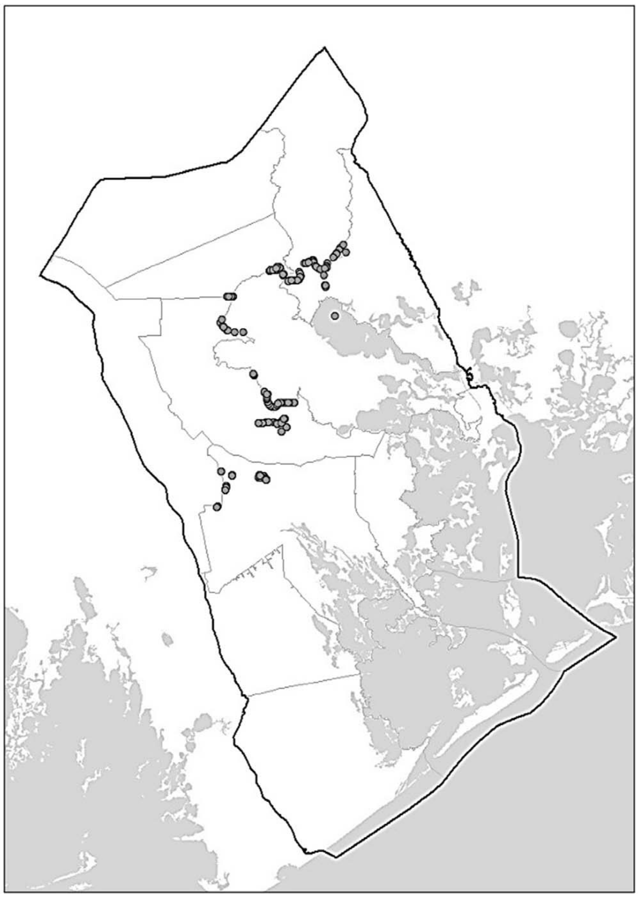

Figure 2. Survey photo points from 2020 collected to visually verify the presence or absence of (>1 m) emergent vegetation growing on marshlands of subbasins.

sites of new marshland gain from changes detected using the NDWI method for majority water-to-land cover transition between 2005 and 2018. The criteria of identifying emergent vegetation in these survey photos was intended to separate marshland locations with emergent vegetation growth from those where only submerged or floating aquatic vegetation was growing in large patches on otherwise open-water cover. It should be noted that, due to shallow water depths all along such a route through marshlands and canals, it was necessary to maintain a distance of more than 150 m between the boat location of the geo-tagged photos and the nearby shorelines at all times. This safety precaution did not alter the quality of these validation data, but rather required proximity adjustments in the subsequent spatial analysis performed.

Statistical Analysis

The Zonal Statistics Tool in ArcGIS Desktop version 10.7 (ESRI, Redlands, California, U.S.A.) was used to calculate area totals of digital raster layers (*e.g.*, NDWI maps) within the zones defined by another polygon layer, such as HU12 subbasins or boat survey locations layer of photo points. The internal conversion for an input polygon zone used the cell center method in the ArcGIS Polygon to Raster Tool to first rasterize the input using the preset raster cell size. Once an input polygon zone was converted to a raster zone using the same cell size and cell alignment of the raster layer, statistics (*e.g.*, mean, maximum, minimum, standard deviation) of cell values within each zone were computed by overlaying the zones on the raster layer.

The Euclidean Distance Tool in ArcGIS was applied to determine the distances to a point feature in the study area, such as an oil and gas well location. For each point location, the Euclidean distance to that point from any other point was determined by calculating the hypotenuse with x_max and y_max as the other two legs of the triangle. This tool derives the true Euclidean distance, rather than, for example, the distance between raster grid cell margins. The shortest distance to a source is determined, and if it is less than the specified maximum distance, the value is assigned for the center cell location in a new 30-m resolution output raster layer.

RESULTS

Subbasins of the western Barataria Basin were mapped at 30-m resolution using Landsat NDWI to estimate and compare marshland areas lost or gained. Boat survey photos were used to validate the results from Landsat NDWI mapping for locations where land gains were detected between 2005 and 2018.

Wetland Loss

The comparison of Landsat NDWI maps from 2005 to 2018 showed the locations within subbasins where majority land cover has converted to majority water cover since Hurricane Katrina (Figure 3a). A total of 42.3 km^2 was estimated to fall into the category of recent wetland loss. The leading subbasins for land-to-water conversion area since 2005 were Bayou Palourde, Bay Vasier, and Bay Jaque (Table 2), which make up greater than 50% of the southwestern portion of the study area.

