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Use of NDVI and Landscape Metrics to Assess Effects of Riverine Inputs on Wetland Productivity and Stability

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Abstract

Alterations to Louisiana's river systems and local hydrology have resulted in reduced freshwater, sediment, and nutrient inputs to wetland landscapes, causing significant negative impacts on marsh productivity and stability. This study set out to assess regional- and basin-scale impacts of river connectivity and sediment availability on wetland productivity. Satellite data were used in conjunction with river discharge, river sediment concentration, and wetland accretion data to evaluate correlations between river connectivity and wetland productivity and stability. Significant correlations were observed between river connectivity and Normalized Difference Vegetation Index (NDVI) and Aggregation Index (AI) values across a 10 year period of analysis. Moderate correlations ($r^2 = 0.51$) between mean NDVI and AI values were observed for all wetland vegetation in coastal Louisiana. Middle Coast wetlands had the highest river connectivity and significantly higher aboveground productivity, spatial integrity, and wetland area. The Chenier Plain, with moderate sediment and nutrient inputs, consisted primarily of moderate productivity and integrity. The majority of the inactive Deltaic Plain, which is largely sediment deprived, consists of landscapes with the lowest wetland productivity and spatial integrity. This study linked wetland area, configuration, and productivity with river connectivity to provide an enhanced understanding of river and sediment importance for wetland stability and restoration.

Keywords Wetland productivity · Landscape pattern analysis · River connectivity · Coastal Louisiana · Remote sensing technologies

Introduction

Over the last century, flood risk reduction measures constructed in south Louisiana have significantly reduced connectivity between the Mississippi River system and coastal marshes (Kesel 1988, Mississippi River Delta Science and Engineering Special Team (MRDSEST) 2012). In the rapidly subsiding Mississippi River Delta (active and inactive deltas), this disconnect has resulted in sediment and nutrient deficits which have contributed to Louisiana's 4877 km^2 (km^2) of wetland loss (a net wetland change of −25%) that occurred between 1932 and 2010 (Craig et al. 1979; Turner 1997; Kennish 2001; Couvillion et al. 2011). Considering projected rates of relative sea-level rise, it is expected that river connectivity and sediment delivery to wetland landscapes will become increasingly vital for maintaining and restoring wetland ecosystem structure and functions (Jankowski et al. 2017).

The ecological benefits of a connected ecosystem (i.e., wetlands open to hydrological fluxes) have long been assumed (Mitsch and Gosselink 2007) and are often the target of restoration activities (Wang et al. 2017). Many of Louisiana's large-scale wetland restoration plans include river connectivity measures (i.e., sediment and nutrient delivery) to promote wetland primary productivity and wetland landscape stability. Primary productivity is defined as the rate of conversion of solar energy into plant matter during a certain period of time (Schowalter 2011; Cronk and Fennessy 2016), and wetland stability is defined as the balance between the structural mass and dissipative forces within an ecosystems (Webster et al.

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1975). Although numerous small-scale studies have shown that the addition of, or increase in fresh water, sediment, and nutrient combinations increase wetland extent, biomass, and vigor (Martin et al. 2002; DeLaune et al. 2005; McFalls et al. 2010; Roberts et al. 2015; DeLaune et al. 2016), the long term effects of those connections, and the ability to mimic natural riverine processes and create new wetlands, is still debated (Kearney et al. 2011; MRDSEST 2012; Suir et al. 2014).

Hydrologic connectivity, which is defined as the water-mediated transfer of matter, energy, and organisms within or between elements of the hydrologic cycle, is a fundamental element of ecological integrity in wetland landscapes (Amoros and Roux 1988; Heiler et al. 1995; Pringle 2003; Freeman et al. 2007). Historically, Louisiana has had an abundance of riverine connectivity, consisting of a complex network of rivers and distributaries (green lines in Fig. 1) that traversed the Middle Coast and Deltaic Plain (Fisk 1944). However, flood risk reduction features have disconnected or restricted those nourishing rivers and bayous from large expanses of wetland landscapes. South of the Old River Control Structure near Simmesport, Louisiana, approximately 2350 km of federally maintained primary levees have been constructed along the Atchafalaya River and Mississippi River. These levees, in addition to declining suspended load (80% decrease since the middle of the nineteenth century), have resulted in significant reductions in unconfined and overbank distribution of sediment (Kesel 1988, 1989). Because only the lower reaches of the Atchafalaya River (lower 48 km) and Mississippi River (lower 32 km) are un-leveed, the unconfined or overbank distributions of river waters are typically discharged onto or over the continental shelf, or into relatively isolated and emaciated wetlands (Walker and Rouse Jr 1993; Suir et al. 2014). Some Atchafalaya River waters are transported through smaller crevasses and pathways and into nearby Middle Coast and active delta wetlands (Swarzenski 2003) (Fig. 1, yellow lines within the Middle Coast region). The Gulf Intracoastal Waterway (GIWW) is a primary Atchafalaya River distributary, conveying river water approximately 50 km east and 80 km west of the river (Swarzenski 2003).

Traditionally, measures of wetland ecosystem condition have relied on labor-intensive ground-based surveys (Tucker et al. 1985). Although in situ data can be useful, surveys across large wetland landscapes are often hindered by time, access, and resource restrictions. However, space-borne imagery have been shown to provide spatial and temporal perspectives on ecological phenomena that would otherwise be difficult to evaluate (Anderson and Gaston 2013; Suir et al. 2018). Previous studies have shown remote sensing data and applications can significantly supplement traditional field-based collections and provide critical knowledge elements for more efficient inventorying and monitoring of wetland resources,

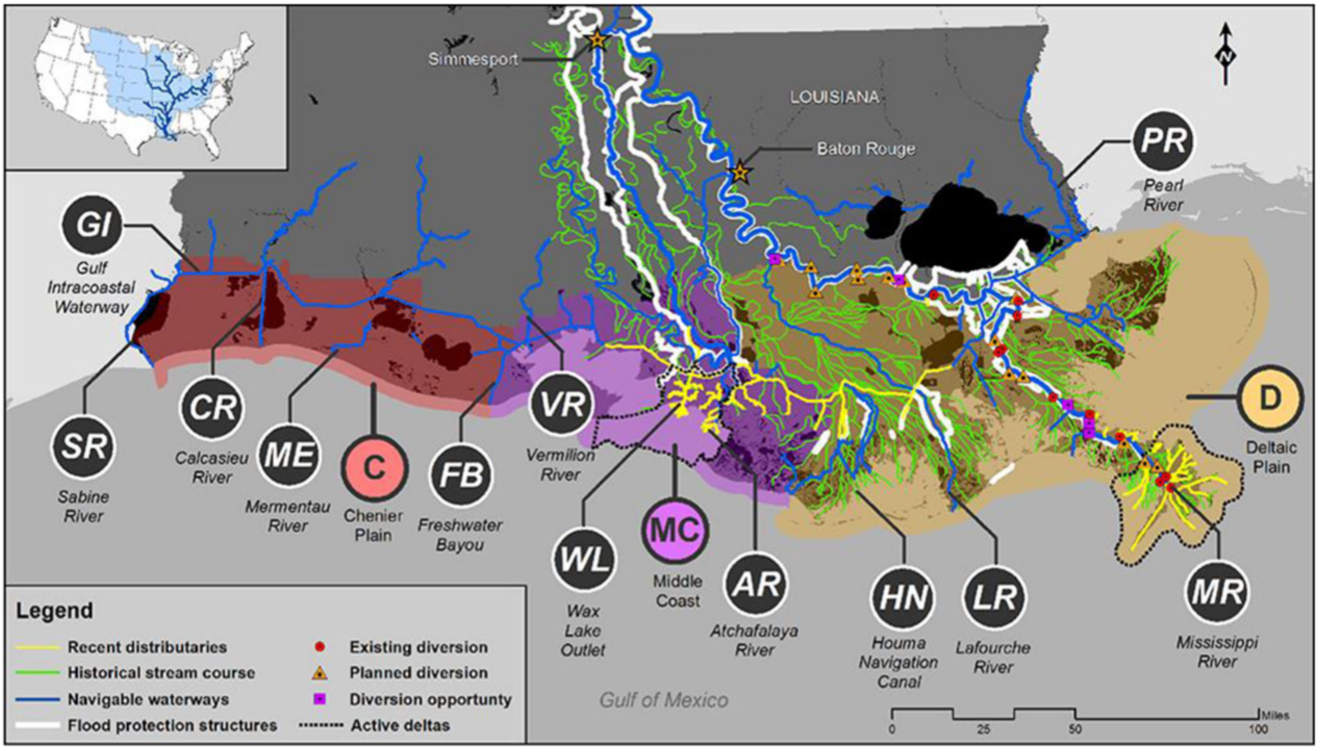

Fig. 1 Map depicting the Mississippi River drainage basin (inset), major navigable waterways, flood risk reduction levees, historical and recent tributaries, diversions, and active deltas in coastal Louisiana (Fisk 1944, Huh et al. 2001, Khalil 2012, Shi and Wang 2009, USACE 2006)

forecasting of resource conditions and stability, and formulating adaptive management strategies (Suir et al. 2011; Suir and Sasser 2019).

