



Land Area Changes in Coastal Louisiana After Hurricanes Katrina and Rita

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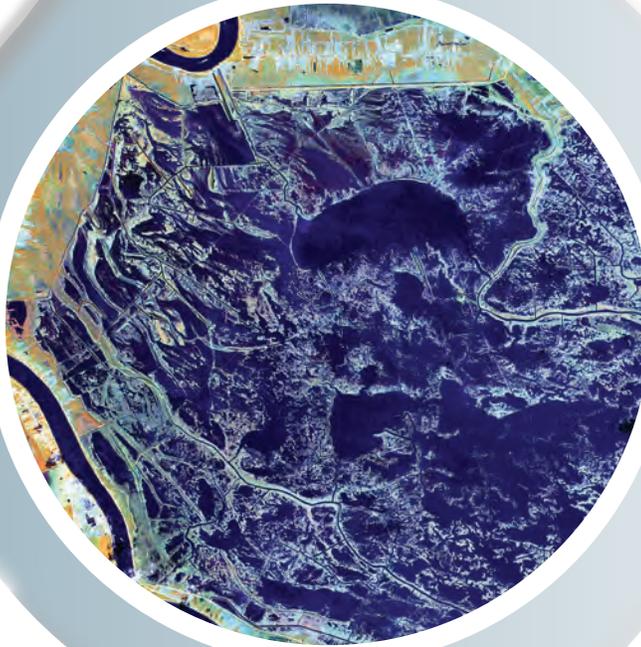
Comparison of classified Landsat Thematic Mapper (TM) satellite imagery acquired before and after the landfalls of Hurricanes Katrina (August 29, 2005) and Rita (September 24, 2005) demonstrated that water area increased by 217 mi² (562 km²) in coastal Louisiana.

Approximately 82 mi² (212 km²) of new water areas were in areas primarily impacted by Katrina (Mississippi River Delta basin, Breton Sound basin, Pontchartrain basin, Pearl River basin), whereas

117 mi² (303 km²) were in areas primarily impacted by Rita (Calcasieu/Sabine basin, Mermentau basin, Teche/Vermilion basin, Atchafalaya basin, Terrebonne basin).

Barataria basin contained new water areas caused by both hurricanes, resulting in some 18 mi² (46.6 km²) of new water areas. The fresh marsh and intermediate marsh communities' land areas decreased by 122 mi² (316 km²) and 90 mi² (233.1 km²), respectively. The brackish marsh

and saline marsh communities' land areas decreased by 33 mi² (85.5 km²) and



28 mi² (72.5 km²), respectively.

These new water areas identify permanent losses caused by direct removal of wetlands. They also indicate transitory water area changes caused by remnant flooding, removal of aquatic vegetation, scouring of marsh vegetation, and water-level variation attributed to normal tidal and meteorological variation between satellite images. Permanent losses cannot be estimated until several growing seasons have passed and the transitory impacts of the hurricanes are minimized. The purpose of this study was to provide preliminary information on water area changes in coastal Louisiana acquired shortly after both hurricanes' landfalls (detectable with Landsat TM imagery) and to serve as a regional baseline for monitoring posthurricane wetland recovery.

Introduction

The U.S. Geological Survey's (USGS) National Wetlands Research Center analyzed land loss or change to water immediately after Hurricanes Katrina and Rita. Analysis was based on USGS Earth Resources Observation and Science (EROS) Data Center's multiple Landsat TM satellite images of coastal Louisiana acquired immediately before and after the landfalls of Katrina and Rita. A series of seven Landsat TM scenes acquired between October 16 and October 25, 2005, provided a snapshot of land-water area changes after the storms. Total water area increased by 217 mi² (562 km²) after the hurricanes according to a comparison of the 2004 and 2005 classified imagery.

The 217 mi² (562 km²) of new water area occurring after the hurricanes contains losses caused by direct removal of wetlands as well as transitory water area changes caused by remnant flooding, removal of aquatic vegetation, scouring of marsh vegetation, and water-level variation caused by normal tidal and meteorological variation between images.

Estimation of permanent losses cannot be made until several growing seasons have passed and the transitory impacts of the hurricanes are minimized.

Methods

Landsat TM imagery is used for Earth-imaging applications. The satellite acquires a 115 mi (185 km) by 106 mi (170 km) scene of coastal Louisiana every 16 days at approximately 9:30 a.m. Central Standard Time in the visible, near-infrared, and mid-infrared spectral wavelengths. The satellite's spatial resolution of 98 ft (30 m) is sufficient to reliably identify features several acres (hectares) in size, and the mid-infrared band is particularly useful for identifying land and water changes occurring in wetlands (Braud and Feng, 1998). Recent identification of new water areas relies on visual assessments of imagery, image classification to determine land-water areas by date, and spatial-temporal comparison of the resultant classified land-water data sets to identify changes in water area after the hurricanes. The persistent appearance of new water bodies on multiple poststorm images under varying water-level conditions indicates that the marsh was probably removed by the storm surge or wind-induced wave erosion, and it is less likely that the images represent flooded land.

Complete coverage of coastal Louisiana was obtained by acquiring four adjacent, north-south image paths, each covering one-quarter of coastal Louisiana. Between-path images are acquired within 1 week, with a side-lap of approximately 22 percent. Ten days are required to obtain complete coverage of coastal Louisiana, given optimal, cloud-free weather conditions. Each path contained two images acquired contemporaneously except for the westernmost image. Twenty-one scenes were acquired, classified, and

then mosaicked together by year to represent fall 2001, fall 2004, and fall 2005 land-water conditions by using a standard land-water classification methodology developed for prior land-water assessments in coastal Louisiana (Barras and others, 2003; Morton and others, 2005; Barras, 2006). Classified scene mosaicking for each time period was ordered from east to west, based on visual assessment of scene water-level conditions, assessment of water-level gage readings (when available), and the ability to discern aquatic vegetation over the scene. Classified land-water data based on scenes acquired under moderate water-level conditions and with easily identifiable aquatic vegetation were allowed to overlay adjacent scenes during the mosaicking process. Scene mosaicking order from October 16 to October 25, 2005, was based on scenes possessing greater posthurricane landfall acquisition periods overlaying scenes with lesser posthurricane acquisition periods.

Using fall data for land-water classification and comparison minimized marsh seasonal variation. The land-water mosaics were masked to match the Louisiana Coastal Area (LCA) boundary to provide spatial consistency with prior land-water change assessments (Barras and others, 2003). The masked coastal land-water data sets were then combined with the 2001 marsh community types data set for identifying new water area changes by marsh communities (Chabreck and others, unpub. data, 2001) following a similar methodology used to integrate marsh type information with classified land-water data for the LCA effort (Twilley and Barras, 2003).

The southeastern Louisiana images were acquired 8 weeks after Katrina's landfall and 4 weeks after Rita's landfall, providing adequate time for most storm-surge-flooded areas to drain. Water levels within the comparison were considered normal in southeastern Louisiana, although some remnant flooding remained in a few leveed areas outside of the comparison area.

The southwestern Louisiana images were acquired 3 and 4 weeks after Rita's landfall, when portions of southwestern Louisiana were still partially flooded from storm surge. The 2001 marsh community types, "other" class, and multiple Landsat scenes were used to identify flooded agricultural/pasture land as well as flooded developed areas occurring within the southwest portion of the study area. An additional 16 mi² (41 km²) of flooded agricultural area occurring within the LCA trend area was identified by using TM imagery bracketing Rita's landfall and was added to the flooded land class.

