Freshwater River Diversions for Marsh Restoration in Louisiana:

Twenty-Six Years of Changing Vegetative Cover and Marsh Area

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[1] The restoration of Louisiana's coastal wetlands will be one of the largest, most costly and longest environmental remediation projects undertaken. We use Landsat data to show that freshwater diversions, a major restoration strategy, have not increased vegetation and marsh coverage in three freshwater diversions operating for 19 years. Two analytic methods indicate no significant changes in either relative vegetation or overall marsh area from 1984 to 2005 in zones closest to diversion inlets. After Hurricanes Katrina and Rita, these zones sustained dramatic and enduring losses in vegetation and overall marsh area, whereas the changes in similar marshes of the adjacent reference sites were relatively moderate and short-lived. We suggest that this vulnerability to storm damage reflects the introduction of nutrients in the freshwater diversions (that add insignificant amounts of additional sediments), which promotes poor rhizome and root growth in marshes where below-ground biomass historically played the dominant role in vertical accretion.

1. Introduction

[2] The dramatic loss of one-fifth of Louisiana's wetlands present in the 1930s [*Britsch and Dunbar*, 1993], is one of the world's major ecological disasters. These losses threaten wetland-dependent Gulf of Mexico fisheries, make coastal Louisiana more vulnerable to hurricanes, and deprive millions of migratory birds of over-wintering habitats [*National Research Council*, 2006]. A modeling study suggests that the collapse of weakened marsh plants during Hurricane Katrina compromised their ability to mitigate storm surge flooding of New Orleans [*Resio and Westerink*, 2008], implying that storm damages will be worse if a projected increase in intense hurricanes from climate change is realized.

[3] Since the enactment of the Coastal Wetland Protection, Planning and Restoration Act (CWPPRA) in 1990, 151 projects have been untaken in the Louisiana Coastal Area (LCA).

Freshwater diversions from the Mississippi River represent the largest restoration initiatives in terms of the scale of impact. They are also the most costly. The Davis Pond diversion, for example, cost $106 million to build [*U. S. Army Corps of Engineers*, http://www.mvn.usace.army.mil/pao/dpond/davispond.htm] and another $100 million to repair. The Myrtle Grove diversion, planned for completion in 2013 could cost ~$417,000,000 [*U. S. Army Corps of Engineers*, 2010] (Table A1, Auxiliary Materials). Future costs aside, the State of Louisiana is committed to building diversions as the best way to "reconnect the river to the deltaic plain" [*Day et al*., 2007], reasoning that the greater freshwater influx would lower salinity, and increase accretion and plant vigor because of the higher suspended sediment and nutrient inputs.

[4] The scientific basis for the benefits of freshwater diversions is not settled. A recent model [*Blum and Roberts*, 2009] suggests that the deltaic plain will shrink by 15,000 km^2 by 2012 because of sediment deficits and accelerated sea level rise. Nonetheless, it is not certain whether diversions would provide any additional mineral sediment to brackish marshes, where some of the greatest losses occurred [*Barras et al.,* 2008]. Further, the available data indicate that vertical accretion is correlated with *in situ* organic accumulation (principally root and rhizome material), not mineral sediment inputs [*Nyman et al.*, 1993; *Turner et al.*, 2000]. Excessive nutrient influx into the Caernarvon diversion marshes (the largest freshwater diversion created) is linked to the widespread occurrence of low soil strength (by field shear vane tests), indicating that these marsh sediments are potentially highly erodible; in fact, land losses from Hurricane Katrina were especially high [*Howes et al.*, 2010]. The strong support given diversions by some local wetland scientists [*Boesch*, 2006; *Day et al*., 2007] has been reason enough for policy makers to commission feasibility studies for future diversions [*NRC*

Committee on the Review of the Louisiana Coastal Protection and Restoration (LACPR) Program, 2009].