The purpose of this study was to assess the impacts of riverine inputs on wetlands by using remote sensing data to compare hydrologically connected landscapes (Middle Coast) to areas that are either more disconnected (Deltaic Plain) or connect to low volume rivers (Chenier Plain). Ecosystems with higher hydrologic connectivity are assumed to contain more stable and productive wetlands due to increased nutrient and sediment delivery. The specific objectives of this study were to: (1) evaluate sediment delivery potential from major navigable waterways; (2) assess regional- and basin-scale correlations between river connectivity and wetland productivity; and (3) evaluate trends in wetland stability and correlations to productivity and river connectivity.

Methods

Study Area and Assessment Units

The study area, encompassing approximately 14,000 km^2, consisted of Louisiana wetlands that are influenced by coastal processes (Fig. 2). To assess potential correlations between wetland productivity and hydro connectivity; while considering seasonal trends, geomorphic settings, and episodic impacts; multi-scale assessment units were established. These include (1) Geomorphologic Zones (GZ), (2) River Buffers (RB), (3) Watershed Basins (WB), and (4) Vegetation by Basin units (VB). The GZ consist of three distinct geomorphologic areas within coastal Louisiana. These zones, Chenier Plain, Middle Coast, and Deltaic Plain, have and continue to develop under different coastal processes (Fig. 1). Likewise, the RB units allow for assessments of condition and influence, but specifically as a function of distance from primary rivers. The RB consist of buffers that radiate at 5 km increments (based on Visser et al. 2003) from each river to a total distance of 40 km or to distances of overlapping coverages from neighboring RB.

The WB units consist of Louisiana drainage basins and subwatersheds (Louisiana Department of Environmental Quality (LDEQ) 2004). Since LDEQ basins delineate catchment areas of a river (up to its confluence), they serve as suitable units of hydrologic connectivity. Since some watershed basins are large and encompass distinct subwatersheds of interest, and some are small and adjacent to basins of similar hydrology, several modifications were made to the original boundaries. These modifications include the Sabine and Calcasieu basins, which are moderately small with similar hydrology, so they were combined to form the Calcasieu/Sabine WB unit. Also, since the Atchafalaya River has been shown to substantially influence the western portion of the Terrebonne drainage basin (Visser et al. 2003), the basin was divided into the Penchant Marsh unit to the west (area receiving Atchafalaya River influence) and the more river-disconnected Terrebonne proper unit to the east (Wang et al. 1993). Similarly, since the Pontchartrain drainage basin consisted of hydrologically unique subwatersheds, it was divided into the Pontchartrain proper, Breton Sound, and Biloxi

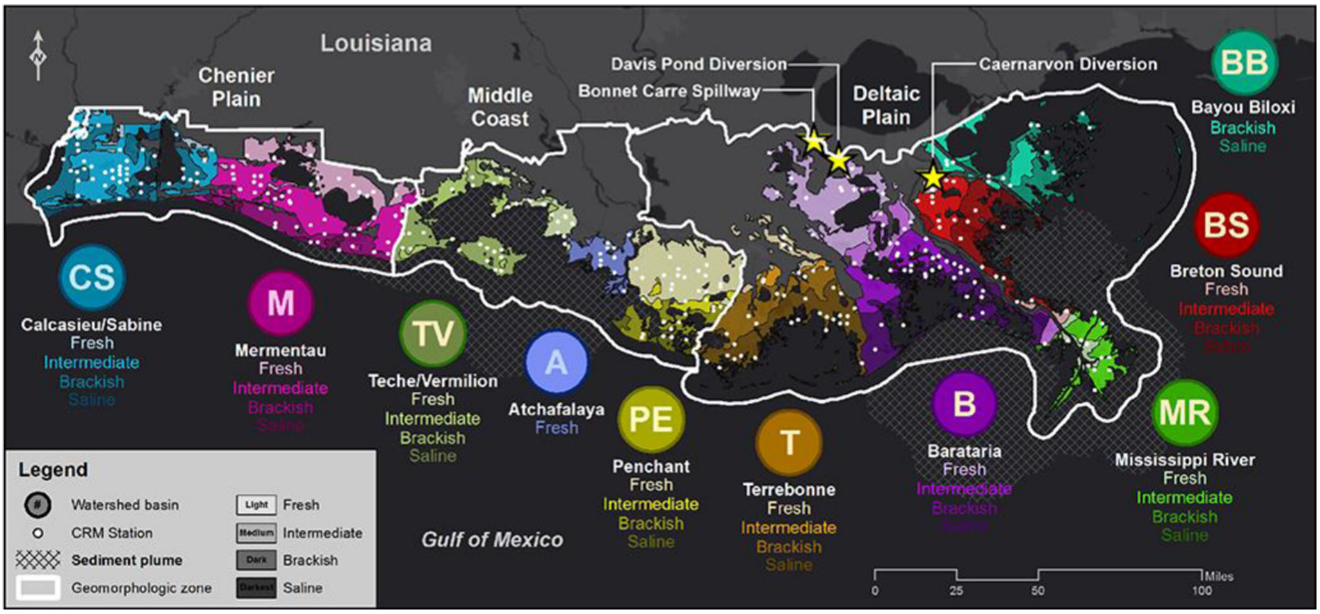

Fig. 2 Coastal Zone, Watershed Basins, and Vegetation by Basins assessment units in coastal Louisiana. White dots represent the locations of the Coastwide Reference Monitoring System (CRMS) stations and hatched areas represent the typical sediment plume for the Atchafalaya and Mississippi Rivers

Marsh units. However, since the Pontchartrain proper subunit consists primarily of forested wetlands and swamp, it was excluded from this study.

Louisiana's marshes have traditionally been characterized by their salt tolerance, and grouped into Fresh (0 to 0.5 practical salinity [S_P]), Intermediate (0.5 to 5 S_P), Brackish (5 to 18 S_P), and Saline (18 to 30 S_P) classes (Sasser et al. 2014). The impacts of sediment and nutrient loading on the plants in each of these vegetation zones can vary significantly (Visser et al. 2003), therefore, the Vegetation by Basin (VB) zones were used to compare productivity for each unique vegetation zone by drainage basin combination (Fig. 2).

Sediment Availability, Accretion, and Land Change

Assessing correlations between plant productivity and riverine inputs require the establishment of sediment delivery potential (Bianchi et al. 2002; Falcini et al. 2012; Roberts et al. 2015; DeLaune et al. 2016). This includes measurements of instream sediment concentration and evaluations of river connectivity to assessment unit wetlands. Mean daily discharge and total suspended sediment data for major rivers in Louisiana were extracted from literature or computed using United States Geological Survey (USGS) National Water Information System data (2016). Additionally, similar methods to Khan et al. (2013) and Turnipseed et al. (2014) were used to assess surface elevation changes within Louisiana's coastal watershed basins. Elevation and accretion data from all available Coastwide Reference Monitoring System (CRMS) stations ($n = 292$; Fig. 2) were used to evaluate surface elevation changes related to the major river flood events in 2008 and 2011 (Fig. 3), as well as the mean elevation changes across the entire CRMS period of collection (2008–2016). CRMS surface elevation table (SET) data provide measures of recent sedimentation (long-term and flood-related) at higher spatial scale than previous data sets and assessments. The extent and density of these CRMS data provide unique opportunities for evaluating cause and effects of elevation and elevation change on wetland processes (Jankowski et al. 2017).

Another indirect measure of long-term sediment delivery involves analyzing land change patterns with distance from sediment source, as described in Visser et al. (2003). The percentage of land change from 1956 to 2008 was calculated with distance from primary Louisiana navigable waterways using the RB assessment zones. The 1956 land and water data (Barras et al. 1994; 1:24,000) are based on panchromatic aerial photography-derived habitat data that were generated by the USGS Wetland and Aquatic Research Center (Suir et al. 2011). The 2008 data consist of land and water classified Landsat Thematic Mapper (TM) imagery that were previously developed for hurricane assessments (Barras 2009). The land and water classified data were resampled and analyzed at a spatial resolution of 28 m. Land change percentages were calculated for each buffer by subtracting the area of land in 1956 from the 2008 area, dividing by the total buffer area, and multiplying by 100.