Marsh burning through either natural or human-induced means is quite common throughout coastal Louisiana and is readily apparent on TM imagery. The burns often reduce vegetation to stubble. Slight increases in water levels will inundate the stubble, causing the burned marsh to appear as a pond or lake, confounding land-water interpretation and classification. A flooded burned marsh class was created to minimize confusion of flooded burned marsh with storm-removed and flooded marsh. Two Landsat scenes acquired on

September 9 and September 21, 2005, were used to identify fresh marsh burns that were later flooded by Rita's surge, which separated known temporarily flooded areas from existing water, direct storm impacts, and flooded marsh. Some areas of persistent flooding in southwest Louisiana were identified as new water areas even after flooded lands and burned marsh were identified. The ability to identify removed marsh versus flooded marsh is limited in these areas until subsequent imagery is obtained under lower water-level conditions.

Posthurricane imagery was used to visually assess land-water variation caused by remnant flooding from the hurricanes, normal tidal and meteorological variation between images, and aquatic vegetation fluctuations. Water level conditions for southeastern Louisiana were also compared against daily and 7-day water-level averages obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Ocean Service's (NOS) Grand Isle, La., tide gage (NOS no. 8761724) readings as applied by Bernier and others (2006), Morton and others (2005) and from review of USGS Louisiana Hydrowatch water elevation data (Louisiana District Webmaster, 2004). Interpretation of water-level conditions was based on prior TM land-water classifications (Morton and others, 2005; Bernier and others 2006). The latest available October 2005 images for southwestern Louisiana were used to minimize post-Rita marsh flooding, to reduce misclassification of flooded marsh with classified water, and to provide contemporaneous imagery with southeastern Louisiana.

Land-water Change Quantification

Quantification of land-water changes was based on comparison of the fall 2004 land-water mosaic with the fall 2005 mosaic. "Fastlands" are developed and agricultural areas surrounded by levees that are generally considered nonwetlands in Louisiana (Louisiana Office of the State Registrar, 2002). All LCA-designated fastland areas, including flooded fastland areas, were excluded from the land-water area comparison. The land-water classifications from fall 2001 and fall 2004 were used to provide prehurricane land-water area variability estimates. Data areas were summarized by major hydrologic basin as defined by the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) (1993) and then by physiographic provinces for presentation. These provinces subdivide coastal Louisiana into the Deltaic Plain on the east, the Marginal Deltaic Plain between the Atchafalaya River and Freshwater Bayou, and the Chenier Plain to the west of Freshwater Bayou (fig. 1).

Total water area increased by 217 mi² (562 km²) between fall 2004 and mid-October 2005 within the 12,918 mi² (33,458 km²) LCA trend area, excluding flooded lands in southwestern Louisiana (table 1). Total unadjusted water area change after the hurricanes was 300 mi² (777 km²). After adjusting for

flooded lands in south-central and southwest Louisiana, the changes were 119 mi² (218 km²) in southeastern Louisiana followed by 85 mi² (308 km²) in southwestern Louisiana. The unadjusted water area for southwestern Louisiana was 181 mi² (469 km²), however, indicating the extent of surge-induced flooding within the LCA trend area.

The 16 mi² (41 km²) increase in water area between 2001 and 2004 should not be interpreted as an indicator of the accuracy of the 2001 and 2004 land-water data sets but rather as an indicator of the variability in land-water classification between typical fall coastal Louisiana Landsat TM data sets. The minimal total water area increase between the two dates is atypical for an area as large as coastal Louisiana. Examination of the 2001 and 2004 land-water data sets show some distinct differences in water area spatial distribution, although the numerical comparison reflects a slight total area difference. Similarly, the 0 mi² (0 km²) land-water change in the Marginal Deltaic Plain between 2001 and 2004 is a summary artifact of combining land-water changes in the Atchafalaya and Teche-Vermilion basins.

Morton and others (2005) examined 23 classified Landsat TM land-water data points obtained between 1983 and 2004 for a 259 mi² (671 km²) study area in the Deltaic Plain and found that land-water classification varied by 5 percent over periods of a few years, with some differences as high as 10 percent between extreme high and low water events.

Review of the 2001 marsh communities' changes by physiographic province show that 71 percent of the coastwide water area increase occurred within the fresh and intermediate marsh communities, whereas 20 percent occurred within the brackish and saline zones (fig. 2; table 2). Over 72 percent of the water area increase within the fresh marsh community occurred in the Chenier Plain and is primarily indicative of remnant flooding in the interior fresh marshes located between Freshwater Bayou and Calcasieu Lake. The water area increase in the intermediate marsh community was greater in the Deltaic Plain; primarily because of the large-scale marsh shearing and scouring that occurred in upper Breton Sound basin from Katrina's surge. The Chenier Plain contained shearing as well as remnant flooding within the intermediate marsh community. The brackish and saline marsh communities accounted for 11 percent and 10 percent of the new water area increase coastwide. Saline marsh community water area increases were greater on the Deltaic Plain than were those on the Chenier Plain, possibly because of the limited extent of saline marshes on the Chenier Plain and normal tidal water level fluctuations partially covering low elevation saline marshes in the Deltaic Plain. Total water area increase in the Marginal Deltaic Plain was small compared to that of either the Deltaic Plain or the Chenier Plain. The relatively large increase of 11 mi² (28 km²) in the fresh marsh community was caused primarily by the removal of aquatic vegetation in the fresh marsh zone located between the Atchafalaya River Delta and East Cote Blanche Bay by Rita's surge.



Land Area Change in Coastal Louisiana After the 2005 Hurricanes: Overview

- 2005 Land
- 2005 Water
- Fastlands: Agricultural, developed, and upland areas surrounded by levees that are generally considered non-wetlands (LDSR, 2002) and that are excluded from calculations of net land area change.
- 2004 to 2005 New Water Areas (Decreased Land Areas): Includes flooded marsh, sheared marsh, eroded marsh, and scoured marsh.
- 2004 to 2005 New Land Areas: Includes wrack, compressed marsh, and aquatic vegetation that is possibly misclassified. These areas are included in calculations of net land area change.
- 2005 Flooded Burned Marsh Areas: Based on imagery review of areas classified as burned marsh within a month to a few weeks of Hurricane Rita's landfall.
- 2005 Flooded Agricultural and Developed Areas: Based on imagery review of new water areas occurring within the "other land" class of Chabreck and Linscombe's marsh community types (unpub. data, 2001).
- Basin Boundary. These boundaries include the sheared area between the hydrologic basins defined by CWPPRA (1988) and the boundary of the LCA study (Barras and others, 2006).
- Hurricane Track

*Data were filtered to depict areas of loss and gain of greater than 2.7 acres (1.1 ha) in size to remove background noise and to increase confidence in the depicted trends.

