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Propensity for erosion and deposition in a deltaic wetland complex: Implications for river management and coastal restoration

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ABSTRACT

The Mississippi River Delta is one of the most rapidly changing area on Earth, with large areas experiencing land loss and smaller areas experiencing loss. While some of the drivers of these changes are well known (high rates of relative sea level rise, reduced sediment inputs, canal dredging), debate exists about other drivers. One area that has received substantial attention is the role of, "river diversions," areas where sediments and water are diverted from the Mississippi River into degrading wetlands with the hope of reinitiating deltaic land building processes. Some authors have argued that diversions lead to reduced shear strengths of wetland soils that make them more vulnerable to storm driven erosion, while other authors have argued that sediments from river diversions will develop stable land. This study examined this controversy in the Cubits Gap Subdelta, an analogue for a large ($>1420\ m^3\ s^{-1}$) river diversion by testing the hypothesis that areas of land gain, and/or resilience to erosion occurred in areas that actively received river sediments and as a result had mineral rich soils with high shear strength. To accomplish this, a Normalized Difference Water Index (NDWI) was developed for Landsat-7 Enhanced Thematic Mapper (ETM+) and Landsat-8 Operational Land Imager (OLI) images. The NDWI was calculated from (Blue − SWIR) / (Blue + SWIR), where SWIR is the shorter wavelength, and yielded land/water boundary maps with 30 m resolution. Results indicate that land gain occurred predominantly in the riverside section of this subdelta where sediments were imported from Mississippi River crevasses and/or dredging. Land loss typically occurred in the distal regions of the subdelta, which had lower levels of sediment supply and greater wave exposure. Sediment geotechnical analyses revealed land loss pixels generally correlated sediments with to high organic contents ($9.0 \pm 1.9\%$), water contents ($54.8 \pm 3.7\%$) and salinity (6.5 ± 2.0 PSU), with low shear strengths ($5.7 \pm 0.8\ kN\ m^{-2}$) and low bulk density ($0.6 \pm 0.8\ g\ cm^{-3}$), whereas land gain pixels generally correlate with low organic content ($3.9 \pm 0.6\%$), water content ($38.1 \pm 4.2\%$) high shear strength ($10.9 \pm 4.1\ kN\ m^{-2}$) and bulk density ($1.00 \pm 0.1\ g\ cm^{-3}$). This study suggests plans to restore the region by partially diverting the flow of the Mississippi River will be most successful if they carry high loads of sediment, and that concerns about the integrity of fresh marsh may be unwarranted if those marshes are sediment rich.

1. Introduction

The modern deltaic plain of Louisiana consists of approximately 25,000 km^2 of wetlands, bays, rivers, and bayous that were created as the Mississippi River deposited sediments in the shallows reaches of the northern Gulf of Mexico over the past 7000 years (Roberts, 1997). During the past century, nearly 4877 km^2, or ~25% of the land area of coastal Louisiana, converted from land to open water (Couvillion et al., 2011). This land loss makes the Mississippi River Delta one of the most rapidly changing environments on earth (Giosan et al., 2014; Syvitski and Saito, 2007). The causes of this land loss are complex and often interact. Reduced sediment inputs, coupled with high rates of subsidence have resulted in a situation in which many marshes can no longer accrete at rates necessary to keep pace with sea-level rise, which leads to land loss (Reed, 2002, LACPRA 2017, Day et al., 2007, Kolker et al., 2011). Hurricanes, wave driven erosion, canal construction, saltwater intrusion, eutrophication and invasive species have also played a major role in driving land loss in Louisiana (Howes et al., 2010; Turner, 1997; Darby and Turner, 2008). The processes that drive land loss, and land gain, in the Mississippi River Delta are potentially significant globally given that deltas across the planet are shrinking and sinking as a result of human activities (Syvitski and Saito, 2007; Giosan et al., 2014).

To offset this ongoing land loss, the State of Louisiana crafted a "Comprehensive Master Plan for a Sustainable Coast" (LACPRA, 2017).

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This plan pursues multiple strategies for restoring wetlands and protecting existing wetlands and coastal communities. One noteworthy strategy is to partially divert the flow of the Mississippi river, which should reinitiate the natural land building processes that originally formed the delta (LACPRA 2017, Roberts, 1997, Kim et al., 2009). This strategy of, "river diversions," is based, in part, on observations that the few areas of delta growth are the areas that actively receive river water including the outlets of the Atchafalaya River, regions of the Birdsfoot Delta of the Mississippi River, and small areas around the Caernarvon and Davis Pond Freshwater Diversions (Wellner et al., 2005; Wells and Coleman, 1987; Roberts, 1997). A summary of these diversion structures is presented in Table 1.

There has been marked controversy surrounding river diversions and their role in coastal change. Some authors have suggested that freshwater diversions adversely affect marsh stability because they results in fresh, eutrophic marshes with plant roots with reduced structural integrity relative to salt marshes (Teal et al., 2012; Howes et al., 2010; Kearney et al., 2011). These authors often point to the Caernarvon Diversion and the response of marshes in nearby Breton Sound to Hurricane Katrina. Here, diversion-influenced freshwater marshes were readily eroded by the storm, whereas nearby uninfluenced salt marshes were more resilient to the storms impacts (Barras, 2006; Howes et al., 2010). This was attributed to the increased root structure, and corresponding increase in shear strength of salt marsh vegetation relative to fresh marsh vegetation. Some authors have cited these observations when suggesting that river diversions are not a worthwhile tool to restore the Mississippi River Delta (Turner et al., 2007; Kearney et al., 2011).