Remote Sensing

Since the Normalized Difference Vegetation Index (NDVI) has well established correlations to plant characteristics (i.e., photosynthetic activity and biomass; Carle 2013), it was used in conjunction with Landsat (28 m) and MODerate Resolution Imaging Spectroradiometer (MODIS, 250 m [bands 1–2] and 500 m [bands 3–7]) satellite imagery to assess wetland productivity. Landsat-derived NDVI data provide higher spatial resolution data that were used in the land and water classification process (see Landscape configuration section below) and the moderate resolution MODIS-derived NDVI data (250 m) were used in all vegetation productivity assessments. The Landsat data (annual data from 2009, 2010, 2011, and 2013) and MODIS data (monthly from 2003 to 2013) were

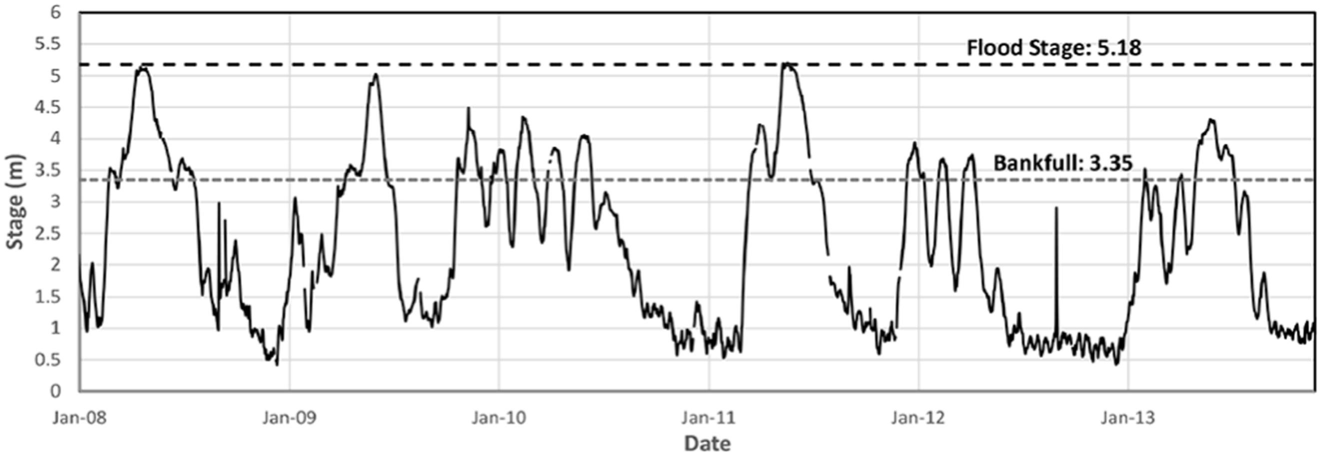

Fig. 3 Daily stage (meters) for the Mississippi River at New Orleans, Louisiana (Rivergages.com accessed 28 Jan 2017)

acquired using the Google Earth Engine (GEE) image service. GEE utilizes radiometrically and atmospherically corrected imagery, and aggregation functions (i.e., use of outlier values to remove cloud cover from neighboring scenes) to create monthly image composites (Strahler et al. 1999; Chander et al. 2009). The GEE service also provides NDVI data that are derived as:

$$NDVI = \frac{NIR - Red}{NIR + Red}, \qquad (1)$$

where this ratio of the near-infrared band (NIR) and red band (Red) is used to measure an ecosystem's ability to capture solar energy and convert it to organic carbon or biomass (Rouse et al. 1974; An et al. 2013). NDVI values range from −1 to 1, where those between −1 and zero (0) are typical of non-vegetation features (e.g., water, cloud, and impervious surfaces), and those between zero and 1 are typical of vegetated features. The higher the NDVI value the higher, generally, the biomass, productivity, and vigor of the vegetation (Carle 2013; Sun et al. 2016). Since NDVI values less than zero (< 0) are typical of non-vegetation features (e.g., water, cloud, impervious surfaces) (Reif et al. 2011; Carle 2013), those were excluded from each Landsat and MODIS-derived NDVI image. Additionally, a 2008 Landsat-derived coastal Louisiana habitat data set (J. Barras, USGS, unpublished data, 2008) was used as a secondary standardized water mask to exclude non-terrestrial vegetation (i.e., aquatic plants) from each NDVI image.

Landscape Configuration

Landscape ecology is based on the premise that there are strong correlations between landscape pattern (configuration) and ecosystem function (Gustafson 1998). One principal metric for assessing wetland landscape structure, and linking to ecosystem function, is the Aggregation Index (AI). This index, which is defined as the frequency with which different pairs of patch types appear side-by-side (McGarigal 2015), was used to assess landscape configuration change over time. Combined with wetland area change, AI provides a measure of landscape condition that positively correlates to landscape integrity and is therefore well suited for assessing wetland stability and potential correlations to plant productivity (Suir et al. 2009; Sun et al. 2015; Couvillion et al. 2016). The class-level aggregation index (AI) is derived as:

$$AI = \left[\sum_{i=1}^{n} \left(\frac{g_{i,i}}{\max\_g_{i,i}} \right) P_i, \right] (100), \qquad (2)$$

where $g_{i,i}$ is the number of like adjacencies between pixels of patch type i (class), $\max\_g_{i,i}$ is the maximum number of like adjacencies between pixels of patch type (class) i (He et al. 2000; McGarigal 2015). The aggregation index, which ranges from zero (0) to 100, approaches zero when the focal patch type is maximally disaggregated (i.e., when there are no like adjacencies of land features within the assessment unit) and100 when the patch type is maximally aggregated into a single, compact patch (i.e., assessment unit consist entirely of land features) (McGarigal et al. 2012). The AI was computed for all assessment units using FRAGSTATS v4.2 (McGarigal et al. 2012) and a sequential series of 16 land and water data sets. Existing land and water data from 1988 to 2008 (Barras et al. 1994; Hartley et al. 2000; Barras 2007; Morton et al. 2005; Barras 2009) were supplemented by performing land and water classifications on newly acquired Landsat TM imagery using ENVI version 5.3 (2009, 2010, 2011, and 2013). All Landsat-derived data used in this study were classified using a standard classification methodology (Barras et al. 2003) to ensure repeatability and consistency, as well as to minimize classification interpretation subjectivity. All classified data were resampled to 28 m pixel size for compatible and comparable land and water data. Confusion matrices (predicted classes versus observed classes) were constructed to assess the accuracy of each land and water classified image. User's accuracy, producer's accuracy, overall accuracy, and Kappa coefficients were computed and analyzed (Congalton 1991; Mathieu and Aryal 2005). The accuracy of land and water classified data were high, ranging in Kappa values from 0.92 to 0.97. The mean AI rates of change, which were determined by calculating the slope of the linear regression by VB, provide a measure of landscape condition that correlates to wetland integrity and stability (Suir et al. 2013; Couvillion et al. 2016). The land and water classified data were also used in conjunction with FRAGSTATS to compute the total Class Area (CA) of wetlands within each assessment unit. CA is the sum of the areas of all patches of the corresponding patch type (McGarigal et al. 2012).

Statistical Analysis

All data sets were transformed and formatted as comma separated values (CSV) files for statistical analyses. In order to attain comparability among NDVI for each assessment scale, statistical analyses were conducted using Statistical Analysis System software version 9.2 (SAS 2010). The PROC GLM procedure was used to perform a one-way analysis of variance (ANOVA) and a means separation test (Tukey's, $\alpha = 0.05$) to evaluate significance of differences between NDVI for each assessment unit. Additionally, a linear regression with coefficient of determination (r^2) was used to evaluate correlations between productivity (NDVI) and stability (aggregation index) with consideration of hydrologic connectivity.

Results

Use of Sediment Potential and Delivery to Assess Hydrologic Connectivity

The mean flows of the Mississippi River and Atchafalaya River (combined with Wax Lake Outlet) are approximately 16,000 m^3 s^{-1} and 6000 m^3 s^{-1}, respectively (Table 1) (Sprague et al. 2009; Rego et al. 2010). The mean sediment concentration of the Mississippi River and Atchafalaya River are approximately 260 mg per liter (mgL^{-1}) and 470 mgL^{-1}, respectively (Rosen and Xu 2013). Since 1950, the Atchafalaya River has conveyed all of the suspended- and bed-sediment load of the Red River, and approximately 35%, 60%, and 30% of the Mississippi River's suspended sediment, bed sediment, and latitude flow (all river system water passing through latitudinal plane), respectively (U.S. Army Corps of Engineers (USACE) 2004, Hupp et al. 2008). The remaining primary rivers (excluding the GIWW) have reported mean flows that range from 33 to 219 m^3 s^{-1}, and mean sediment concentrations that range from 17 to 56 mgL^{-1} (Rosen and Xu 2011) (Table 1).

Figure 4a illustrates the surface elevation change by CRMS station and mean change by WB units that were computed using pre- (mean surface elevation between October 2010 and April 2011) and post- (July 2011 to November 2011) 2011 flood data. These findings are similar to those by Falcini et al. (2012), who observed sites within the Atchafalaya (1.61 ± 0.96 g per cubic centimeter [g cm^{-2}], $n = 14$) and Mississippi River Deltas (1.14 ± 0.78 g cm^{-2}, $n = 9$) had the greatest 2011 flood related accumulation of sediment. Figure 4a also shows the WB units near or between large river outfalls (i.e., Terrebonne and Barataria) or floodway systems experienced the highest mean elevation increases. Though Falcini et al. (2012) observed more moderate relative sediment accumulation in these WB units (Terrebonne 0.42 ± 0.18 g cm^{-2}, $n = 14$ and Barataria 0.34 ± 0.22 g cm^{-2}, $n = 8$), the dissimilarities are potentially due to differences in assessment area scale and sample locations. Accretion data from the 2008 Mississippi River flood correspond to the elevation data and trends that were observed with the 2011 flood, therefore, those data are not shown here for brevity. Panel B of Fig. 4 illustrates the elevation change rate for each CRMS station from 2006 to 2016. Across the period of record the elevation trends were similar to those that were observed pre- and post-floods, with higher increases in relative elevation around high flow and high sediment-concentration rivers (i.e., Atchafalaya River and Mississippi River).