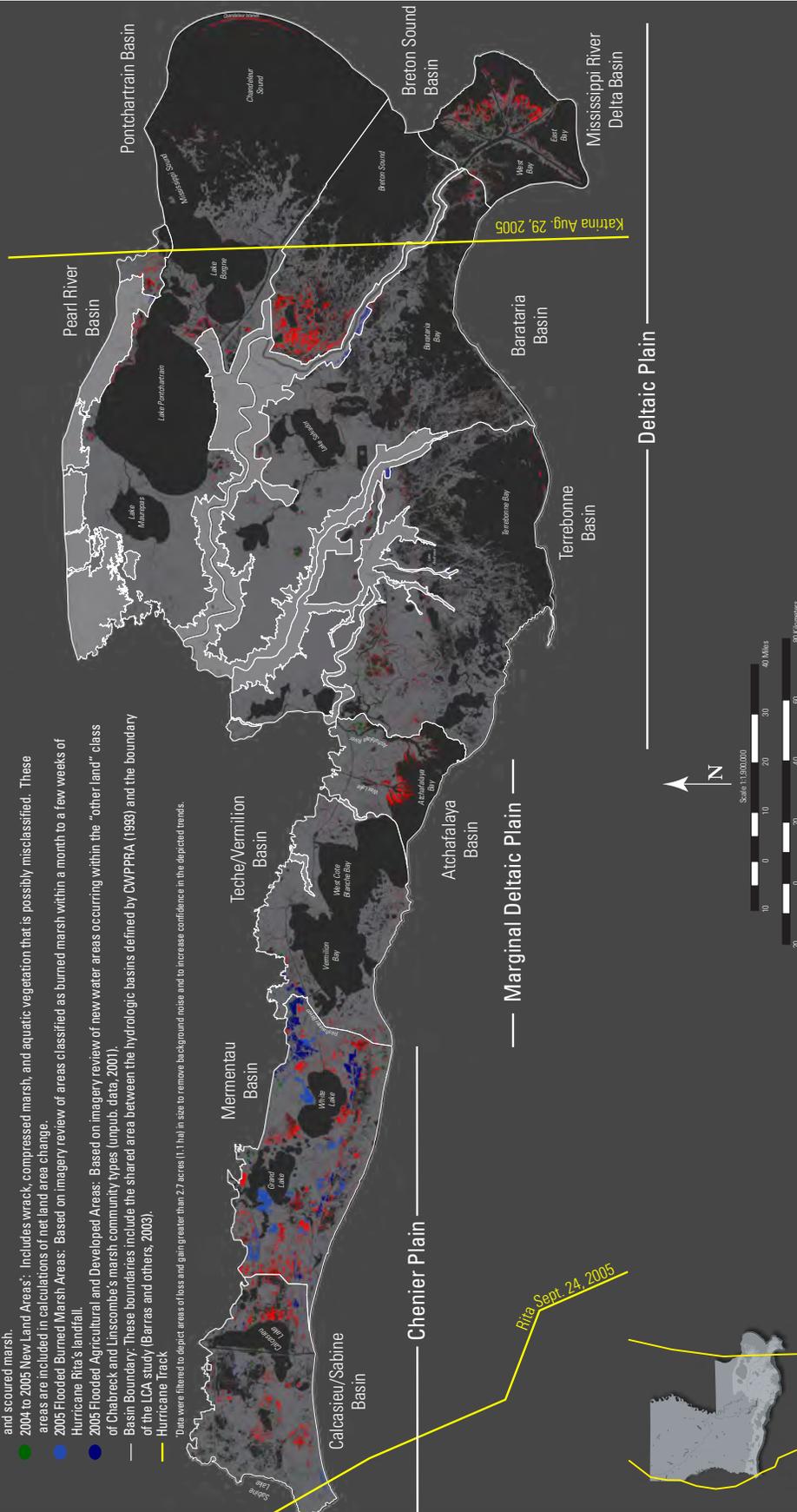


Figure 1. Overview of land area change in coastal Louisiana after the 2005 hurricanes (Barras, 2006).

Table 1. Land area changes in coastal Louisiana after Hurricanes Katrina and Rita occurring within the Louisiana Coastal Area (LCA) trend area in 2005.

[The Barataria, Breton, Mississippi River, Pearl River, Pontchartrain, and Terrebonne basins compose the Deltaic Plain. The Atchafalaya and Teche-Vermilion basins compose the Marginal Deltaic Plain. The Calcasieu-Sabine and Mermentau basins compose the Chenier Plain. ag, agricultural]

Period	Deltaic Plain		Marginal Deltaic Plain		Chenier Plain		Total	
	mi ²	km ²	mi ²	km ²	mi ²	km ²	mi ²	km ²
Fall 2001								
Land	3,768	9,759.12	708	1,833.72	1,463	3,789.17	5,939	15,382.01
Water	5,606	14,519.54	756	1,958.04	617	1,598.03	6,979	18,075.61
Total	9,374	24,278.66	1,464	3,791.76	2,080	5,387.20	12,918	33,457.62
Fall 2004								
Land	3,740	9,686.60	708	1,833.72	1,475	3,820.25	5,923	15,340.57
Water	5,634	14,592.06	756	1,958.04	605	1,566.95	6,995	18,117.05
Total	9,374	24,278.66	1,464	3,791.76	2,080	5,387.20	12,918	33,457.62
Fall 2005								
Land	3,621	9,378.39	691	1,789.69	1,311	3,395.49	5,623	14,563.57
Water	5,753	14,900.27	770	1,994.30	689	1,784.51	7,212	18,679.08
Flooded burned marsh	0	0.00	0	0.00	43	111.37	43	111.37
Flooded ag/pasture impoundment	0	0.00	3	7.77	37	95.83	40	103.60
Total	9,374	24,278.66	1,464	3,791.76	2,080	5,387.20	12,918	33,457.62
2001–04 land area change								
Net land area change	-28	-72.52	0	0.00	12	31.08	-16	-41.44
2004–05 land area change								
Net land area change	-119	-308.21	-17	-44.03	-164	-424.76	-300	-777.00
Flooded lands*	0	0.00	3	7.77	80	207.20	83	214.97
Adjusted land area change	-119	-308.21	-14	-36.26	-84	-217.56	-217	-562.03

* Includes flooded burned marsh and flooded agricultural and developed areas.