[5] The effectiveness of diversions to mitigate marsh loss has not been quantitatively evaluated. However, three major diversions, Caernarvon, West Point a la Hache, and Naomi, have operated since the early 1990s (Figure 1, Table A1), providing an opportunity to assess trends in plant condition and total marsh area before and after diversions began. The vegetation in all three diversions spans the common marsh types in the LCA, including fresh (*Panicum hemitomon*, *Sagittaria lancifolia*), intermediate (*Leptochloa fusca*, *Panicum virgatum*), brackish (*Spartina patens*, *S. cynosuroides*), and saline marshes (*Spartina patens*, *Distichlis spicata*) [*Sasser et al.*, 2008]. Invasive species like Chinese tallow (*Triadica sebifera*) and water hyacinth (*Eichornia crassipes*) are also common. The Caernarvon diversion is more directly influenced by the Gulf of Mexico through Breton Sound than are the smaller Naomi and West Point a la Hache diversions, and has substantially greater river freshwater inputs. Hurricane Katrina (2005) passed directly east of it in Breton Sound.

We use Landsat Thematic Mapper imagery in a spectral mixture model developed in studies of low salinity, microtidal marshes [*Kearney et al.* 2002], which was cross-referenced with comparisons from aerial photography to analyze changes in marsh vegetation cover and total marsh area since 1984 for these three diversions. The inherently wide geographic capture of changes afforded by high resolution satellite imagery provides a spatial and temporal perspective on the conflicting ideas about the efficacy of diversions to restore marsh.

2. Data and Methodology

[6] We analyzed twelve Landsat TM/ETM+ data sets (Path 22 Row 39) collected between 1984 and 2009. The criteria used for selection were: 1) dates coinciding with peak or near-peak

vegetation growth; 2) a tidal stage near mean low low water (MLLW); 3) high atmospheric clarity (little haze or cloud cover); 4) regular intervals between observations; and 5) the inclusion of scenes bracketing major hurricanes (Table A2).

[7] The spectral mixing model is based on spectral indices for vegetation, soil, and water. It more consistently characterizes marsh spectra end members than the more common principal components approach [*Rogers and Kearney*, 2004]. Three indices were calculated by normalizing the difference between Landsat bands to produce a spectral space (NDX) that approximates the optimal spatial model for spectral unmixing and, thus, more tightly defines the following vegetation, water and soil spectral end members: NDVI = (band 4_{NIR} – band 3_{Red}) / (band 4_{NIR} + band 3_{Red}); NDWI = (band 3_{Red} – band 5_{IR}) / (band 3_{Red} + band 5_{IR}); and NDSI = (band 5_{IR} – band 4_{NIR}) / (band 5_{IR} + band 4_{NIR}) [*Rogers and Kearney*, 2004].

[8] We calculated radiance for twelve, co-registered Landsat TM and ETM + scenes using standard remote sensing techniques and equations [*Jensen*, 2002; *Chander et al*., 2009]. Atmospheric correction of the imagery was undertaken by the FLAASH module for deriving spectral surface reflectance [*Berk et al., 2002*]. The unsupervised, K-means algorithm in the ENVI image processing software was used to classify Landsat bands 3, 4, and 5 composite data into two classes, marshland (vegetation + soil) and water, with the former used as an indicator of overall change in marsh coverage.

[9] Although the spectrally unmixed Landsat data yield percent spectral reflectances derived for vegetation, water, and soil, we present only the data for pixels dominated by the vegetation spectral reflectance index (estimated to be 40% or more based on previous work in mid-Atlantic coast marshes [*Kearney and Riter*, 2011]). Lastly, we used ArcGIS software to calculate the

percentages of pixels dominated by vegetation spectra, and those classified as marshland within pre-selected zones in the diversions and in two reference areas (Figure 1).