A third hydrologic connectivity assessment was performed using the land change with distance from river method described in Visser et al. (2003). Similar to findings by Visser et al., land loss increased with distance from sediment source for most Chenier Plain and Middle Coast basins (Table 2). This was not true for all basins, especially those neighboring the Atchafalaya and Mississippi Rivers basins (i.e., Teche/Vermilion, Terrebonne, and Barataria basins), since their outer regions receive large concentrations of sediments through coastal processes, thereby superseding the influence from nearby smaller rivers (Rego et al. 2010). This was also not true for the Mississippi River West and East locations (Table 2), which are either disconnected (west), or consist of small catchments in high energy environments (east) where the Mississippi River transports large proportions of its sediment beyond the delta's wetlands (Winer 2011). Conversely,

Table 1 Mean daily discharge and mean total suspended solids (TSS) for primary rivers in coastal Louisiana. Modified from Benke and Cushing (2011)

River	Basin	Mean Flow (m^3 s^{-1})	Mean TSS (mgL^{-1})	Source
Sabine	Calcasieu/Sabine	219	17	Rosen and Xu 2011
Calcasieu	Calcasieu/Sabine	72	18	Rosen and Xu 2011
Mermentau	Mermentau	82	26	Rosen and Xu 2011
Vermilion	Teche/Vermilion	33	56	Rosen and Xu 2011
GIWW west of WLO[a]	Vermilion	158	177	Swarzenski 2003
Atchafalaya/Wax Lake Outlet[b]	Atchafalaya	6227	469	Rego et al. 2010, Rosen and Xu 2013
GIWW east of Atchafalaya[c]	Penchant	156	137	Swarzenski 2003
Houma Navigation Canal	Terrebonne	90	41	LDEQ 2016, USGS 2016
Lafourche	Barataria	35	27	LDEQ 2016, USGS 2016
Mississippi	Mississippi River	16,339	259[d]	Sprague et al. 2009, Thorne et al. 2008

[a] West of the Wax Lake Outlet to Cypremort Point

[b] Flow and TSS for Atchafalaya and Wax Lake Outlet combined

[c] East of the Atchafalaya River to the Houma Navigation Canal

[d] Mississippi River at Tarbert Landing

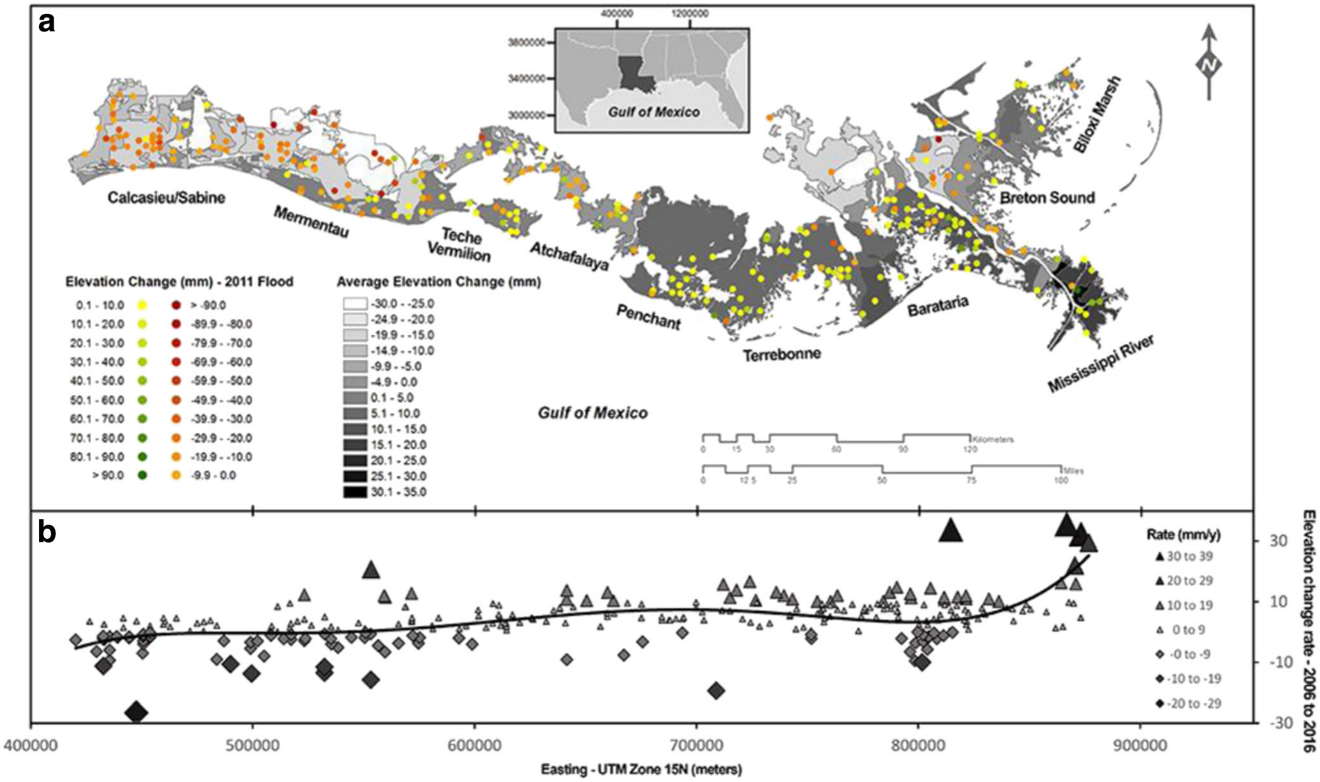

Fig. 4 Baseline and flood-related relative elevation change across the Coastwide Reference Monitoring System (CRMS) period of record (2006 to 2016). Panel **a** shows the change in elevation (pre- and post-2011 Mississippi River flood) for all CRMS stations (yellows to greens represent increasing elevations and oranges to reds represent decreasing elevations) and the mean elevation change by watershed basin (polygons). Panel **b** represents the total elevation change rates, where increases are represented by triangles and losses by diamonds. Magnitude of change is color ramped in all panels

within the northern Breton Sound basin (Mississippi River North, Table 2), data corroborate those by Visser et al. (2003) which show that the buffers receiving freshwater inputs through the Caernarvon diversion (25 km and 30 km) are those with the lowest land loss percentages.

Wetland Productivity by Assessment Unit

Figure 5 illustrates the spatial variability and patterns of NDVI across the Chenier Plain, Middle Coast, and Deltaic Plain units. The mean NDVI, per pixel, ranged from 0.01 (standard

Table 2 Coastal wetland change (1956 to 2013) with distance from primary rivers

Location	Basin	Distance from River (km)							
		5	10	15	20	25	30	35	40
		Land Change (%) from 1956 to 2013							
Sabine River	Calcasieu/Sabine	−8.9	−10.5	−20.8	−25.0	−40.4	−30.2	–	–
Calcasieu River	Calcasieu/Sabine	−7.3	−19.1	−31.8	−23.1	−24.3	−27.2	–	–
Mermentau River	Mermentau	−10.8	−14.2	−13.5	−13.5	−9.0	−12.2	−12.9	−16.7
Vermilion/Freshwater Bayou	Teche/Vermilion	−15.7	−10.8	−12.7	−8.6	−10.2	−7.8	−6.5	−5.9
Atchafalaya/Wax Lake Outlet	Atchafalaya	2.2	−3.4	−2.3	−11.0	−7.5	−7.6	−6.7	−7.3
GIWW (Atchfalaya Influence)	Multiple	−9.6	−10.6	−14.0	−15.0	−15.9	−12.6	–	–
Houma Navigation Canal	Terrebonne	−22.1	−25.8	−17.1	−14.9	−16.8	−15.6	−8.7	−5.1
Bayou LaFourche	Barataria - west	−23.8	−24.2	−16.4	−15.7	−14.3	−9.5	−12.2	−10.0
Mississippi River West	Barataria - east	−32.8	−40.3	−32.6	−8.4	−5.0	−7.1	−10.6	−16.5
Mississippi River East	Mississippi River	−22.6	−15.0	−10.5	−9.5	−5.9	−1.5	0.1	−1.1
Mississippi River North	Breton Sound	−13.1	−23.6	−21.3	−16.6	−7.7	−7.0	−7.4	−5.4