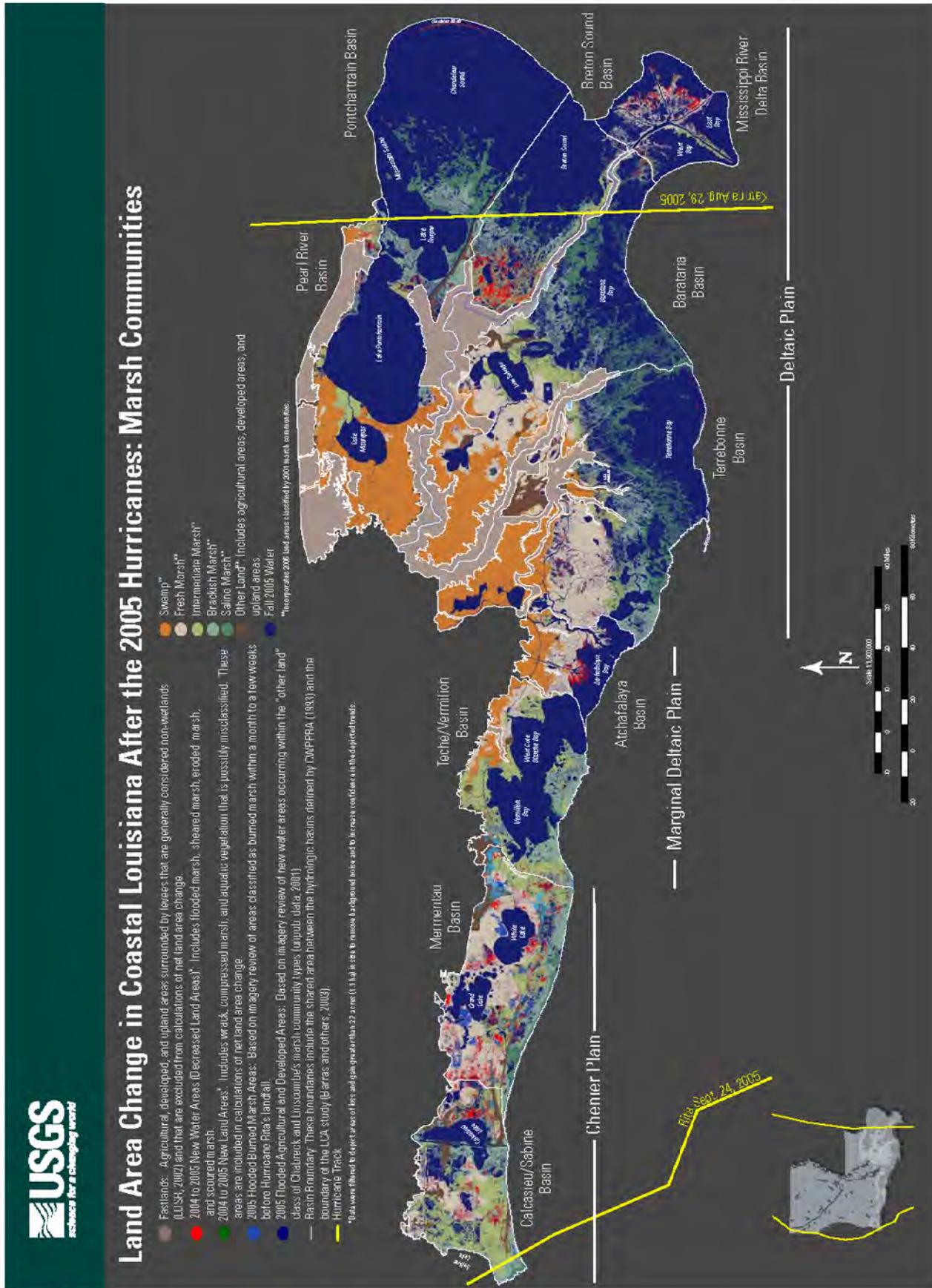


Figure 2. Land area change in coastal Louisiana after the 2005 hurricanes: marsh communities (Barras, 2006).

Table 2. Coastal Louisiana land area changes from fall 2004 to fall 2005 occurring within the Louisiana Coastal Area (LCA) trend area by 2001 marsh communities.

[The Barataria, Breton, Mississippi River, Pearl River, Pontchartrain, and Terrebonne basins compose the Deltaic Plain. The Atchafalaya and Teche-Vermilion basins compose the Marginal Deltaic Plain. The Calcasieu-Sabine and Mermentau basins compose the Chenier Plain]

Community	Deltaic Plain		Marginal Deltaic Plain		Chenier Plain		Total	
	mi ²	km ²	mi ²	km ²	mi ²	km ²	mi ²	km ²
Fall 2004								
Forested wetlands	1,161	3,006.99	168	435.12	0	0.00	1,329	3,442.11
Other land	209	541.31	35	90.65	153	396.27	397	1,028.23
Fresh marsh community	777	2,012.43	175	453.25	590	1,528.10	1,542	3,993.78
Intermediate marsh community	439	1,137.01	193	499.87	455	1,178.45	1,087	2,815.33
Brackish marsh community	527	1,364.93	129	334.11	222	574.98	878	2,274.02
Saline marsh community	627	1,623.93	8	20.72	55	142.45	690	1,787.10
Water*	5,634	14,592.06	756	1,958.04	605	1,566.95	6,995	18,117.05
Total	9,374	24,278.66	1,464	3,791.76	2,080	5,387.20	12,918	33,457.62
Fall 2005								
Forested wetlands	1,160	3,004.40	168	435.12	0	0.00	1,328	3,439.52
Other land	207	536.13	33	85.47	131	339.29	371	960.89
Fresh marsh community	755	1,955.45	165	427.35	500	1,295.00	1,420	3,677.80
Intermediate marsh community	390	1,010.10	191	494.69	416	1,077.44	997	2,582.23
Brackish marsh community	509	1,318.31	126	326.34	210	543.90	845	2,188.55
Saline marsh community	600	1,554.00	8	20.72	54	139.86	662	1,714.58
Water*	5,753	14,900.27	773	2,002.07	769	1,991.71	7,295	1,8894.05
Total	9,374	24,278.66	1,464	3,791.76	2,080	5,387.20	12,918	33,457.62
2004–05 net area change								
Forested wetlands	1	3	0	0	0	0	1	3
Other land	2	5	2	5	22	57	26	67
Fresh marsh community	22	57	10	26	90	233	122	316
Intermediate marsh community	49	127	2	5	39	101	90	233
Brackish marsh community	18	47	3	8	12	31	33	85
Saline marsh community	27	70	0	0	1	3	28	73
Water*	-119	-308	-17	-44	-164	-425	-300	-777

* Includes the 83 mi² (214.97 km²) of flooded lands consisting of flooded burned marsh and flooded agricultural and developed areas. After adjustment for these flooded areas, the net increase in water area (decrease in land) was 217 mi² (516 km²).

After the hurricanes the classified land-water datasets were spatially compared to produce an output change data set identifying the locations of new water and land areas occurring by fall 2005. The land-water change data set was filtered to remove changes below 2.7 acres (0.01 km²), to remove “noise,” and to provide a more accurate change interpretation. The new water area changes were displayed over the 2005 land-water marsh community type data sets to assist in identifying, interpreting, and verifying persistent water areas caused by storm impacts.

Verification

Changes in water area that were identified by Landsat were verified by review of multirate, multiresolution imagery bracketing the hurricanes; by small plane overflight of TM-identified new water bodies located in southeastern and south-central Louisiana on November 18 and December 9, 2005; and by limited field investigations. The imagery review indicated origin, variability, and duration of new water bodies. The small plane overflights provided a quick and efficient way to verify the existence of new or expanded water bodies over southeastern Louisiana. Field investigations provided water-depth information for selected new water bodies adjacent to Lake Lery, within the Breton Sound basin. According to the NOS Grand Isle gage, daily average water levels during both verification flights were within 2.4 inches (6.1 cm) of water levels shown on the October 25, 2005, Landsat image that covered the majority of the southeastern Louisiana study area.

Shear Definition

A host of terms is used to describe hurricane impacts on wetlands, such as rolled marsh, compressed marsh, inverted marsh, flipped marsh, folded marsh, ripped marsh, scoured marsh, and marsh balls. This report defines areas of persistent new water bodies occurring after the hurricanes where marsh vegetation was either completely or partially removed as “shears.” Shears may include features defined by the other terms listed above, but the key characteristic is the presence of persistent new water bodies that appear in multiple posthurricane images acquired over a period of a few months to a year after the storm’s landfall. The hurricanes’ surge also expanded existing ponds in fresh, intermediate (less saline than brackish), and brackish marshes with some limited expansion in saline marshes. These features are defined as shear-expanded ponds and may contain compressed, rolled, or inverted marsh, as well as scoured marsh and direct shoreline erosion. For example, shears in fresh marshes tend to compress or fold perpendicular to the surge’s direction if located in a storm’s northwest quadrant, forming northwest to southeast trending ponds. Existing ponds may be expanded

to the northwest by compression of the marsh forming the pond’s northwestern shoreline. Shears in brackish and saline marshes tend to remove vegetation to the underlying clay and/or to the root mat, forming an intertwined mosaic of removed and partially removed marsh. Shears in intermediate marshes may contain folding and compression as well as the scouring prevalent in the brackish and saline marshes. These conditions vary, even within shear complexes, and require verification by small plane overflight, by examination of high-resolution imagery, and by field investigations to provide a final shear classification (fig. 3).

Southeastern Louisiana (Deltaic Plain)

New water bodies and expanded water bodies formed on the eastern side of the Mississippi River basin; the northwestern portion of the Breton Sound basin, from Delacroix to Caernarvon (Barras, 2007, fig. 7A); the northern and eastern shorelines of Lake Borgne; and along the north shore of Lake Pontchartrain from Mandeville to the Mississippi border, including extensive impacts in the Pearl River basin (fig. 1). Some expanded ponds and limited shoreline erosion were identified in the Labranche wetlands located east of the Mississippi River, between Laplace and Kenner (Barras, 2007, figs. 12A, 12B, and 12C). The smallest new water body identified with TM imagery and verified by small plane overflight was approximately 4 acres (0.02 km²) in the saline Bayou Biloxi marsh (Barras, 2007, figs. 4A and 4B). The largest new lake was approximately 1,200 acres (4.86 km²) located in the intermediate marsh of upper Breton Sound basin (Barras, 2007, fig. 7B), and a 570-acre (2.31-km²) shear was located in the fresh marsh adjacent to the east bank of South Pass (Barras, 2007, fig. 3C) in the Mississippi River basin (Barras, 2007, fig. 3A). Visual observations based on small plane overflight confirmed that some of the new water areas consist of shallow ponds where the marsh surface has been sheared or ripped to the root mat or to the underlying firm substrate of clay by storm surge (Barras, 2007, fig. 7S).