3. Results

[10] We examined whether demonstrable changes occurred in vegetative cover after diversion operations began by comparing changes in the relative percent vegetation cover before and after the diversions opened, while excluding the period after Hurricanes Katrina and Rita. The percent vegetation in the diversions and the Caernarvon reference site was highest in the zone closest to the diversion inlets (Zone 1 in Figure 2a-e). Field observations and Landsat imagery collected from 27 August 1995 to 22 August 2005 indicate that this phenomenon is mostly a response to algae and floating vegetation in the open water areas, rather than to the presence of deeply-rooted marsh vegetation. The most salient aspect in the trends in percent vegetation cover, a nominal indicator of vegetation vigor, is the lack of a statistically-significant change before or after the diversions opened, and before Hurricane Katrina, regardless of zone (Figures 3a, c, A1a, c). Reinforcing this conclusion are the very low student t-test results testing for differences in the percent vegetation in all zones for before and after opening the diversion, despite the small sample sizes (1.10, 8 degrees of freedom (df) for Caernarvon diversion; 0.64, 14 df for West Pointe a la Hache; and 0.73, 14 df for Naomi; and for zones closest to diversion inlets (Caernarvon diversion, 0.11, 7 df)).

[11] Similar trends were found using the K-means classification to estimate change in the percent land (equivalent to the percent vegetation + percent soil in the NDX model) attributable to diversion operations (Figures 2f-j). There were no statistically significant differences in the percent land cover for before or after diversion operations (and before Hurricanes Katrina and Rita) for the three diversions and two reference sites (Figures 3b, d, A1b, d). The picture that

emerges is of modest shifts between sampling dates, suggesting that the differences reflect inter-annual variability more than any other cause. Interestingly, although the t-tests again do not support a definitive change, there are suggestions of a minor decline and recovery to previous levels after the beginning of diversion operations in the innermost zones of the three diversion sites, while the outermost zones show an overall decline in land coverage. This slight trend is presumably unrelated to the effects of the diversions because the diversion began operations in the early 1990s and the subtle (if statistically non-significant) changes in vegetative cover in the diversion sites mirror those in the reference sites.

[12] We conducted a simple linear regression to test if there was a statistically-significant relationship between the changes in percent vegetation and percent marsh area over time. The results for the Caernarvon diversion and its control site are representative. The slopes for the derived regression lines and the close values for the means suggest that the relative trends in vegetation and marsh area characterizing both areas before the construction of the diversion were not discernibly altered after operations began (Figure 3a-f). The one distinct change between pre- and post-diversion operations is the greater range in values after diversions started. But, because it characterizes both diversion and the reference site, this shift was probably endemic to this particular region (Figure A1) and had little to do with the influx of nutrient-rich diversion waters. In summary, the trajectory of landscape-level change in the three diversions is one of continuity, with only a suggestion of temporal variability in the zones closer to the Gulf of Mexico.

[13] Six hurricanes affected coastal Louisiana since 1984. Nonetheless, it is evident that Hurricanes Katrina and Rita were clearly the most destructive, and the damage done to the marshes in the three diversions was no exception. For example, vegetation coverage/condition in

the Caernarvon diversion declined by 142 km^2 after the hurricanes (~33 %; Figure 2). It is evident, however, that the severity of the damage varied among diversions as a whole, within zones of individual diversions, between the same zone position from different diversions, and between the diversion and the paired control sites. Moreover, the trajectories of post-storm recovery show similar differences (Figure 2).

[14] Because the track of Hurricane Katrina crossed close to the Caernarvon diversion, it is not surprising that wetlands there were most affected by this storm compared to wetlands in the other two diversion sites. Yet, the sharpest drop in percent vegetation (>30%) within this diversion occurred in zones 1 through 4, which are farthest away from the storm's track and also the zones most directly affected by the freshwater flows from the diversion inlet (Figure 2b). By comparison, the declines in percent vegetation and overall marshland in the zones furthest from the inlets were typically much smaller than those closest to the inlets (Figure 2). In addition, the vegetation in these outer zones showed greater resiliency with larger post-hurricane gains (relative to losses sustained) in percent vegetation and overall marsh area despite being closer to the Gulf of Mexico where the storm surge and waves from Hurricane Katrina were greatest [*Knapp et al.*, 2006]. Overall, there was a dramatic increase in open water in the Caernarvon diversion as a consequence of the storm – as is apparent in the fly over video of the area in March 2010 (Animation A1, Figure A3). The vegetation in the Caernarvon reference site, however, did not the show the same level of decline as indicated either by the percent vegetative cover or total marsh area, with only the northern-most zone (which receives some Caernarvon diversion water) displaying the precipitous drop in both indicators so characteristic of the Caernarvon diversion. Furthermore, although Hurricane Katrina also passed directly over the

reference site, these marshes quickly rebounded in the years following the storm ([*Knapp et al.*, 2006]; Figures 1c, 2b, d).