The loss of saline marsh land to water was most concentrated along the shorelines and previously vegetated margins of the Bayou Ferblanc and Leeville oil and gas fields, particularly along the Pipeline Canal and the Southwestern Louisiana Canal with its North and South Lakes, just east of Leeville (Figure 3). Recent (since 2005) wetland loss has been pervasive on either side of LA Highway 1, between 3 and 5 km north of Port Fourchon. Three other lines of extensive wetland loss covering several square kilometers were especially noticeable in the recent NDWI change map, namely in the Little Lake subbasin of Jefferson Parish near Bayou Saint Denis, all along several crisscrossing canals in Dupre Cut, and in Bayou Perot north of the inlet to Harvey Cutoff.

The spatial layer of center-point locations for all recent NDWI land loss cells was next overlaid on the 30-m gridded map of Euclidean distances (Figure 4a) to each historical oil and gas well location within the subbasins study area. The histogram of the distance-to-a-well location for all recent land loss cells within the study area showed this distribution to be strongly skewed (coefficient >1.5; Joanes and Gill, 1998), indicating a negative exponential probability function, to the lower range (<500 m) of possible distance values (Figure 4b).

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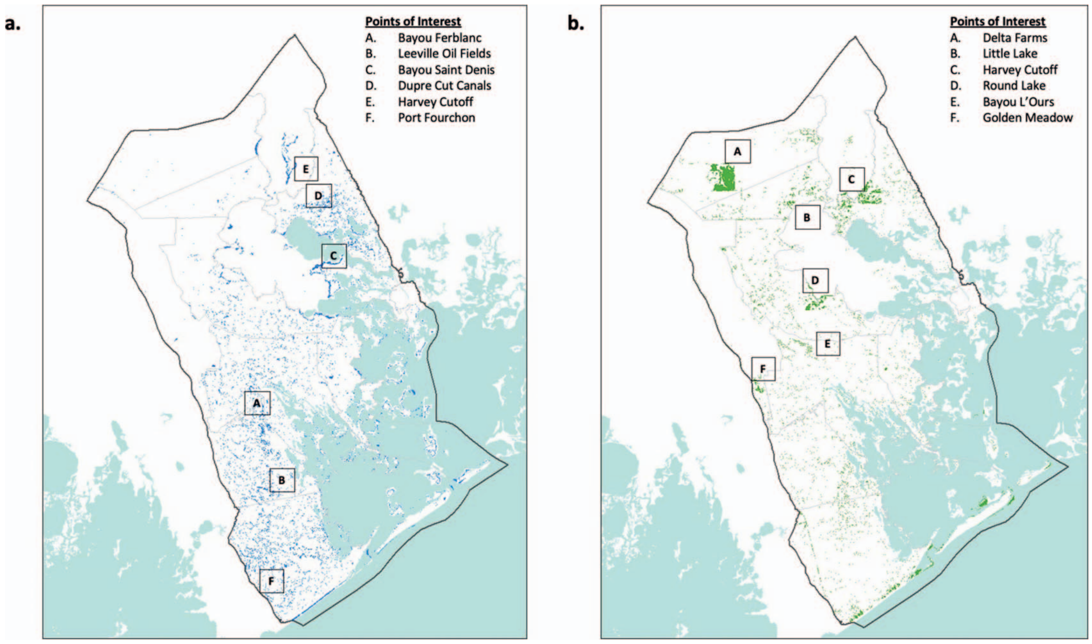

Figure 3. Maps of Landsat NDWI change maps from 2005 to 2018 for the locations within subbasins where (a) majority land cover has converted to majority water cover and (b) majority water cover has converted to majority land cover.

The quartile breakpoints for this distribution of these distances were calculated as <241 m, 381 m, 524 m, and >782 m.

Broken down further by subbasins, those among both the lowest average and maximum distance-to-a-well for recent wetland loss cells were Delta Farms, Hackberry Bay, Bay Vasier, Bay Jaque, and Bayou Perot (Table 3). Subbasins wherein the mean distance-to-a-well for recent wetland loss cells was highest (>1500 m) were Bayou Palourde and Caminada Bay.