The shears in upper Breton Sound basin ranged in depth from 1 inch (2.54 cm) to 3 ft (91.44 cm) based on field investigations (G. Steyer, USGS, oral commun., 2006). Imagery review of this basin reveals large shallow mudflats bordering exposed marsh spoil banks and other elevated features. Slight variations in water level exposed large areas of flats between subsequent followup images. A March 2, 2006, Landsat 5 scene revealed some revegetation occurring on the shallow flats. Field investigations conducted in early March of 2006 indicated that annuals yellowcress (*Rorippa palustris*) and butterweed (*Packera glabella*), as well as algae, colonized some of the flats (B. Perez, USGS, oral commun., 2006). Another scene acquired on June 6, 2006, revealed expanded revegetation of the shallow flat areas bordering exposed marsh as well as the presence of potential aquatic vegetation. Most



Figure 3. Example of marsh shearing after Hurricanes Katrina and Rita in the intermediate marsh community of upper Breton Sound to the southwest of Delacroix, La.

of the exposed marsh areas occurring within the fresh and intermediate marsh community types located in the northwest portion of the basin were reflecting strongly in the near-infrared, indicating vegetative growth. Field investigations are required to identify the type of vegetation growing in this area.

The submerged marsh surface is visible in other areas (fig. 3). Remnant marsh balls and other debris, not large enough to be identified with TM imagery, litter some of the sheared areas, while other areas appear as large shallow ponds or lakes with large areas of exposed mud flats that vary depending on water level. Groups of small, interconnected ponds have been expanded in some areas by the shearing of the intervening marsh.

Areas of floating fresh marsh (C. Sasser, Louisiana State University, oral commun., 2006) and some scrub/shrub were completely removed in the northern Pearl River basin (Barras, 2007, fig. 5B), while a series of shears was cut across the southern portion of the basin (Barras, 2007, fig. 5A). The fresh and intermediate marshes in northwestern Breton Sound basin were completely rearranged, displaying multiple large northwest to southeast trending shears (Barras, 2007, fig. 7A). Large deposits of wrack accumulated adjacent to and/or on top of spoil banks and natural distributary channels and often completely surrounded black willow (*Salix nigra*) and shrubs (Barras, 2007, fig. 7H). Shallow mudflats, peppered by marsh balls and other debris, were present throughout the area. Ninety percent (37 mi² of the 41 mi² (96 km² of the 106 km²)) of new water area appearing after the hurricanes in Breton Sound basin occurred within the 2001 intermediate marsh community.

The more mineral-rich brackish and saline marshes fared better, as indicated by the lack of large new water areas in central Breton Sound basin and the Bayou Biloxi marsh. Examination of high-resolution color infrared digital orthophoto quarter quadrangles (DOQQs) acquired in late October 2005 shows the presence of small shears, below the detectable spatial resolution of TM imagery present in these marshes.

Fringing shoreline erosion and the formation of small ponds were observed in the brackish-saline marshes, but the greatest impacts occurred in the more organic fresh and intermediate marshes of the eastern Mississippi River basin (Barras, 2007, fig. 3A), upper Breton Sound basin, and Pearl River basin (Barras, 2007, fig. 5A). Compression features of 1 mi (1.6 km) or more long were observed in upper Breton Sound basin. Smaller but distinct compression features of 0.5 mi (0.8 km) in length were also observed in the North Shore marsh (Barras, 2007, figs. 8A and 8C). The eastern Mississippi River basin also suffered some impacts from Hurricane Ivan (September 16, 2004), as observed when comparing the fall 2001 to the fall 2004 imagery. The Chandeleur Islands' land area decreased from 5.6 mi² (14.50 km²) from fall 2004 to 2 mi² (5.18 km²) by fall 2005 (Barras, 2007, fig. 1).

Areas west of the Mississippi River were impacted more by Rita than by Katrina, as observed by comparison of Landsat

imagery acquired on September 15, 2005, after Katrina but before Rita's landfall. Areas of significant shoreline erosion, possibly caused by wave action from Katrina's northwesterly winds were, however, detected along the southern shorelines of Lake Salvador and Little Lake in central Barataria basin, 35 mi (56 km) east of Katrina's track (Barras, 2007, figs. 11A and 11B). Similar lakes located 60–70 mi (97–113 km) west of Katrina's track in Terrebonne basin did not display similar erosion along their southern shorelines.

Rita's surge rearranged Katrina's wrack in upper Breton basin and caused the formation of limited new ponds and some expanded ponds from central Barataria basin across the Terrebonne basin to the Atchafalaya River. These impacts occurred primarily in fresh and intermediate marshes, although similar effects were observed in brackish marshes. Rita reactivated some shears originally formed by Hurricane Andrew and later reactivated by Hurricane Lili in western Terrebonne basin.

Areas of submerged and floating aquatic vegetation were shifted or removed by Rita's surge. Some of the changes in water and land area in the floating fresh marshes of the Barataria and Terrebonne basins were caused by the removal of floating and submerged aquatic vegetation by storm surge. Other land-water area changes were caused by normal changes in aquatic vegetation distribution between the fall 2004 and fall 2005 imagery. Review of multiple Landsat images was used to identify areas where land-water changes were caused by storm surge rather than by normal distribution changes. The fresh and intermediate marshes often contain extensive floating and submerged aquatic vegetation in October and November, and identification of these areas with Landsat imagery varies between excellent and poor, depending on vegetation reflectance characteristics. Surge removal of submerged and floating aquatic vegetation was noticeable west of Bayou Dularge and south of Bayou Penchant in the western Terrebonne basin (Barras, 2007, figs. 15A, 15B, and 18A).

Water level effects are also noticeable in the marshes north of Lake Boudreaux, as evidenced by exposure of low-elevation marsh and flats during low water-level conditions on the October 25, 2005, image versus higher water levels on the November 7, 2004, image (fig. 1).

Representative examples of before and after Landsat imagery and oblique photography used to identify and verify new water areas caused by storm impacts in south Louisiana are available in Barras, 2007.

South-central Louisiana (Marginal Deltaic Plain)

Primary impacts from Rita's surge to Louisiana's south-central coast were the removal of floating and submerged aquatic vegetation from the Atchafalaya River west to East Cote Blanche Bay (fig. 2). The surge basically removed

vegetation from the Atchafalaya River and Wax Lake Deltas, existing ponds, lakes, and bayous, as well as expanded some existing ponds (Barras, 2007, fig. 19A). Surge impacts increased to the west. Rita's surge expanded some shears formed by Hurricane Lili (October 3, 2002) near Marone Point (Barras, 2007, fig. 19B). Marsh scouring and some small shears were present in the southeast quadrant of Marsh Island. Some new shears and surge-expanded ponds ranging from 4.94 to 70 acres (0.02 to 0.28 km²) were present in the intermediate and brackish marsh communities east of Freshwater Bayou (Barras, 2007, fig. 21A). Accumulated wrack was evident along southeastern-facing spoil banks. Some flooding of impounded agricultural areas and fresh and intermediate marshes occurred east of Intracoastal City.