[15] In contrast to the damage to the Caernarvon diversion, the changes in the percent vegetation were minor in the Naomi and West Pointe a la Hache diversions, and in the Myrtle Grove reference site (Figure 2a, c, e). Marsh conditions at all sites west of the Mississippi River showed a decrease in percent vegetation after the hurricanes, but these changes were not statistically significant (Figure A1e, g). The West Point a la Hache diversion, located about 20 km west of Hurricane Katrina's path, displayed a greater decline in percent vegetation than in the Naomi diversion (40 km) or Myrtle Grove reference site (30 km) (Figure1). The recovery at all sites, which was substantial in the Noami and West Point a la Hache sites, was interrupted by Hurricanes Gustav and Ike in 2008 – a decline which persisted through 2010 (Figure 2 a-e).

[16] Moderate precipitation events few days before, or even several weeks of sporadically rainy weather before the Landsat observations collected in 1986, 1999, and August 2004 and 2005, appear to have had a greater effect on the percent vegetation at the Myrtle Grove reference site than Hurricanes Katrina and Rita (Figure 2c, h). Moreover, although Myrtle Grove has large open water ponds where edge (shore) erosion might be expected from storm waves, it survived Hurricane Katrina relatively intact. The overall marsh area in the West Point a la Hache site, however, declined after the storm, especially in the zones closest to the inlet, paralleling the drop in percent vegetation.

4. Summary and Conclusions

[17] We have shown that three long-running diversion projects initiated to restore Mississippi Delta coastal marshes failed to increase vegetation cover or overall marsh area. We argue, particularly with respect to the Caernarvon diversion and the zones closest to the inlet, that the

apparent stability in emergent vegetation before Hurricane Katrina is probably an artifact of widespread algae and floating vegetation growth spurred by excess nutrients, as well as the proliferation of Chinese tallow (*Triadica sebifera*) on spoil banks and channel levees [http://www.nwrc.usgs.gov/factshts/154-00.pdf]. This broad-leafed plant appears "brighter" in Landsat band 5 and contributes to the over-estimation of percent marsh vegetation. Whether or not the continued stability in marsh vegetation after inception of diversion operations was real or biased by the spread of non-marsh vegetation, our analysis demonstrates that declines in vegetation in the diversion sites from Hurricanes Katrina and Rita were greater than in the reference areas, with the subsequent recovery in the diversions also noticeably slower than in the reference areas.

[18] We believe that the three freshwater diversions failed to increase vegetation health or area because of the physiological consequences of high nutrient flux and greater flooding of marsh plants [*Swarzenski*, 2008]. The agricultural literature has established that N loadings as little as 30 kg ha^{-1} can cause severe lodging (stem collapse) and low root growth in cereals (i.e., graminoids; [*Mulder*, 1954]). Recent (2002) estimates of the annual nitrate and total N inputs at the Caernarvon diversion range from 2-5 million kg (45-114 kg ha^{-1}), and 3-7 million kg (~68-159 kg ha^{-1}), respectively, and were augmented by rainfall (nitrate, 0.55 million kg yr^{-1} and total N, 0.64 million kg yr^{-1}) [*Day and Ko*, 2003; *Hyfield et al*., 2008]. Fertilization of brackish marshes would promote lower rhizome and root biomass [*Valiela et al.*, 1976], accelerated decomposition rates [*Godshalk and Wetzel*, 1978; *Sundareshwar et al.*, 2003] and stems vulnerable to collapse (lodging) from high winds [*Resio and Westerink*, 2008]. In fact, research on Louisiana wetland vegetation [*Darby and Turner*, 2008; *Turner*, 2010] documented shallow and limited rooting in *Spartina alterniflora*, resulting in weak substrate structure and shear

strength [*Howes et al.*, 2010; Turner 2011]. Moreover, nitrogen additions to freshwater wetlands enhance carbon losses [*Bragazza, et al.*, 2006; *Mack et al*., 2004].