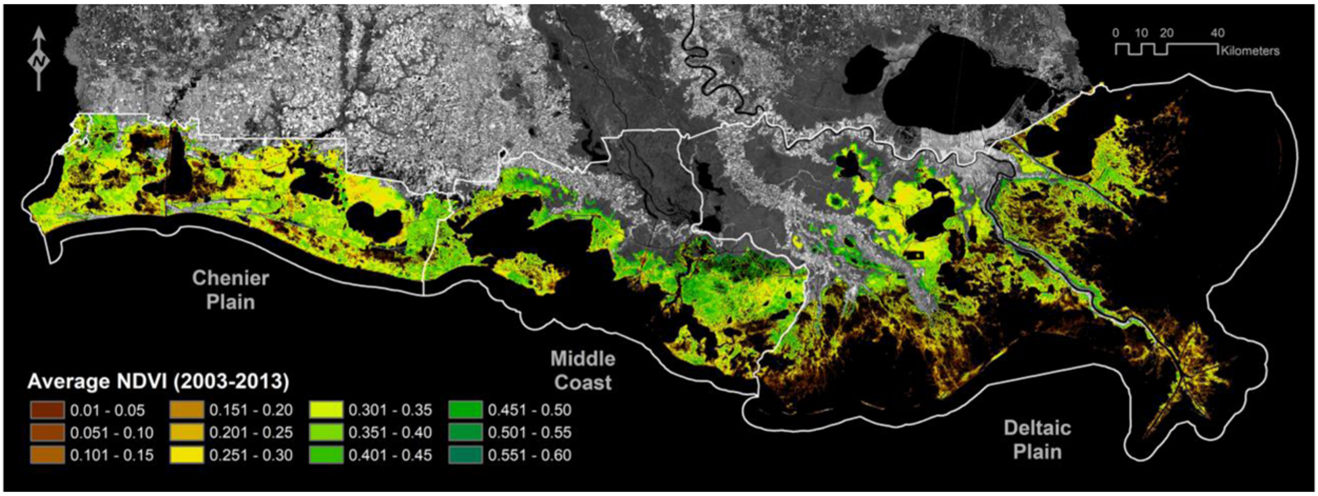

Fig. 5 Productivity classification based on quartile distribution of mean Normalized Difference Vegetation Index values (2003–2013) in coastal Louisiana

deviation [SD] 0.0) to 0.769 (SD 0.12) across the 2003 to 2013 period of analysis. The Chenier Plain had a mean NDVI of 0.48 (SD 0.10) and consisted primarily of moderate vegetative productivity (orange hues). Figure 5 also shows large expanses of wetlands within the Middle Coast region were highly productive (dark green hues), with a mean NDVI of 0.55 (SD 0.12). The Deltaic Plain, which consisted of a mixture of high to low productivity (green and red hues, Figure 5), had a mean NDVI of 0.4 (SD 0.17).

Watershed basins are delineated by drainage area and therefore provide units that are useful for assessing hydrology-related landscape processes and condition (Fig. 2). Figure 6 shows mean NDVI values from 2003 to 2013 for each watershed basin in coastal Louisiana, and the corresponding means for the Middle Coast, Chenier and Deltaic Plains (dashed lines). The Calcasieu/Sabine and Mermentau basins (comprising the Chenier Plain), had mean NDVI values of 0.46 (SD 0.09) and 0.5 (SD 0.11), respectively. This was lower than those of the Middle Coast but higher than the Deltaic Plain basins. The Middle Coast basins, Teche/Vermilion, Atchafalaya, and Penchant, had mean NDVI values of 0.53 (SD 0.1), 0.59 (SD 0.14), and 0.53 (SD 0.1), respectively. The mean productivity in these Middle Coast units were significantly higher than all but the Mermentau basin, which receives Atchafalaya River sediment and nutrients through shoreward transport and onshore deposition (Gammill et al. 2002; Draut et al. 2005). The Deltaic Plain basins, Terrebonne, Barataria, Breton Sound, Biloxi Marsh, and Mississippi River, had the lowest NDVI values, at 0.36 (SD 0.06), 0.44 (SD 0.08), 0.45 (SD 0.12), 0.41 (SD 0.06), and 0.36 (SD 0.12), respectively.

Correlations were observed between the Louisiana vegetation zones (Fresh, Intermediate, Brackish, and Saline) and vegetation biomass (NDVI) (Fig. 7, dashed lines). These findings corroborate those in previous research, which show that lower salinity environments typically consist of plants with higher leaf area and productivity (Gough and Grace 1998; Steyer 2008; Janousek and Mayo 2013). Figure 7 also provides a representation of the mean NDVI value for each VB unit. The Atchafalaya River influence is evident in each of the four vegetation zones. In the fresh zone the higher NDVI values occur in basins that are in closest proximity to the Atchafalaya River. Also, even though the Terrebonne Basin is not in the Middle Coast GZ, the fresh portion of this basin frequently receives large inflow of Atchafalaya River water by way of the GIWW (Swarzenski 2003). Within the intermediate zone many of the basins had similar mean NDVI values, except for the Teche/Vermilion and the Mississippi River basin areas, which accounted for the maximum (0.54) and minimum (0.36), respectively.

Similar trends occurred in the brackish and saline zones, where NDVI values were highest for the Chenier, Teche-Vermilion, and northeastern Deltaic Plain basins. The high NDVI values in the brackish and saline portions of the Chenier and Teche-Vermilion basins are likely due in part to westward marine transport of Atchafalaya River sediment and nutrients (Gammill et al. 2002). The presses contributing to higher Deltaic Plain values in the brackish and saline zones are less obvious, but could be due to impacts of Caernarvon Freshwater Diversion sediments on Breton Sound wetlands, and nutrient and suspended solids from coastal discharges (from Pearl River and Lake Pontchartrain passes) assimilating in the Bayou Biloxi system (Poirrier and Handley 2002).

Flood Impacts on Vegetation Productivity

Figure 8 illustrates departure from average values comparing MODIS-derived NDVI from August 2011 (post-flood peak biomass) to average August values from non-flood years (and excluding years with major hurricane events). The

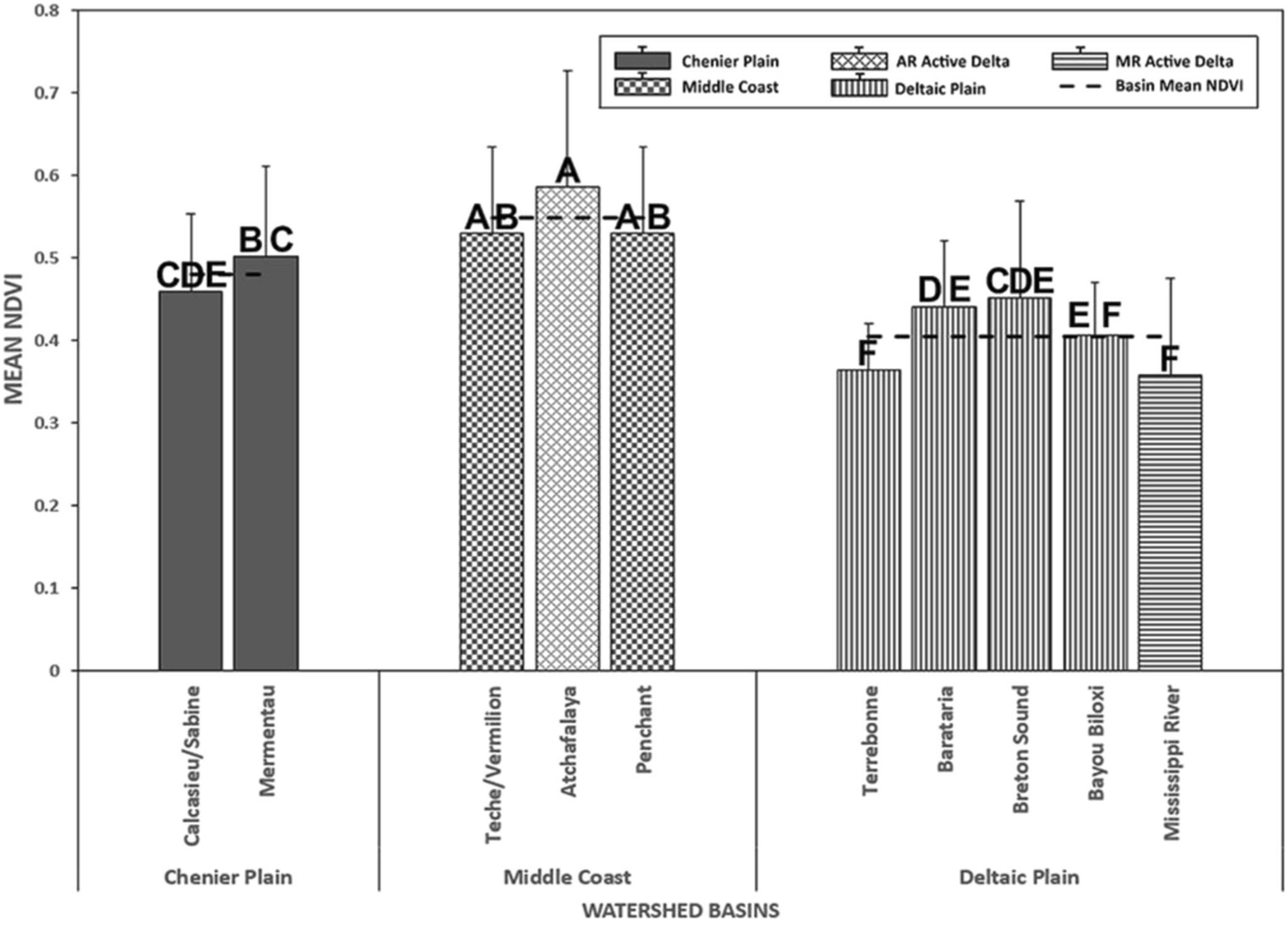

Fig. 6 Mean Normalized Difference Vegetation Index values (2003 to 2013) for each geomorphologic zone (dashed line) and watershed basin (bars) in coastal Louisiana. Bars with the same letter are not statistically different at $p < 0.05$ (Tukey's HSD test)