Wetland Gain

Comparison of Landsat NDWI maps from 2005 to 2018 showed the locations within western Barataria Basin subbasins where majority open-water cover has converted to majority wetland cover since Hurricane Katrina (Figure 3b). A total of 34 km^2 was estimated to fall into this category of recent wetland gain. The leading subbasins for land-to-water conversion area since 2005 were Delta Farms, Bayou Palourde, Dupre Cut, and Brusle Lake. Subbasins wherein land gains have exceeded land losses since 2005 were Delta Farms, Brusle Lake, and Bayou Des Amoreux (Table 2).

Table 2. *Total land losses and gains in subbasins estimated from Landsat NDWI comparison, 2005 to 2018.*

Subbasin Name (USGS HU12)	Land Loss Area (km^2)	Land Gain Area (km^2)
Bay Jaque	5.7	2.4
Hatchet Lake	1.8	1.2
Bay Vasier	6.1	3.2
Brusle Lake	3.5	4.4
Dupre Cut	5.1	4.7
Little Lake	3.0	0.7
Hackberry Bay	2.5	0.2
Bayou Perot	1.2	0.7
Delta Farms	0.4	6.8
Bayou Des Amoreux	0.3	2.4
Bayou Palourde	9.8	4.7
Caminada Bay	1.5	1.3
Barataria Bay Waterway	1.0	0.3
Breton Canal	0.4	1.0
Total	**42.3**	**34.0**

Several locations of clustered wetland gains were apparent in the recent (since 2005) NDWI change map, namely in the eastern Delta Farms marshlands, along the northwestern margins of Little Lake, throughout Bayou Perot on both sides of Harvey Cutoff just north of Turtle Bay, in marshlands southeast of Round Lake, and in waters south of Bayou L'Ours near Golden Meadows. A selection of photos taken at locations along the boat survey route near Harvey Cutoff in July 2020 illustrated the stature of emergent marshland vegetation growth detected by the NDWI land gain map from 2005 to 2018 (Figure 5).

Ground-Truth Validation

Comparison of geo-tagged photographs gathered at all locations along the July 2020 boat survey route (shown in Figure 2), wherein emergent marshland vegetation was observed, resulted in 100% (135 out of 135 photos) accuracy confirmation that the NDWI method for majority water-to-wetland cover transition between 2005 and 2018 could detect green emergent vegetation cover at every photo location recorded. The need to maintain a safe distance of more than 150 m between the boat route and the nearby shorelines (due to shallow water passage through some canals) was accommodated in this analysis by applying a 200-m buffer around each photo center point, within which Landsat NDWI mapping

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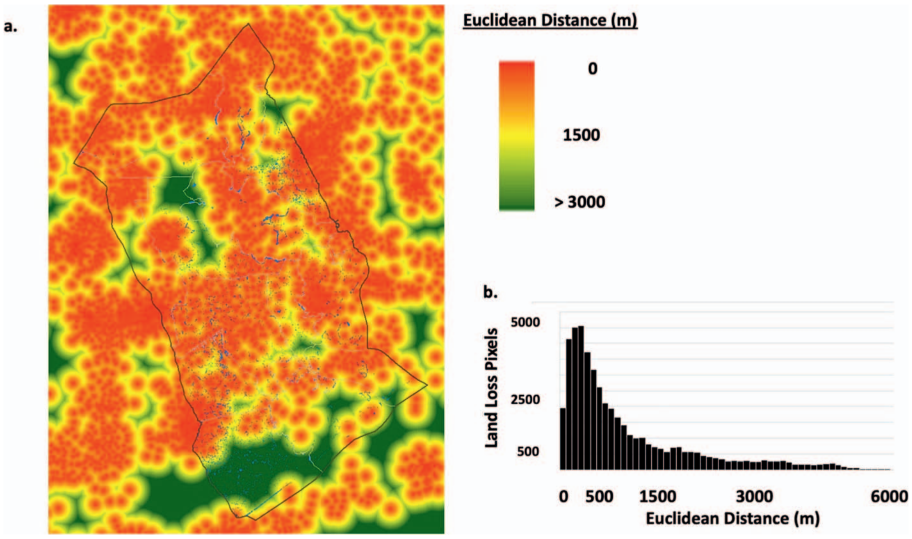

Figure 4. (a) Map of the Euclidean Distances to each historical oil and gas well location within the subbasins study area and (b) histogram of the distance-to-a-well for all recent land loss cells within the study area.

showed one or more majority land pixels at all photo locations from 2018 imagery.