Southwestern Louisiana (Chenier Plain)

Rita's surge and flooding impacts were greater west of Freshwater Bayou. Review of recent Landsat scenes indicate that persistent flooding of impounded marsh and agricultural areas continued from October 2005 through early April 2006 between Freshwater Bayou and Calcasieu Lake to the west (Barras, 2007, fig. 20). Areas with particularly persistent flooding included the fresh marsh community located along the eastern shoreline of White Lake and between White Lake and Pecan Island; the intermediate marsh located southwest of Grand Lake; the intermediate and brackish marshes bordering the east-central and southeastern Calcasieu Lake shoreline; and the fresh marsh just to the northwest of West Cove in Calcasieu Lake. Wrack was present along most south and southeasterly facing canal and pipeline spoil banks as well as along impoundment levees throughout the Chenier Plain, with a few wrack accumulations exceeding 100 acres (0.40 km²) just north of Johnsons Bayou and south of the Sabine National Wildlife Refuge (NWR).

Surge-created shears were present over the entire Chenier Plain. Over 1,200 acres (4.86 km²) of intermediate marsh contained within the southern portion of the Freshwater Bayou Wetlands restoration project were removed by Rita's surge (Vincent and others, 2000). A series of north-south trending shears located in the brackish marsh south of Pecan Island were identified bordering the southern extent of the Pecan Island Gas Field (with one shear exceeding 300 acres (1.21 km²)) and forming between parallel north-south pipeline canals approximately 2,200 ft (0.67 km) apart (Barras, 2007, fig. 21A). Another 350-acre (1.42-km²) shear was identified in intermediate marsh 1.6 mi (2.57 km) to the east of Deep Lake in Rockefeller Wildlife Refuge (Barras, 2007, fig. 23). A brackish marsh peninsula, surrounded by Mud Lake a few miles east of Johnsons Bayou, contained a 70-acre (0.28-km²) shear, while the marsh 2 mi (3.22 km) due north of the peninsula contained another 140-acre (0.57-km²) shear

(Barras, 2007, fig. 25). The largest shears were located in intermediate marsh 2 mi (3.22 km) north of Johnsons Bayou and south of the Sabine NWR, 11 mi (17.70 km) east of Rita's landfall at Sabine Pass. The total marsh area removed exceeded 2,600 acres (10.52 km²). Large wrack accumulations were located along the Sabine NWR Freshwater Pool southern levee system, immediately north of the Johnsons Bayou shear. Several narrow linear north-northwest by south-southeast oriented shears, as much as a mile (1.6 km) or more in length, extended from a large 200-acre (0.81-km²) shear located in the intermediate marsh bordering the east side of the Sabine NWR Freshwater Pool. Large accumulations of wrack were visible between the linear shears.

The fresh and intermediate marsh communities south of Sweet Lake, located inland 12 mi (19.3 km) from the Gulf of Mexico, contained a few shears as large as 200 acres (0.81 km²) and significant areas where floating aquatic and submerged aquatic vegetation were removed (Barras, 2007, fig. 24). Large accumulations of wrack were found along south-facing spoil banks and along the southern bank of the Gulf Intracoastal Waterway (GIWW).

Persistent flooding of impounded marsh, impounded agricultural areas, and burned marsh areas through April 2006 caused by Rita's surge confounds southwestern Louisiana land-loss area estimates. Some of the persistent flooded marsh areas identified as new water areas in the fall 2005 dataset were drained by May 2006 but also contained large new burned marsh areas (Barras, 2007, figs. 22A and 22D). Comparison of February, March, April, and May 2006 images showed that some of the drained areas were partially reflooded at later dates (Barras, 2007, figs. 22B, 22C, and 22D). Many of the drained areas occurring in persistently flooded areas from October 2005 through February 2006 appeared similar to exposed mudflats, which indicates that these areas were lower than surrounding marsh because of vegetation collapse or removal and were likely to retain water and appear as ponds under wetter conditions. The drought conditions from the fall of 2005 through the spring of 2006 across coastal Louisiana further complicate land-water interpretations since the post-Rita vegetation recovery is not representative of normal precipitation conditions. Some areas of surge-flooded marsh appeared similar to bare earth or dry mudflats rather than resembling growing vegetation by May 2006. Other areas appeared to be growing, particularly where Rita's surge quickly drained from the marsh, similar to surge-residence patterns in southeastern Louisiana. These areas were located east of Freshwater Bayou and west of Johnsons Bayou, adjacent to the eastern shoreline of Sabine Lake, and brackish and saline marshes appeared to be growing within 1–2 mi (1.6–3.2 km) of the gulf shoreline. Some of the shears south of Pecan Island were partially drained, whereas others remained as ponds, indicating varying shear depths on the same May 2006 image.

Historical Comparison

The distribution of Katrina's and Rita's new water areas varied coastwide. Shears were often located in marshes fringing 1956–2000 loss areas, but they were also distributed in historically stable areas such as upper Breton Sound basin and the lower Pearl River basin (fig. 4; Barras, 2007, figs. 5C, 5D, and 7G). Land loss is occurring in these areas, but at low rates when compared to higher land-loss rate areas such as those in the Barataria and Terrebonne basins. The 1956–2004 loss for Breton Sound basin was 67 mi² (173.53 km²). The 2004–05 increase in water area after Katrina and Rita was 41 mi² (106 km²), a 61 percent increase in water area. The total water area increase between 2004 and 2005 for east of the Mississippi River was 79 mi² (205 km²), exceeding the projected 2000–2050 rate of 61 mi² (158 km²) based on comparison of 1978–2000 loss and gain trends (Barras and others, 2003).

Rita's surge removed remnant marsh located within historical land-loss areas that collapsed rapidly during the mid-1960s to the mid-1970s in western Barataria basin and eastern Terrebonne basin (Morton and others, 2005; Barras, 2007, figs. 13A, 13C, 14A, 14C, and 15B). Katrina's surge did the same in historical land-loss areas of the Pontchartrain basin, along the north shore of Lake Pontchartrain, and in the Labranche wetlands (Barras, 2007, figs. 10B, 12A, and 12D). Shears and scoured marsh were present between the GIWW and the west shoreline of Lake Borgne, however, just east of Alligator Point, a historically stable area (Barras, 2007, figs. 6A and 6C). Remnant contiguous marsh, located between historical loss areas and the Gulf of Mexico shoreline on the eastern side of the Mississippi River Delta was removed by Katrina's surge. The distribution of new water areas in southwestern Louisiana followed a similar pattern. Shears often occurred in marshes fringing historical loss areas or in remnant marshes occurring within areas with historical loss but also occurred in historically stable areas. Shears in stable marsh areas were often associated with expansion of existing small ponds but were also observed in areas of contiguous marsh where vegetation was either partially or completely removed. The flooding present on the Chenier Plain in the fall of 2005 precludes definitive quantitative comparison with historical losses, although selected areas of potential loss could be identified and quantified by imagery review.