highest positive departure values (greens and yellows) were observed in the Atchafalaya, Mississippi River, upper Mermentau and Barataria, and parts of the Teche-Vermilion and Bayou Biloxi basins. These areas either receive freshwater and sediment through natural riverine processes, marine transport of river constituents, or through diverted river water. Moderate to low positive departures (orange) were observed in a majority of the Calcasieu-Sabine and Mermentau basin wetlands. The negative departures in NDVI values (red) were observed in the upper Penchant, and lower Terrebonne and Barataria basins. Though these departures were negative, they were relatively small, and potentially due to floating aquatics, flood duration, and salinity shifts within wetlands (Coastal Protection and Restoration Authority (CPRA) of Louisiana 2017).

Assessing Relationships Between River Connectivity and Wetland Stability

Figure 9 illustrates the Aggregation Index (AI) rates of change (slope) for each VB unit, which were computed using 16 land and water classified Landsat images from 1988 to 2013. Though the AI slopes ranged from −0.24 (red) to 0.01 (dark green), the majority of VB units experienced decreasing AI rates over this period. Only the Atchafalaya Fresh and Teche Saline units experienced positive rates of AI. Rates for these units were most closely matched by the Barataria Fresh and Mississippi River delta units, which experienced small decreasing rates of AI. Most VB units experienced moderately negative AI rates, except for the more saline Terrebonne and Barataria units, and the fresher Breton Sound units, which experienced the largest negative rates of change. The more stable AI rates in Atchafalaya, Teche, and Mississippi River units are anticipated results with their proximity to large river influence. However, stable AI in the upper Barataria is less expected, but potentially due to river inputs through the GIWW and Davis Pond Diversion (Fig. 2), and its inland position, which limits the erosive pulses and presses that are active in the intertidal zone. The less stable AI rates in lower Terrebonne and Barataria basins are also anticipated since these regions are highly sediment deprived and have been

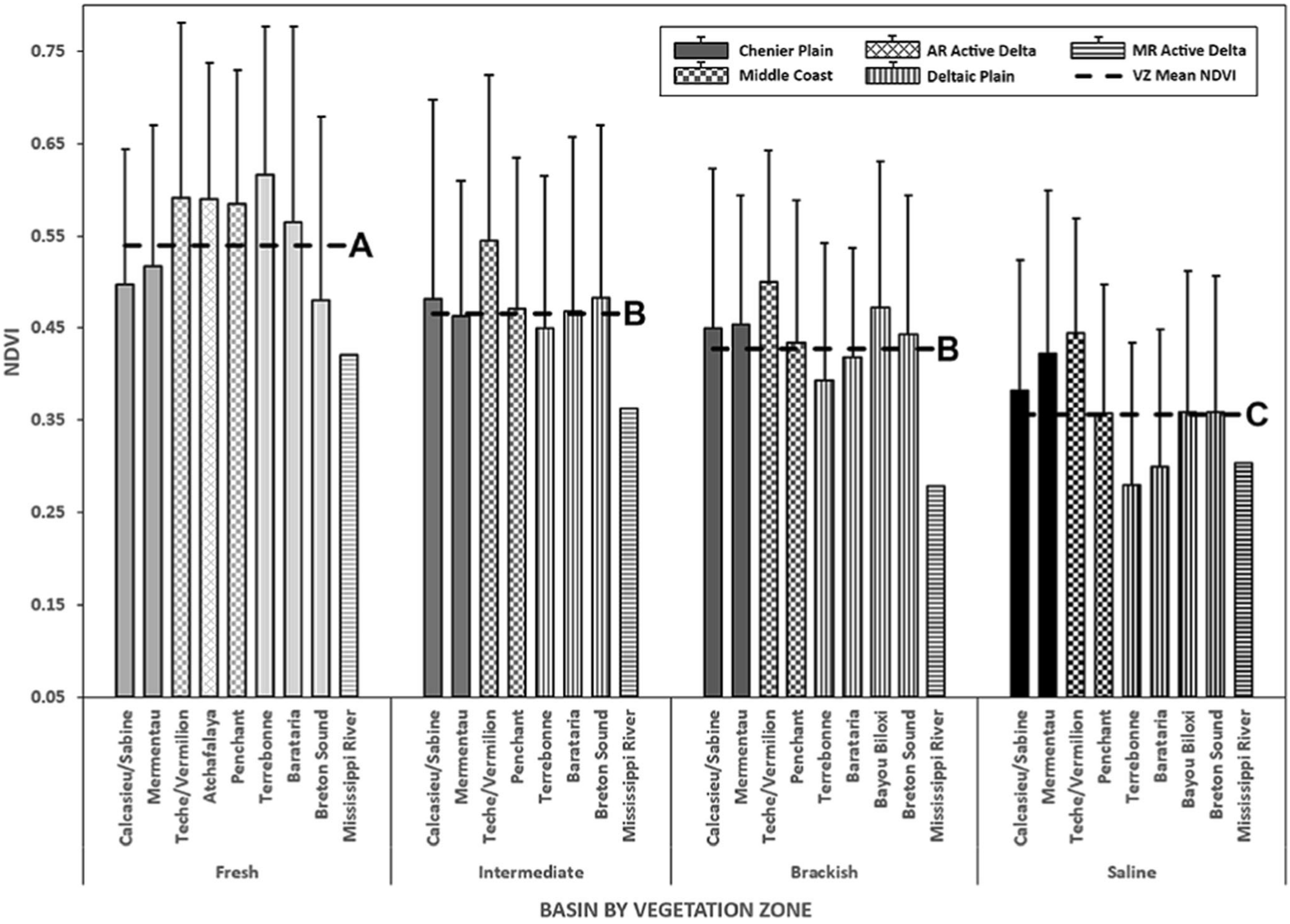

Fig. 7 Mean Normalized Difference Vegetation Index values for each vegetation zone (dashed line) and basins (bars) within vegetation zone. Dashed lines with the same letter are not statistically different at $p < 0.05$ (Tukey's HSD test)

subjected to salinity intrusion, oil and gas access canal impacts, and accelerated rates of subsidence (Sasser et al. 1986). The less stable AI in the upper Breton Sound basin is potentially due to Hurricane Katrina impacts (Barras 2007). Figure 9 also illustrates the range of AI and wetland stability in the GZ units.

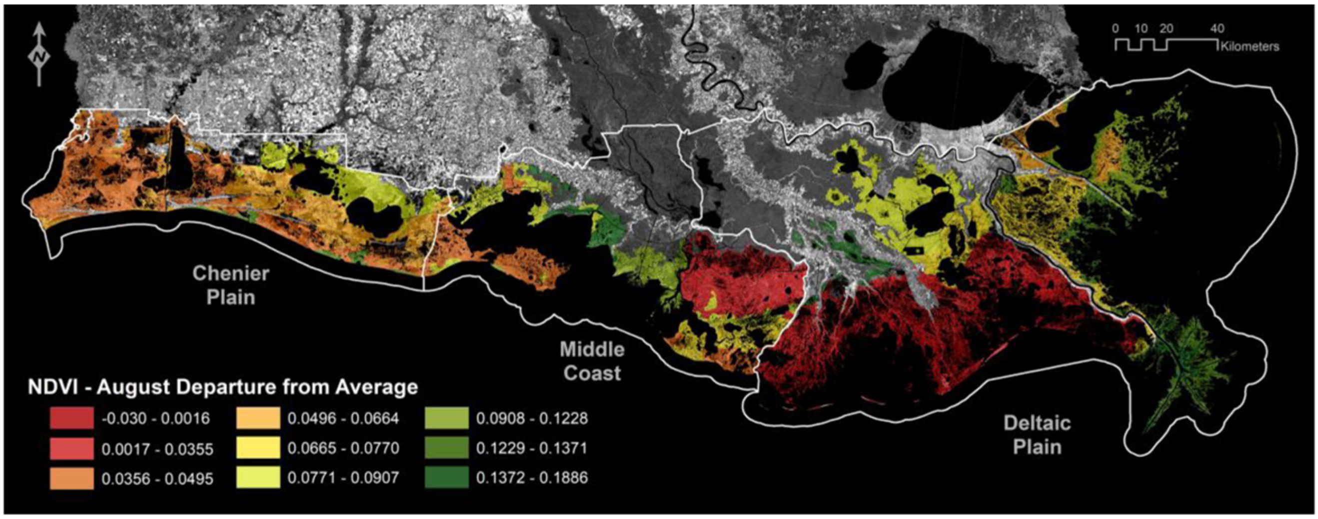

Fig. 8 Departure from average using Normalized Difference Vegetation Index from August 2011 (post-flood peak biomass), where greens represent above-average vegetation productivity and reds represent below-average productivity