The area observed within a 200-m buffer zone in the shoreline direction would have covered approximately 15,700 m^2. Overlaying the observed buffer zone area for each photo point on the NDWI land gain map from 2005 to 2018 showed that 30% of the buffer zone areas were nearly completely covered with recent marshland vegetation growth, whereas 59% were at least half-covered with recent marshland vegetation growth.

Marshland Restoration Project Sites in Lafourche Parish

The following passages report the results for the marshland project restoration sites of Turtle Bay, Little Lake/Round Lake, and Bayou L'Ours.

Table 3. *Summary statistics by subbasins for the distance to an oil or gas well location for all recent (2005–2018) land loss cells within the study area.*

Subbasin Name (USGS HU12)	Maximum (m)	Mean (m)	Standard Deviation (m)
Bay Jaque	2322	587	414
Hatchet Lake	2974	805	630
Bay Vasier	2255	502	364
Brusle Lake	4018	1086	917
Dupre Cut	2543	832	556
Little Lake	3951	926	770
Hackberry Bay	2116	518	351
Bayou Perot	1973	587	348
Delta Farms	2026	471	276
Bayou Des Amoreux	3188	859	748
Bayou Palourde	6084	2528	1461
Caminada Bay	4080	1567	978
Barataria Bay Waterway	3192	1450	941
Breton Canal	1673	406	263

Turtle Bay Landbridge Shoreline Protection Projects

This series of shoreline wall structures has been installed along the west bank of Bayou Perot and the north shoreline of Little Lake in Lafourche Parish, and along the east bank of Bayou Perot and the east and west banks of Harvey Cutoff in Jefferson Parish, essentially outlining the marshland area of the Dupre Cut subbasin shown in Figure 5. Approximately 3310 m of shoreline protection structures were completed in 2004, 3220 m were completed in 2009, and 6520 m were completed in 2017 under what has been called the Barataria Basin Landbridge Shoreline Protection project.

Based on an analysis conducted by the USGS, land loss rates in this area were nearly –1% per year over the period 1984 to 2016; shoreline erosion along the northeast shore of Turtle Bay was estimated at approximately 1.5 m per year (CPRA, 2019). Nonetheless, NDWI land cover change mapping from 2005 to 2018 indicated that about 4.7 km^2 of open water has been (re)occupied by new marshland area since 2005 within these recently protected shorelines of the Dupre Cut subbasin (Table 2, Figure 5). Emergent vegetation communities were verified as growing on new marshland at more than 70 boat survey photo locations in 2020.

Another phase of the Turtle Bay Marsh Creation and Critical Area Shoreline Protection project is currently in the planning stages, with the goal of creating approximately 1.5 km^2 (377 acres) and protecting approximately 1.2 km^2 (300 acres) of marshland using sediment dredged from Turtle Bay. Certain containment dikes will be degraded as necessary to reestablish hydrologic connectivity with adjacent wetlands, and approximately 870 m of critical shoreline will be conserved.

Little Lake/Round Lake Shoreline Protection

This project area covers 5.6 km^2 (1374 acres) of marshland and open-water habitat found along the southern margins of Little and Round Lakes (Curole and Hartman, 2017). The