Comparison of Prior Hurricane Impacts

The combined impacts of Katrina and Rita on land area changes (identified by using Landsat TM imagery from 1983 to the present) exceeded impacts from other hurricanes in coastal Louisiana (including Andrew). Prior Landsat-based assessments identified shears as large as 800 acres (3.24 km²) from Andrew (August 26, 1992) in the fresh marsh community

of western Terrebonne basin, bordering the Atchafalaya River (Barras, 2007, fig. 16C). Impacts from Andrew's surge were detected 85 mi (137 km) to the east in central Barataria basin near Bayou Rigolettes, increasing in frequency and magnitude toward Andrew's landfall near Morgan City, La. Hurricane Lili's landfall (October 3, 2002), near the mouth of Freshwater Bayou, created a series of northeast to southwest trending shears in the contiguous fresh and intermediate marsh west of Bayou Sale 30 mi (48.28 km) to the east (Barras, 2003, 2007, fig. 19C). The largest shear was 175 acres (0.71 km²) with the marsh completely removed to the underlying clay. Significant internal marsh shearing was not observed in the marsh adjacent to Freshwater Bayou. Lili's surge caused detectable impacts 95 mi (153 km) to the east, north of Wonder Lake in central Terrebonne basin, and caused some expansion of older Andrew shears as well as created some smaller new shears in western Terrebonne basin (Barras, 2007, fig. 16B). Lili's surge removed and rearranged floating and aquatic vegetation within fresh and intermediate marsh communities across the entire impact area, including the Atchafalaya River and Wax Lake Deltas with rack visible east to Lake Boudreaux. Observed impact severity increased westward towards Lili's landfall.

Either Lili or Tropical Storm Isadore (September 26, 2002) caused a series of small northwest to southeast trending shears in the intermediate marsh of upper Breton Sound basin in an area that was completely rearranged by Katrina's surge north of Lake Lery (Barras, 2007, fig. 9). The largest detected shear was 55 acres (0.22 km²) with several smaller shears concentrated within an 8-mi-wide (12.9-km-wide) swath, indicating that the fresh and intermediate marshes located there were susceptible to storm surge. The eye of Hurricane Ivan passed approximately 60 mi (97 km) to the east of the Mississippi River Delta on September 16, 2004, before making landfall near Pensacola, Fla., later that day. Significant shoreline erosion was observed on the eastern side of the delta on both southeasterly and northern facing shorelines (Barras, 2007, fig. 3D). No significant internal marsh shearing was observed, but wrack was dispersed along the eastern side of the active delta. The Chandeleur Islands suffered some overwashing and cutting from Ivan's surge.

Many of Andrew's shears were revegetated by the time that Lili impacted the western Terrebonne and Atchafalaya basins. Some of the larger shears remained as ponds or lakes, but they were often partially or entirely covered with vegetation. Several smaller new shears ranging from 10 to 30 acres (0.04 to 0.12 km²) were created by Lili's surge in the fresh marshes bordering Atchafalaya Bay, between East Cote Blanche Bay and the Atchafalaya River (Barras, 2007, fig. 18B). Some of the shears appeared to result from removal or flipping of shrub/scrub vegetation, typically wax myrtle (*Morella cerifera*). Both the Atchafalaya River and Wax Lake Deltas were choked with aquatic vegetation by the fall of 2003. The shears 10 mi (16 km) further east, located closer to the historical wetland loss areas, remained partially open (Barras, 2007, fig. 16B). Only Lili's larger shears remained



Land Area Change in Coastal Louisiana After the 2005 Hurricanes: A Historical Perspective (from 1956)

— Basin Boundary: These boundaries include the shared area between the hydrologic basins defined by CWPPRA (1993) and the boundary of the LCA study (Barras and others, 2003).
 — Hurricane track

- 1956 Land
- 1956 Water
- Fastlands: Agricultural, developed, and upland areas surrounded by levees that are generally considered non-wetlands (LOSS, 2002) and that are excluded from calculations of net land area change.
- LCA Area Not Included in the 1956 Data Coverage
- 1956 to 2004 Land Loss: Based on direct comparison of 1956 and 2004 land-water data.
- 1956 to 2004 Land Gain: Based on direct comparison of 1956 and 2004 land-water data.
- 2004 to 2005 New Water Areas (Decreased Land Areas): Includes flooded marsh, sheared marsh, eroded marsh, and scoured marsh.
- 2004 to 2005 New Land Areas*: Includes wrack, compressed marsh, and aquatic vegetation that is possibly misclassified. These areas are included in calculations of net land area change.
- 2005 Flooded Burned Marsh Areas: Based on imagery review of areas classified as burned marsh within a month to a few weeks before Hurricane Rita's landfall.
- 2005 Flooded Agricultural and Developed Areas: Based on imagery review of new water areas occurring within the "other land" class of Chabreck and Linscomb's marsh community types (unpub. data, 2001).

*Data were filtered to depict larger areas of loss and gain greater than 3.5 acres (1.4 ha) in size and to remove noise and increase the confidence of the depicted trends. **Data were filtered to depict areas of loss and gain greater than 2.7 acres (1.1 ha) in size to remove noise and to increase confidence in the depicted trends.

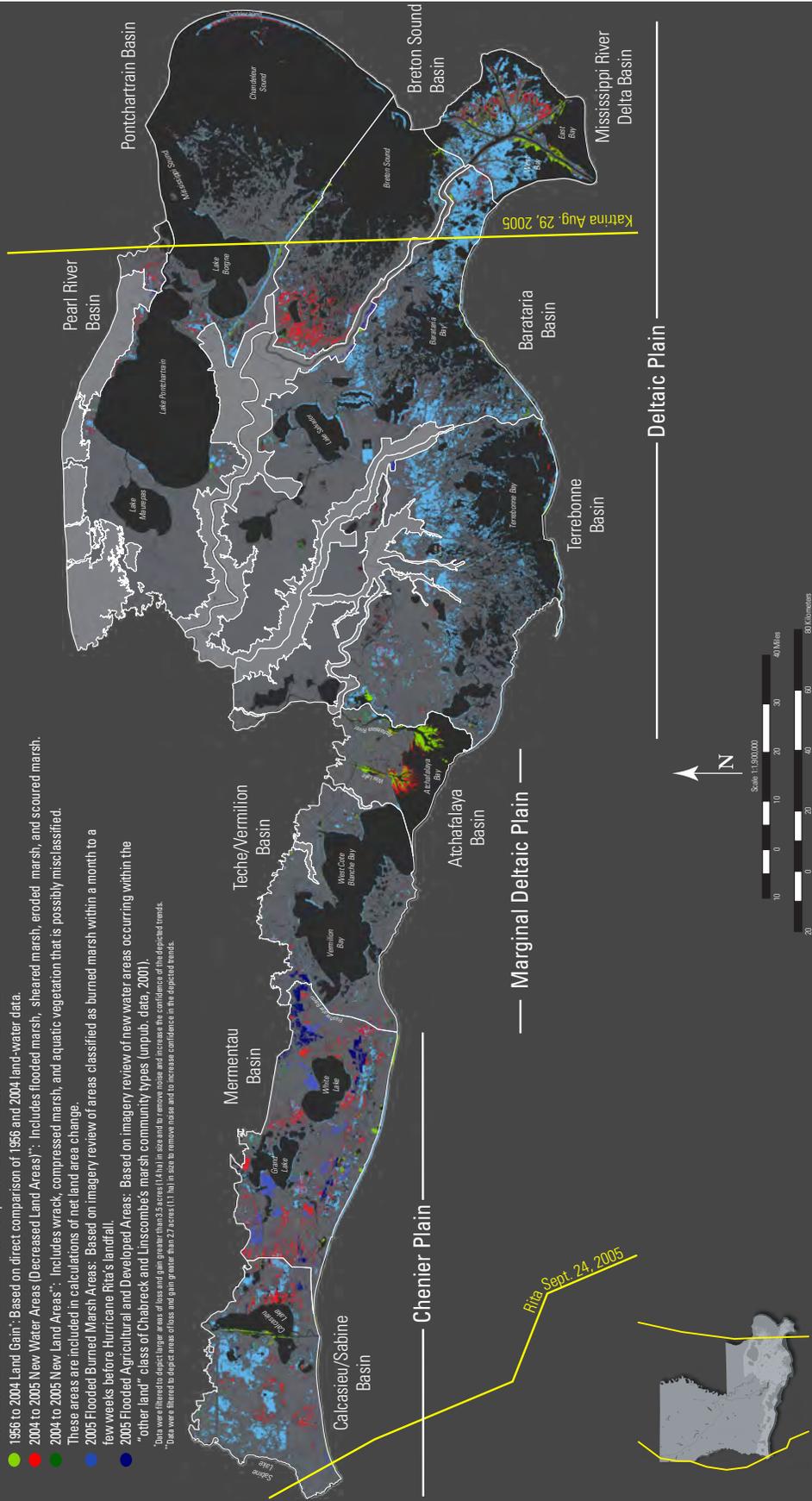


Figure 4. Land area change in coastal Louisiana after the 2005 hurricanes: a historical perspective (Barras, 2006).