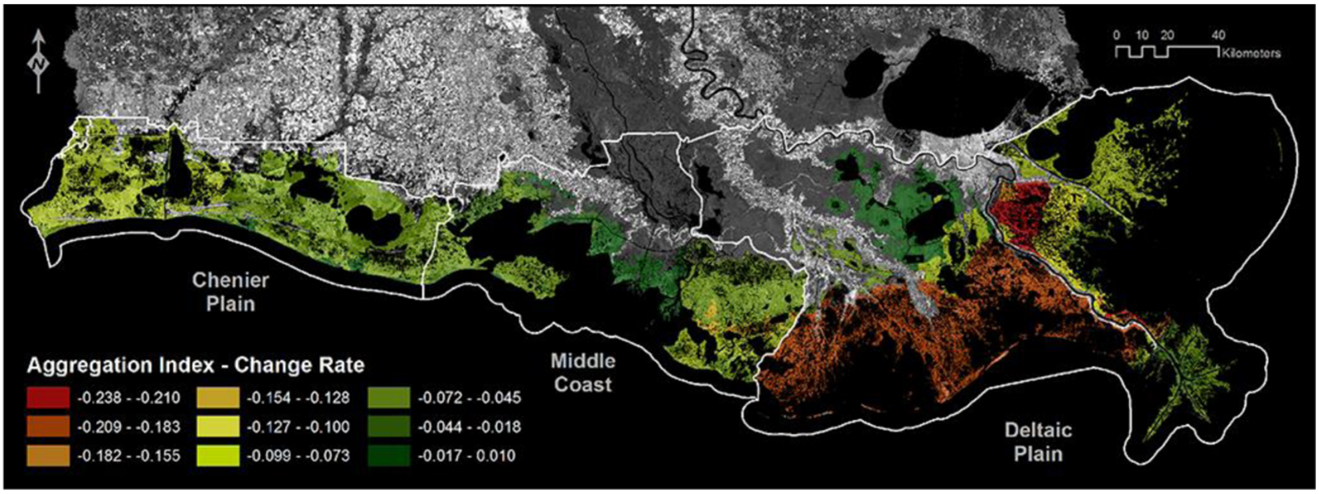

Fig. 9 Landsat derived Aggregation Index mean change rate (1988 to 2013) by Vegetation by Basin assessment unit and assessed by geomorphological zone. Dark green areas represent wetland landscapes with highest stability and red areas with lowest stability

While Aggregation Index provides temporal and spatial measures of wetland structure, combining with Class Area (CA) and NDVI values allows for assessments of additional linkages between river connectivity with wetland productivity and spatial integrity. Figure 10 illustrates the AI (yellow bars), CA (red bars), and NDVI (green bars) rates for each VB zone, and provides a means for comparing productivity, spatial integrity, and stability as a function of river connectivity. The majority of VB zone wetlands exhibited moderate positive NDVI values, and moderate to high negative CA and AI rates across the period of analysis, with few zones near the minima and maxima. Similar relative trends exist across these metrics, with wetland areas in close proximity to large river influence (i.e., Middle Coast basins), or those that receive river sediment via marine processes (Mermentau basin), having the highest productivity and stability. Conversely, VB zones with lesser river influence (Calcasieau/Sabine), especially those with higher susceptibility (i.e., energy, altered hydrology, and subsidence; Deltaic Plain basins) experienced the lowest productivity and stability.

While each of these metrics provides separate measures of wetland structure or function, individually they lack the ability to link causal mechanisms to, and relationships between, wetland productivity and stability. Figure 11 plots the mean NDVI against the mean AI for all VB across the 1988 to 2013 period to evaluate correlations between wetland productivity and spatial integrity. The plot shows moderate correlations ($r^2 = 0.51$) between NDVI and AI, where higher NDVI values typically return higher AI values. Anomalies occur in areas where major hurricanes have impacted wetland productivity, which has been shown to affect NDVI values, even over long time periods (Li et al. 2016). Figure 11 shows the higher NDVI and AI combinations are dominated by the Middle Coast VB, the moderate NDVI and AI combinations are

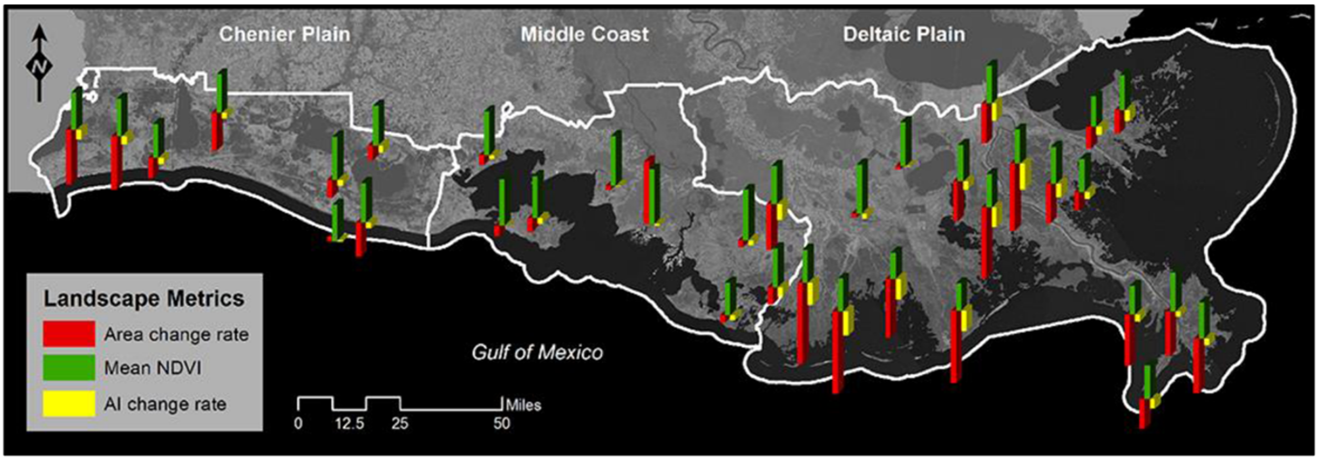

Fig. 10 Landsat derived mean Normalized Difference Vegetation Index (NDVI) values (green bars, above and below axis represents positive and negative values, respectively), and Class Area (CA) and Aggregation Index (AI) change rates (red and yellow, respectively), for each vegetation by watershed basin assessment unit