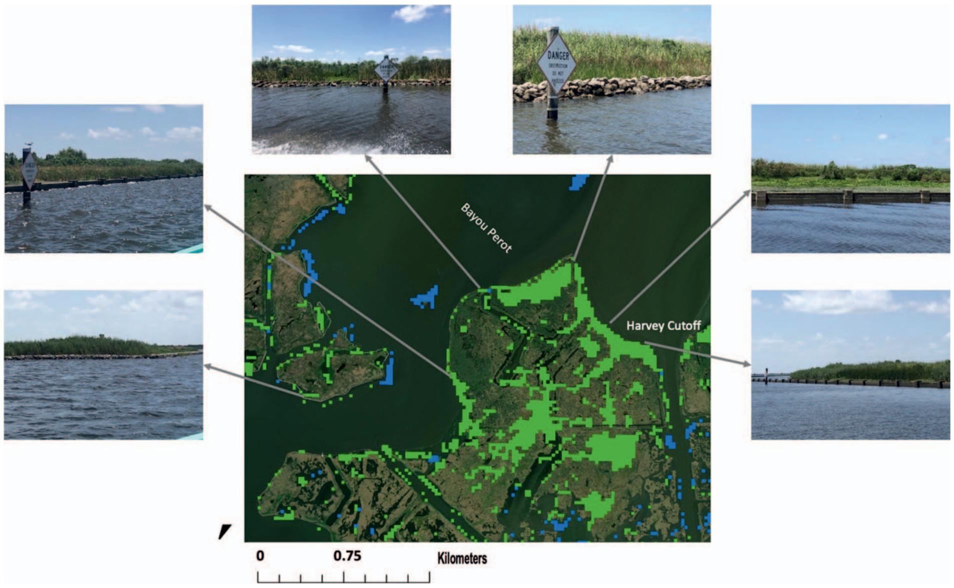

Figure 5. Map of Landsat NDWI change from 2005 to 2018 for the Turtle Bay Landbridge Shoreline Protection Projects, with blue pixels for majority land cover that has converted to majority water cover and green pixels for majority water cover that has converted to majority land cover.

shoreline protection component extends for 7917 m, from the eastern bank of the Breton Canal to the western bank of John the Fool Bayou along the southern shoreline of Little and Round Lakes. Construction of the rock dikes began in 2006 and was completed in 2007. Several earthen containment dikes were placed along the border of the marsh creation and nourishment area starting in 2006 as well.

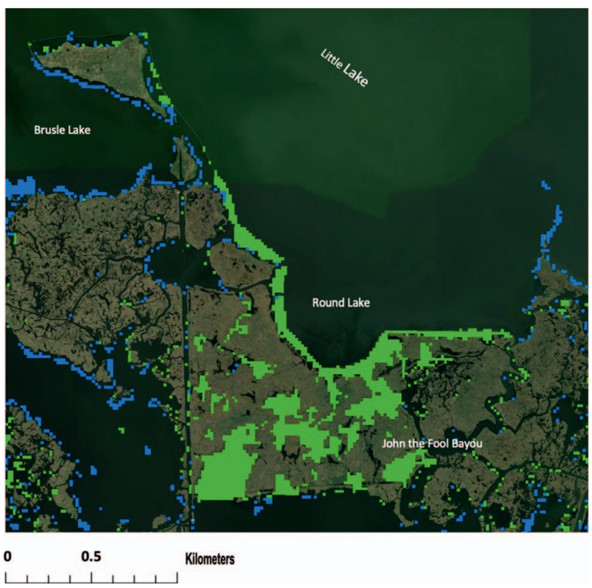

Figure 6. Map of Landsat NDWI change from 2005 to 2018 for the Round Lake Shoreline Protection Project, with blue pixels for majority land cover that has converted to majority water cover and green pixels for majority water cover that has converted to majority land cover.

NDWI cover change mapping from 2005 to 2018 indicated that more than 1 km^2 of open water has been (re)occupied by newly growing marshland cover since 2005 within the recently protected shorelines of Round Lake (Figure 6). These new vegetation communities were verified as growing on land at 50 boat survey photo locations in 2020. Across the project area shown in Figure 6, on all shorelines outside of the Round Lake Protection project, extensive land loss to majority open water was detected using NDWI cover change mapping from 2005 to 2018.

Bayou L'Ours Terracing

This restoration project was located just south of Bayou L'Ours and Round Lake. The Lafourche Parish government, Ducks Unlimited, and Conoco Phillips partnered in 2012 to build terraces with more than 730 m of small earthen levees, constructed with material dredged from the water bottom and planted initially with marsh grass along the raised shorelines. NDWI cover change mapping from 2005 to 2018 indicated that the combined lengths of all these earthen terraces were readily detected as newly growing marshland often no more than two Landsat 30-m-pixels wide (Figure 7). Emergent marsh vegetation communities dominated by *S. patens* were verified as growing on the terraced land at 13 boat survey photo locations in 2020. Although these terraces are not the same as natural wetlands, they have established elevated ridges designed to reduce wave energy and promote future sedimentation in the Bayou L'Ours.