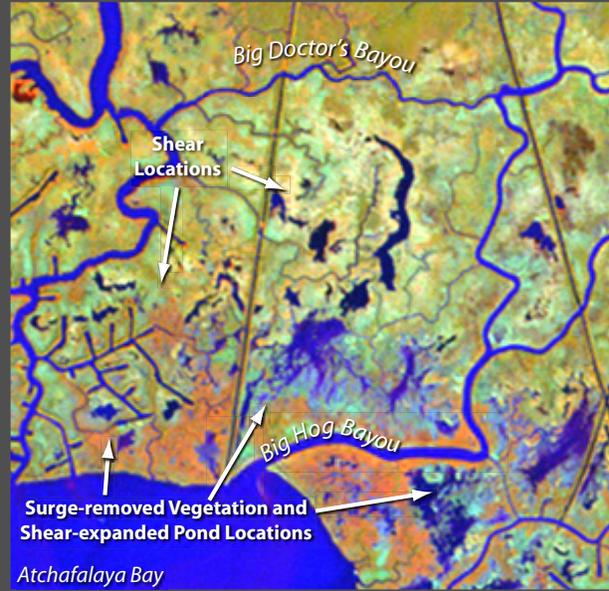


Big Hog Bayou, Louisiana
Comparison of Marsh Shears After Hurricanes Andrew, Lili, and Rita
(Landsat 5 Thematic Mapper Satellite Imagery)
Fresh Marsh Community Type

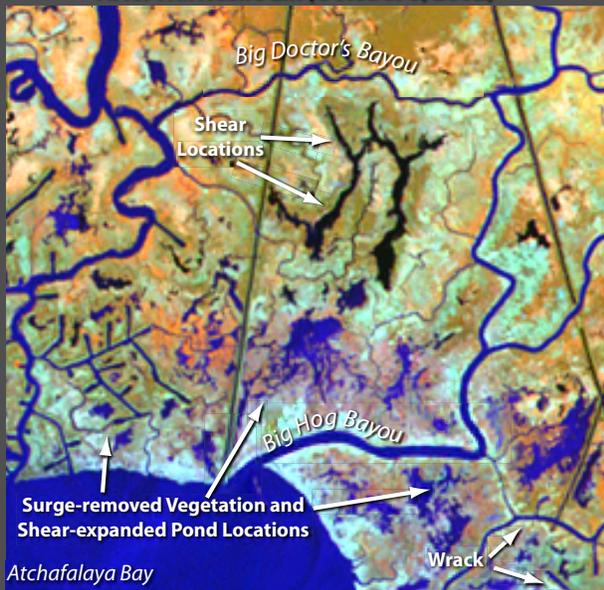
October 11, 1991



November 29, 1992
 After Hurricane Andrew (August 26, 1992)



October 16, 2002
 After Hurricane Lili (October 3, 2002)



October 16, 2005
 After Hurricane Rita (September 24, 2005)



Produced by:
 U.S. Department of the Interior
 U.S. Geological Survey
 National Wetlands Research Center, Lafayette, La.

Map ID: USGS-NWRC 2006-11-0452
 Map Date: June 26, 2006



Image Source:
 Landsat 5 Thematic Mapper Satellite Imagery
 is provided by the USGS EROS Data Center.
 Bands 4 (near-ir), 5 (mid-ir), and 3 (visible red)
 are displayed.

Figure 5. Big Hog Bayou multiple hurricane impacts.

open near Marone Point and the Wax Lake Delta by the fall of 2004. Some of these shears were either covered or partially covered by wrack from Rita's surge, whereas other existing shears were expanded (fig. 5; Barras, 2007, figs. 19A and 19B). The smaller shears north of Lake Lery were partially covered with aquatic vegetation, but they were still clearly visible in fall of 2004 until either being removed or obscured by wrack from Katrina's surge. Rita's surge expanded shears originally formed by Andrew and later expanded by Lili, in western Terrebonne but also partially covered existing shears with wrack deposits (Barras, 2007, figs. 16A and 18A).

Conclusions

The magnitude and distribution of new water areas caused by Katrina and Rita exceed prior hurricane impacts detected with Landsat TM Imagery since 1983. Katrina's impacts were identified east of central Barataria basin to the Louisiana-Mississippi border. Rita's impacts were identified from Breton Sound basin west to the Louisiana-Texas border. Fresh and intermediate marsh community types located near or to the east of hurricane landfalls may experience detectable shearing at Landsat TM spatial resolutions. Brackish and saline marsh communities appear to be more resilient to shearing than are fresh and intermediate marsh communities. The spatial distribution and magnitude of shears are dependent on hurricane landfall orientation, surge coverage area and duration, and marsh community type. Natural and artificial barriers facing storm surge accumulate wrack and may reduce surge shearing for areas located behind them.

The 217 mi² (562 km²) of new water area contains (1) land losses that may be permanent, caused by direct removal of wetlands by storm surge; and (2) transitory water area increases caused by the following: (a) remnant flooding of marsh and impounded areas, including agricultural and developed areas; (b) removal of floating and submerged aquatic vegetation; (c) scouring of marsh vegetation; and (d) water-level variations caused by normal tidal and meteorological variation between images. The new land occurring after the hurricanes contains land gains caused by the following: (1) wrack deposition, (2) rearrangement of existing marsh areas moved by storm surge, (3) aquatic vegetation that is possibly misclassified, and (4) water-level variations caused by normal tidal and meteorological variation between images. These transitory gains and losses are included in calculations of net land area change. New water areas occurred in both stable regions and in areas of historical loss. Probable losses east of the Mississippi River may approach projected losses from 2000 through 2050 based on 1978–2000 historical losses. Based on imagery of prior hurricane impacts, some of the transitory impacts may revegetate quickly in sediment-rich environments, given a paucity of recurrent storms. Hurricane surge impacts reactivate and widen existing

ponds created by prior storm surges. Land-water patterns in some areas reflect cumulative hurricane impacts.

Estimates of permanent coastwide loss will not be available for at least one or two growing seasons given the 5 months of remnant flooding that occurred in southwest Louisiana after Rita's landfall and the persistent dry weather from October through May 2006.

The combined land loss and changes observed from Katrina and Rita occurring within 1 month of each other could potentially be the greatest observed in southern Louisiana. Coastal Louisiana may have incurred multiple hurricane impacts within a month's span in the past, and our current coastal land-water configuration most likely bears the scars of prior storm impacts, some of which may have occurred prior to European colonization. The current annual projected 2000–2050 land loss estimate of 10.3 mi² (26.68 km²) was based on 1978–2000 historical rates (Barras and others, 2003). Perhaps hurricanes play a greater role in shaping the coast than previously assumed, and we lack the information to conclude how these storms sculpt the Louisiana coast over time periods greater than a few decades. Our ability to quickly assess hurricane impacts has greatly improved over the past decade. The ongoing acquisition and analysis of moderate-resolution satellite imagery and available high-resolution imagery coupled with field investigations will provide a clearer picture of wetland recovery and loss in coastal Louisiana after Katrina and Rita.

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