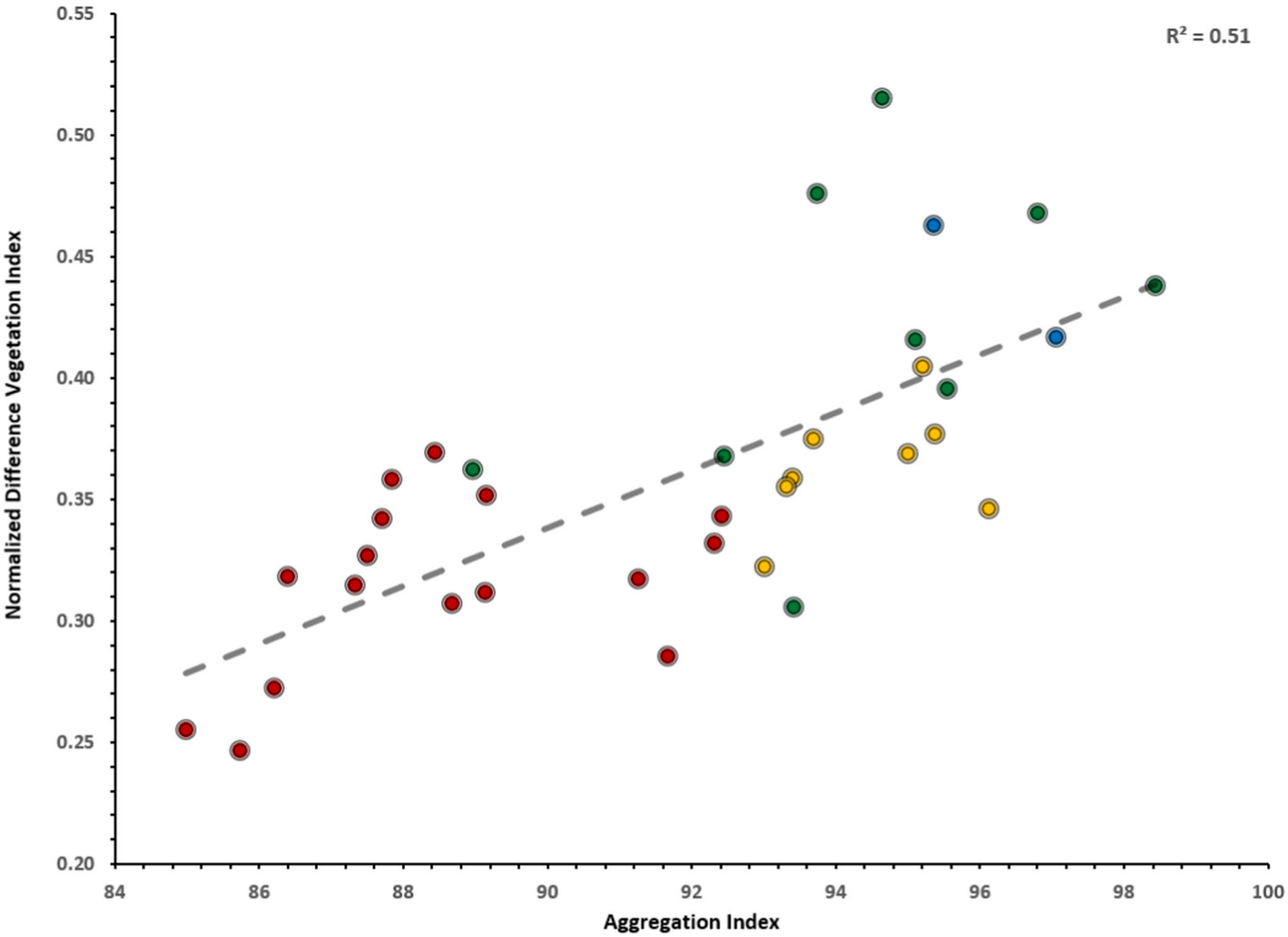

Fig. 11 Coastwide plots of mean Normalized Difference Vegetation Index versus mean Aggregation Index for all vegetation by watershed basin assessment units. The Chenier Plain, Middle Coast, and Deltaic Plain are represented by the orange, green, and red dots, respectively. The blue dots represent assessment units that receive river inputs from distant sources

dominated by the Chenier Plain VB, and the lower NDVI and AI combinations are dominated by the Deltaic Plain VB units.

Discussion

To assess the impacts of river-borne sediment on wetland productivity and configuration, linkages between river and wetlands must be evaluated. This was accomplished by assessing sediment source and potential using river discharge, river suspended sediment concentrations, and trends in wetland accretion rates and land change (with distance from source). The Atchafalaya River and Mississippi River are generally one magnitude higher in mean total suspended sediment concentration and several magnitudes higher in discharge rates than other primary waterways, and therefore have significantly higher sediment potential. To evaluate correlations between river influence on actual sedimentation in wetlands, CRMS accretion data were used to compute long- and short-term trends in surface elevation. The majority of the CRMS stations in close proximity to larger river outfalls or floodway systems (i.e., Bonnet Carré Spillway, which opened on 9 May 2011 to alleviate flooding stress (USACE 2016)) experienced increases in relative surface elevation, while those located at greater distances were dominated by decreases in elevation. These findings corroborate those by Jankowski et al. (2017), who correlated accretion rates with proximity to riverine sediment inputs, connectivity to the Gulf of Mexico, and impacts of Chenier ridges and impoundments.

These assessments of hydrologic connectivity largely corroborate previous smaller-scale studies, where sedimentation and nutrient availability increase with connectivity to riverine source and hydro period (inundation depth and duration), and generally, wetlands in close proximity to highly connected rivers experience higher rates of accretion and lower land loss. Exceptions to these include wetlands receiving sediment from distant sources, areas with increased tidal exchange and more frequent salinity spikes due to hydrologic alterations (i.e., Houma Navigation Canal impacts in Terrebonne Basin) (CLEAR 2006; Steyer et al. 2008), and disconnected wetlands–especially those in rapidly subsiding landscapes (i.e., lower Barataria and Mississippi River basins) (Suir et al. 2013; Suir et al. 2014).

Having established sediment potential and sediment delivery as a function of distance from major rivers in coastal Louisiana, the next step was to evaluate potential linkages between hydrologic connectivity and vegetation biomass or productivity. Vegetation biomass, measured using mean NDVI values, were found to be significantly higher in the Middle Coast unit, followed by the Chenier Plain, and Deltaic Plain. The Middle Coast is a hydrologically connected landscape with riverine, marine, atmospheric, and seasonal processes that deliver high concentrations of river sediment and nutrients to adjacent wetlands and prograding deltas (Wax Lake and Atchafalaya) (Perez et al. 2000, 2003; Rosen and Xu 2013). The Chenier Plain is largely connected to moderate and low sediment and nutrient concentration rivers, however portions are still influenced by the Atchafalaya River (i.e., westward transportation and reworking via marine processes) (Penland and Suter 1989; Gammill et al. 2002; Rosen and Xu 2011). The Chenier Plain has also undergone extreme hydrologic modifications (i.e., navigation, water control structures, oil and gas access canals) that have increased flooding frequency and duration, which in turn has had significant negative impacts on wetland productivity and condition (Gammill et al. 2002, Rosen and Xu 2011). The Deltaic Plain contains some isolated wetlands that receive high inputs from the Mississippi River, and some inputs from the Atchafalaya River (northern Terrebonne via the ICWW), yet most are disconnected wetlands that have undergone extensive degradation (Couvillion et al. 2011).

Similar tends where observed between hydrologically connected watershed basins and vegetation biomass. The general tendency in these data show a positive correlation between wetland productivity and river connectivity. Even when mean NDVI values were not significantly different between some basins, small changes or differences in NDVI values have been shown to be correlated to significant differences in biomass. Tan et al. (2003) quantified the relationship between Landsat-derived NDVI values and wetland vegetation biomass, concluding that each 0.1 change in NDVI value correlates to 500 g/m^2 change in aboveground biomass ($r^2 = 0.82$). Correspondingly, low and decreasing productivity in coastal Louisiana basins have been attributed to marsh deterioration and fragmentation resulting from long-term sediment, nutrient, and freshwater deprivation (Boesch et al. 1994; Day et al. 2000; Cardoch et al. 2002; Couvillion et al. 2016).

A departure from average approach was used to further assess flood-related sediment impacts on plant productivity. This method, which compared end of growing season NDVI-derived mean biomass from non-flood years (baseline) to those from flood years, is a useful measure that links riverine connectivity to plant response. The premise behind this assessment is wetlands with higher river connectivity will receive higher than normal sediment and nutrient inputs (due to major flood events, Day et al. 2016) and will therefore have a higher productivity (or positive departure from average). Watershed basins receiving higher sediment concentrations had the highest positive departure values, while those that were more hydrologically disconnected or were impacted by flood-related impounding or salinity shifts were those with low positive or negative departures values. Overall, the departure from average results demonstrate the direct response of vegetation to floods, and corroborate the previous results of hydrologic connectivity correlations to vegetation productivity.

The final assessment was to evaluate how river connectivity and vegetation productivity might be correlated to wetland spatial integrity and stability. Overall, river-connected Middle Coast wetlands retained higher levels of aggregation and spatial integrity, the Chenier Plain wetlands experienced moderately decreasing aggregation and stability, while the wetlands of the Deltaic Plain experienced a wider range of aggregation change. The results show wetlands with highest river connectivity typically are the most productive and stable. One exception is the Mississippi River Delta, which accumulates more sediment than all other assessment units, however, current sedimentation is insufficient in offsetting the combined effects of altered hydrology, salinity fluxes, wind- and wave-induced erosion, and the high rates of compaction and subsidence (Gagliano et al. 1981).

Conclusions

Remote sensing and landscape pattern analysis provided enhanced techniques for evaluating river influence on biomass and correlations to spatial integrity. MODIS- and Landsat-derived NDVI, CA, and AI, integrated with river discharge, river sediment concentration, and accretion data, were used to perform multi-temporal and -spatial scale assessments to differentiate wetland productivity and stability based on proximity to large river systems. Louisiana wetland productivity is highly associated with seasonality and vegetation zones, susceptible to episodic events (hurricanes and floods), and significantly correlated to river connectivity. This was observed under baseline conditions, post-major flood events, and across short and long periods of observation. Similarly, positive correlations between landscape stability and river influence were observed. Ultimately, these assessments validate assumptions that wetland productivity and stability are at least partial functions of river connectivity. Though wetland loss is often the combined effects of subsidence, energy, saltwater intrusion, and human activities, sediment deprivation has been shown to be a primary driver in the long-term degradation of wetland structure and function. Continued evaluations of wetland productivity and landscape configuration, along with other ecosystem drivers, will provide a greater understanding of river and sediment importance for wetland stability and restoration.

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