[19] Ultimately, the scientific basis for river diversions needs to be more convincing before embarking on a strategy that may result in marshes even less able to survive hurricanes. The evidence indicates that diversions not only fail to conserve mature brackish and tidal freshwater marshes, but disrupt plant physiology in ways that endanger individual plant vigor and overall marsh survival. In this regard, there is no better illustration than the "Hypoxia Zone" of what high nitrogen levels can do to delicate nutrient balances evolved over millennia in nitrogen-lean ecosystems, and the daunting challenges for reversing that damage.

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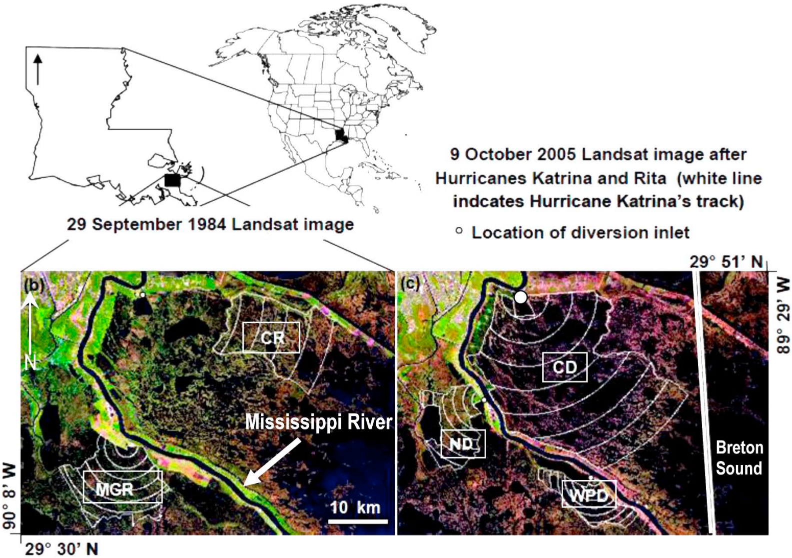
Figure Captions