However, other authors have pointed out that the Caernarvon Diversion does not transport large quantities of sediment to wetlands, given its relatively small discharge (Table 1), and shallow invert depth (Day et al., 2016a). This opposing view holds that it is the dearth of mineral sediments rather than the inputs of nutrient rich freshwater that is primarily responsible for the weakened marshes. Those ascribing to this viewpoint suggest that larger and deeper diversions, which transport greater quantities of both sediment and water, should result in greater land development, and marshes that are more resistant to erosion (Day et al., 2016b; Tornqvist et al., 2007).

Remote sensing technology has been used to identify changes in land and water area in the Mississippi River Delta, on time scales that range from multi-decadal to annual (e.g. Britsch and Dunbar, 1993; Barras et al., 2003; Couvillion et al., 2011), to event/seasonal scale (Barras, 2006). This has been accomplished using moderate resolution systems such as Landsat TM to high resolution systems such as QuickBird; IKONOS, and GeoEYE-1 (Palaseanu-Lovejoy et al., 2011 and Palaneasu-Lovejoy et al., 2013). Most of these earlier studies employed principal components (PCA), independent components analysis (ICA), and an analysis of tasseled cap transformation (TCT) components to developed expanded set of water and vegetation. This work used Landsat-based indices such as blue ratio, Braud index, green normalized difference water index (GNDWI = (Green − NIR) / (Green + NIR)), normalized difference vegetation index (NDVI = (NIR − Red) / (NIR + Red)), normalized difference water index (NDWI = (NIR − SWIR) / (NIR + SWIR)), simple and inverse ratio, and near infrared (Blue/NIR) ratio to produce continuous fractional water maps that are classified into land/water categories using an optimization procedure (Barras et al., 2003; Atkinson and Mahony, 2004; Palaseanu-Lovejoy et al., 2011). Finally, classified images from different time periods were subtracted from each other to determine the amount and percentage area change.

Table 1
Active and planned sediment diversions in Louisiana, including their original purpose and mean annual water discharge (Allison and Meselhe, 2010; Allison et al., 2012; LACPRA, 2017).

Diversion name	Purpose	Water (km^3/year)
Atchafalaya River Delta		
Wax Lake Outlet	Flood control	109
Main Atchafalaya River	Flood control	129
Mississippi River Delta		
West Bay	Land building	33
Cubit's Gap	Natural	52
Baptiste Collette	Natural	49
Bonnet Carre Spillway	Flood control	2
Davis Pond	Salinity control	3
Caernarvon	Salinity control	2
Bohemia Spillway	Flood control	1
Planned		
Mid Barataria	Land building	~67
Mid Breton	Land building	~31
Ama	Land building	~45

Land loss studies have used the spectral water index, which is a numerical indicator derived from two or more visible and shortwave-infrared (SWIR) spectral bands of the electromagnetic spectrum to determine the boundaries between land and water bodies. The NDWI is derived from the SWI and has values that range from −1 to 1, where positive values indicate that the cover type is water and negative if the cover type is non-water. An appropriate threshold of the index has to be established to separate water bodies from other land-cover features based on the spectral characteristics (Ji et al., 2009). McFeeters (1996) adopted the format of the normalized difference vegetation index (NDVI), and developed the normalized difference water index (NDWI), defined as:

$$NDWI = (B_{Green} - B_{NIR})/(B_{Green} + B_{NIR}) \quad (1)$$

Where zero was set as the threshold, the cover type is water if NDWI > 0 and it is non-water if NDWI ≤ 0.

Rogers and Kearney (2004) used red and SWIR bands to produce NDWI, given by:

$$NDWI = (B_{red} - B_{SWIR})/(B_{red} + B_{SWIR}) \quad (2)$$

Xu (2006) modified McFeeters' NDWI, in which the SWIR band was used to replace the NIR band, the threshold value for MNDWI was set to zero, given by:

$$MNDWI = (B_{Green} - B_{SWIR})/(B_{Green} + B_{SWIR}) \quad (3)$$

Ouma and Tateishi (2006) tested five different forms of NDWIs using the reflectance bands of Landsat TM/ETM for detecting and mapping the changes of lake shorelines. They ranked the NDWIs in order of the worst to the best performance for detecting water features as follow:

$$NDWI\text{-}1 = (B_7 - B_5)/(B_7 + B_5) \quad (4)$$

$$NDWI\text{-}2 = (B_4 - B_2)/(B_4 + B_2) \quad (5)$$

$$NDWI\text{-}3 = (B_5 - B_4)/(B_5 + B_4) \quad (6)$$

$$NDWI\text{-}4 = (B_5 - B_2)/(B_5 + B_2) \quad (7)$$

$$NDWI\text{-}5 = (B_7 - B_2)/(B_7 + B_2) \quad (8)$$

Ji et al. (2009) tested all of the above mentioned NDWIs to know which NDWI indices give best result for delineating water features, and to determine the appropriate NDWI threshold so that the water, non-water, and mixture features can be distinguished. Their results indicated that the NDWI calculated from $(B_{Green} - B_{SWIR}) / (B_{Green} + B_{SWIR})$, where SWIR is the shorter wavelength region (1.2 to 1.8 μm), which is equivalent to Landsat spectral bands $(B_2 - B_5) / (B_2 + B_5)$ has the most stable threshold. The present study develops a new algorithm for determining the fraction land and water that builds on these earlier studies, but which yields results with greater precision.