DISCUSSION

Louisiana currently experiences greater coastal wetland loss than all other states in the contiguous United States combined

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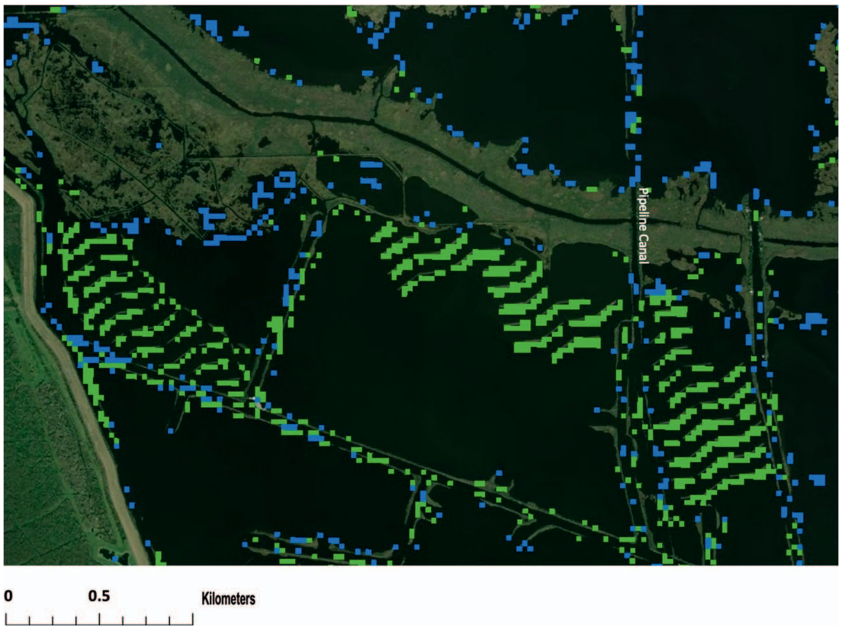

Figure 7. Map of Landsat NDWI change from 2005 to 2018 for the Bayou L'Ours Terracing Project, with blue pixels for majority land cover that has converted to majority water cover and green pixels for majority water cover that has converted to majority land cover.

(Couvillion *et al*., 2017). This study used a time series of Landsat NDWI (Amer, Kolker, and Muscietta, 2017) satellite images for the first time to the author's knowledge to compile statistics on overall losses and gains since 2005 (post-Hurricane Katrina) in wetland areas on the drainages that make up western Barataria Basin of coastal Louisiana. Comparison of water and wetland fractional classes from the Landsat NDWI between 2005 and 2018 showed that land losses to majority water cover exceeded land gains from open-water cover by only 8.3 km^2 over the 1500 km^2 total study area. This is notwithstanding the findings that wetland losses predominated in subbasins in the southern portion of Lafourche Parish (Bayou Palourde and Bay Vasier subbasins), whereas wetland gains predominated in the central portion of Lafourche Parish (Delta Farms).

The consistently low distance of 500 m between the majority of land loss cells and an oil or gas well location and overall (exponentially declining) distribution (Figure 4b) suggests that adverse impacts of historical well drilling and extraction have had a continuing negative impact on marshland degradation and loss in the Barataria Basin since 2005. In contrast, the significantly higher mean distance-to-a-well for recent land loss areas within Bayou Palourde and Caminada Bay indicates that these subbasins have been the exception to the pervasive pattern of a high frequency of recent wetland loss to water due to close proximity to historical oil and gas well locations. The relatively high concentration of recent land loss detected in Bayou Palourde estuaries surrounding Port Fourchon are classified as predominantly saltwater wetlands and have the closest connection to waters of the Gulf of Mexico of any in the study area. With diminishing protection from eroding barrier islands of Terrebonne and Lafourche Parishes, and facing repeatedly strong surges during frequent tropical storms (*e.g.*, from Matthew in 2004; Katrina and Rita, 2005; Gustav, 2008; and Isaac, 2012), these rapidly shrinking marshlands of Bayou Palourde and Caminada Bay have been subject to a unique combination of disturbances. In fact, Caminada Bay was among the subbasins with the lowest recent land gain area detected since 2005 by NDWI image comparison.

The inference that there can be pervasive adverse impacts from accelerated subsidence triggered by development and operations of oil and gas wells (as reported by Morton, Buster, and Krohn, 2002) on current wetland loss patterns in Lafourche Parish is supported by additional evidence from Turner and McClenachan (2018), who reported on coastal Louisiana wetland losses from the indirect effects of digging canals and spoil banks. The mechanisms identified in this study to explain long-term causes of wetland degradation from oil and gas canals and spoil banks derive largely from hydrologic damming that creates waterlogged soils and potentially toxic sulfide accumulation. Day *et al*. (2019) added that subsidence and other toxic impacts of produced water near spoil banks may be contributing to wetland losses in the Mississippi Delta.