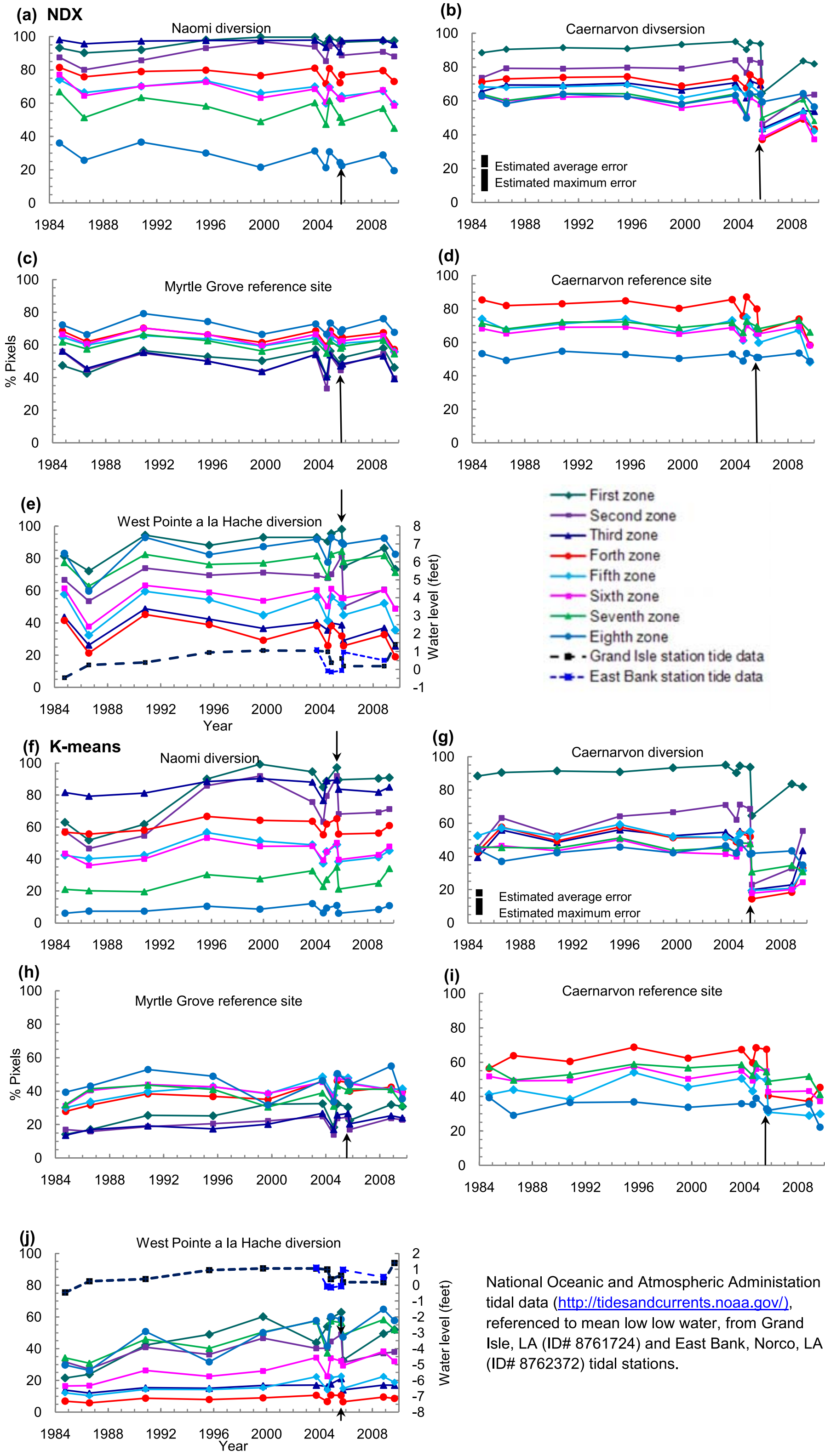
Figure 1. (a) Study area location (black rectangle) in southeastern Louisiana, USA. The locations of zones in the reference sites (b) and in the diversions (c) are indicated by the white lines and the letters in rectangles identify individual diversions and reference sites. CD = Caernarvon diversion; CR = Caernarvon reference site; ND = Naomi diversion; WP = West Point a la Hache diversion; MGR = Myrtle Grove reference site.

Figure 2. Figure (a-e) shows the NDX model results for the percentage of pixels dominated by the vegetation spectral index (y-axis) as opposed to the soil and water spectral indices. These values roughly correlate with the amount of spatial coverage of marsh vegetation in the pixel as well as its biomass. Figure 2 (f-j) shows the percentage of pixels classified as land or marsh area by K-means algorithm of Landsat bands 3-5 (y-axis) in diversion and reference zones. The black arrows when Hurricanes Katrina and Rita made landfall.