Nevertheless, the important contribution made by several shoreline protection and marshland nourishment projects to offset wetland losses over the past 15 years in Lafourche Parish should not be underestimated. Three of the projects reviewed and mapped in this Landsat study for current NDWI vegetation cover, and validated conclusively for recent marshland recovery and protection locations in 2020 boat survey photos, indicate that these seawall construction and dredging projects have helped substantially balance wetland losses along many shorelines just nearly outside of the project

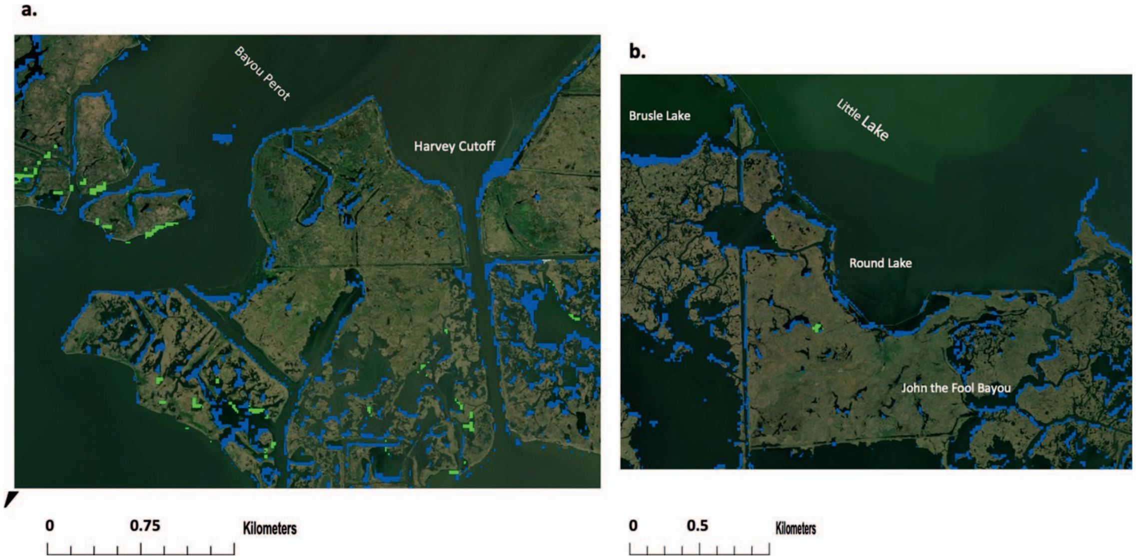

Figure 8. Map of the USGS (Couvillion *et al*., 2017) wetland change product over the period 2006 to 2016 for the (a) Turtle Bay Landbridge and (b) Round Lake Shoreline projects, with blue pixels for majority land cover that has converted to majority water cover and green pixels for majority water cover that has converted to majority land cover.

boundaries. More such projects are in the implementation stages (CPRA, 2019; LACPRA, 2017), and NDWI image mapping to date suggests that restoration of many more kilometers of new marshlands in Lafourche Parish can be expected as a result.

Wetland gains since 2005 near the town of Larose in the Delta Farms subbasin stand out as another example of a detectable shoreline restoration project in Lafourche Parish. The U.S. Army Corps of Engineers, America's Wetland Foundation, Ducks Unlimited, the Louisiana Coastal Protection and Restoration Authority, and other organizations partnered to complete the construction of new earthen berms with grass planting in 2016. This project was designed primarily to narrow the Gulf Intracoastal Waterway, which was dredged in this area starting in the 1920s. Judging from the land gains detected by Landsat NDWI mapping (Figure 3b), this project has succeeded in slowing erosion and saltwater intrusion into the adjacent Delta Farms area, which was once a wetland that was drained and farmed for sugar cane, until a levee break in 1971 that resulted in flooding of the entire farm property (Defelice and Picou, 2007; DNR, 2019).

It is worth noting that the often-referenced USGS coastal land area change product for Louisiana, dating from 1932 to 2016 (Couvillion *et al*., 2011; Couvillion *et al*., 2017) yields very different results for both wetland loss and gain throughout Lafourche Parish when compared to the changes in the Landsat NDWI cover classes developed by Amer–, Kolker, and Muscietta (2017). Although Couvillion *et al*. (2017) commented on an observed coastwide "net stability" in Louisiana wetland area observed over the past 8 years (2008–2016), perhaps associated with a lower frequency of major storms, they did not imply that wetland loss had ceased or slowed recently in Lafourche Parish. Moreover, their land loss *vs*. land gain maps for Lafourche Parish since 2005 reflect an overwhelming net loss of marshlands. The USGS coastal land area change product of Couvillion *et al*. (2017) estimated total wetland loss area between 2006 and 2016 at 76.6 km^2 over the drainages that make up western Barataria Basin and only 5.5 km^2 of wetland gains since 2005 over the same area. This USGS wetland loss total since 2005 was nearly twice as large as the total loss area derived using the Landsat NDWI developed by Amer, Kolker, and Muscietta (2017), and the USGS wetland gain area since 2005 represents less than 20% of the wetland gain area derived using the Landsat NDWI for the same the drainages.

When examining the USGS coastal land area change product more closely at three of the shoreline protection and marshland nourishment projects completed over the past 15 years in Lafourche Parish (Figures 8 and 9), only a few hectares of wetland gain were detected between 2005 and 2016 across these project sites. Rather, practically all of the marshland growth locations validated as recent NDWI land pixels from the 2020 boat survey photos were identified instead as wetland loss areas in the USGS coastal land area change. For the Bayou L'Ours Terracing site (Figure 9), the USGS cover change product showed no land-gain pixels at all since 2005, despite the fact that the new terraces constructed in 2013 are clearly visible in the high-resolution (1-m pixels) image basemap. These errors in the USGS classification seemingly result from Couvillion *et al*.'s (2017) method of using the Landsat reflectance bands of green and mid-infrared rather than blue and shortwave infrared reflectance bands for the NDWI derivation, the latter pair of bands being those utilized and validated in field surveys by Amer, Kolker, amd Muscietta (2017) and by Potter and Amer (2020).

Allen Press, Inc. ■ 27 April 2021 ■ 9:49 am Page 9
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Figure 9. Map of the USGS (Couvillion *et al*., 2017) wetland change product over the period 2006 to 2016 for the Bayou L'Ours Terracing project, with blue pixels for majority land cover that has converted to majority water cover and green pixels for majority water cover that has converted to majority land cover.

It was acknowledged by USGS (Couvillion *et al*., 2017) that, "It is important to note that the effects of (marsh) restoration projects are not always visible in the persistent change map because areas which were lost and then regained as a result of restoration do not meet the persistent change criteria." It was further explained that only wetland cover changes that have persisted into two following analysis periods would meet that criteria for inclusion as restored marshland in the USGS map product. Such "unconfirmed" changes are instead referred to as "new water investigation areas" and "new land investigation areas." However, both of these USGS "new water" and "new land" classes for the period ending in 2015 were included in in the USGS summary results presented above (Figures 8 and 9) for Lafourche Parish cover change. Because both the Barataria Basin and the Round Lake Shoreline Protection projects (shown as validation examples in Figures 5 and 6) were largely completed by 2009, at least four subsequent yearly analysis periods have been reported by the USGS to detect persistent land gains at these sites. Based on these findings, and on a similar comparative analysis by Potter and Amer (2020) for the Breton Sound Basin to the east of Bayou Lafourche, it must be concluded, therefore, that the USGS coastal land area change product is not reporting widespread wetland area gains in southern Louisiana and may have instead overestimated net marshland losses on sections of the Gulf Coast since at least 2005.

CONCLUSIONS

Although the marshlands around Bayou Lafourche that make up western Barataria Basin have experienced a net loss of wetland to open water over the past few decades and lingering detrimental effects of historical oil and gas well operations, there are more positive results from the validation presented here of several shoreline protection projects in central Lafourche Parish that have substantially offset wetland losses. The impact of these restoration projects should not be overlooked nor undervalued. Construction of new seawalls and sediment dredging projects have helped balance the ongoing shoreline land losses that are still evident and pervasive just outside of these project boundaries. As additional coastal restoration projects are in the planning stages around Bayou Lafourche, there is ample evidence from this analysis of recent Landsat satellite imagery to expect that many more square kilometers of water can be reverted to healthy marshlands within 10 years of restoration structure completions.

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Allen Press, Inc. ■ 27 April 2021 ■ 9:50 am Page 11
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