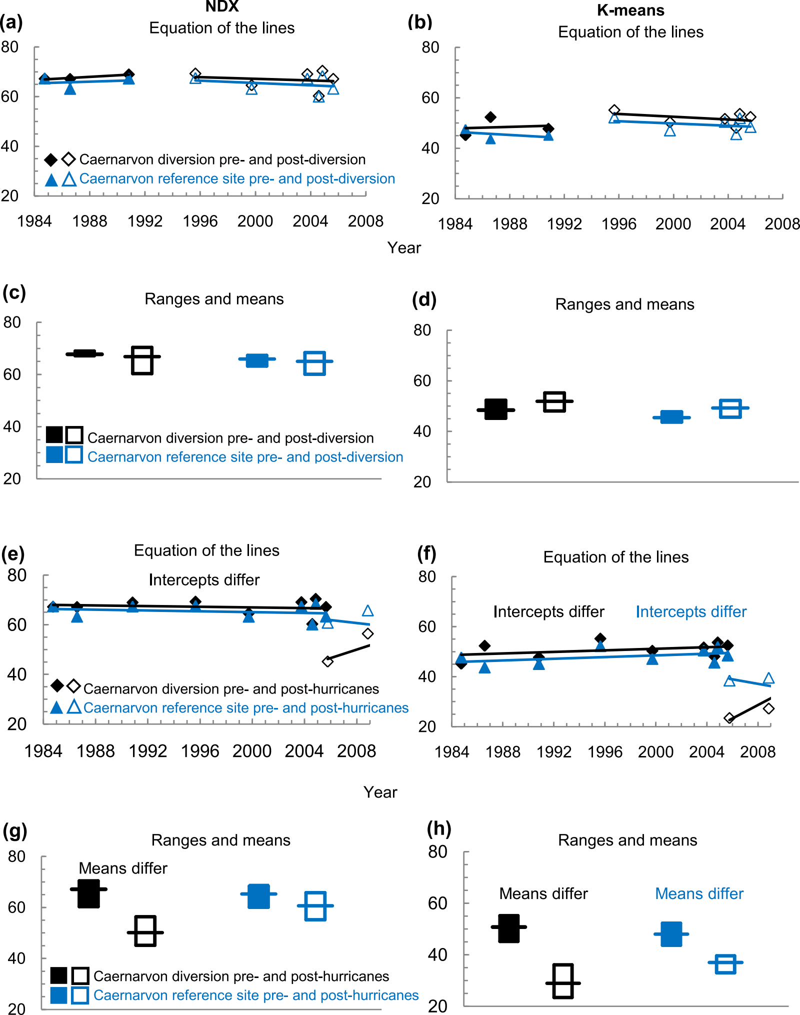
Figure 3. Linear regression analysis of the relationships at the Caernarvon diversion and control site between the percentage of pixels dominated by the vegetation spectral index (a, c, e, and g) and the percentage of pixels classified as land (marsh area) by the K-means algorithm (b, d, f, and h). Figure 3 (a-d) shows the changes at the Caernarvon diversion and reference sites before and after diversion operations began. Figure 3 (e-h) show the trends before and after Hurricanes

Katrina and Rita. (See also Figure A1 and Table A3 for these data for all diversions and reference sites).


9 October 2005 Landsat image after
Hurricanes Katrina and Rita (white line
indcates Hurricane Katrina's track)
Location of diversion inlet
29 September 1984 Landsat image
(b)
N
CR
MGR
Mississippi River
10 km
90° 8' W
29° 30' N
(c)
29° 51' N
89° 29' W
CD
ND
WPD
Breton
Sound



(a) NDX
Naomi diversion
(b)
Caernarvon divsersion
Estimated average error
Estimated maximum error
(c)
Myrtle Grove reference site
% Pixels
(d)
Caernarvon reference site
(e)
West Pointe a la Hache diversion
Water level (feet)
Year
First zone
Second zone
Third zone
Forth zone
Fifth zone
Sixth zone
Seventh zone
Eighth zone
Grand Isle station tide data
East Bank station tide data
(f) K-means
Naomi diversion
(g)
Caernarvon diversion
Estimated average error
Estimated maximum error
(h)
Myrtle Grove reference site
% Pixels
(i)
Caernarvon reference site
(j)
West Pointe a la Hache diversion
Water level (feet)
Year
National Oceanic and Atmospheric Administation tidal data (http://tidesandcurrents.noaa.gov/), referenced to mean low low water, from Grand Isle, LA (ID# 8761724) and East Bank, Norco, LA (ID# 8762372) tidal stations.



NDX
K-means
(a)
Equation of the lines
(b)
Equation of the lines
Caernarvon diversion pre- and post-diversion
Caernarvon reference site pre- and post-diversion
Year
(c)
Ranges and means
(d)
Ranges and means
Caernarvon diversion pre- and post-diversion
Caernarvon reference site pre- and post-diversion
(e)
Equation of the lines
Intercepts differ
(f)
Equation of the lines
Intercepts differ
Intercepts differ
Caernarvon diversion pre- and post-hurricanes
Caernarvon reference site pre- and post-hurricanes
Year
(g)
Ranges and means
Means differ
(h)
Ranges and means
Means differ
Means differ
Caernarvon diversion pre- and post-hurricanes
Caernarvon reference site pre- and post-hurricanes