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# Forecasting landscape effects of Mississippi River diversions on elevation and accretion in Louisiana deltaic wetlands under future environmental uncertainty scenarios

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A B S T R A C T

Large sediment diversions are proposed and expected to build new wetlands to alleviate the extensive wetland loss (5000 km$^2$) affecting coastal Louisiana during the last 78 years. Current assessment and prediction of the impacts of sediment diversions have focused on the capture and dispersal of both water and sediment on the adjacent river side and the immediate outfall marsh area. However, little is known about the effects of sediment diversions on existing wetland surface elevation and vertical accretion dynamics in the receiving basin at the landscape scale. In this study, we used a spatial wetland surface elevation model developed in support of Louisiana's 2012 Coastal Master Plan to examine such landscape-scale effects of sediment diversions. Multiple sediment diversion projects were incorporated in the model to simulate surface elevation and vertical accretion for the next 50 years (2010–2060) under two environmental (moderate and less optimistic) scenarios. Specifically, we examined landscape-scale surface elevation and vertical accretion trends under diversions with different geographical locations, diverted discharge rates, and geomorphic characteristics of the receiving basin. Model results indicate that small diversions (<283 m$^3$ s$^{-1}$) tend to have limited effects of reducing landscape-scale elevation loss (<3%) compared to a future without action (FWOA) condition. Large sediment diversions (>1500 m$^3$ s$^{-1}$) are required to achieve landscape-level benefits to promote surface elevation via vertical accretion to keep pace with rising sea level.

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## 1. Introduction

Controlled river diversions, defined here as reintroducing historical flow from the Mississippi River into interdistributary basins, are one of the critical engineering methodologies used in coastal restoration in Louisiana (Day et al., 2001; DeLaune et al., 2003; Lane et al., 2006; Day et al., 2009; Allison and Meselhe, 2010; Paola et al., 2011; Meselhe et al., 2012; Teal et al., 2012). These diversions are designed to (1) increase sediment supply and delivery for maintaining and building wetlands, (2) establish a proper salinity gradient for sustaining fisheries production, and (3) transform and reduce nutrient loads before it can enter coastal oceans and exacerbate offshore hypoxia (Day et al., 1997, 2001, 2009; LaPeyre et al., 2009; Rivera-Monroy et al., 2013). Even small Mississippi River diversions have shown to be capable of delivering mineral sediments to wetland surfaces (Lane et al., 2006, 2007; Snedden et al., 2007). Sediment diversions from the Mississippi River are expected to play an important role in reducing wetland loss in coastal Louisiana, where approximately 5000 km$^2$ of wetlands have been lost since 1932 at an average rate of ∼43 km$^2$ per year between 1985

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and 2010 (Couvillion et al., 2011). In order to mitigate wetland loss, large sediment diversions (>1500 $m^3 s^{-1}$) have been proposed by the 2012 Louisiana Coastal Master Plan (Allison and Meselhe, 2010; Allison et al., 2012; Peyronnin et al., 2013). Prior to levee construction, crevasses on the Mississippi were fairly common. It's been estimated they were capable of delivering large quantities of freshwater (5000–10,000 $m^3 s^{-1}$) and sediment to adjacent wetlands (e.g., Snedden et al., 2007; Day et al., 2009, 2012).

Coastal wetland surface elevation is one of the most conspicuous indicators of coastal stability (Day et al., 2001; Cahoon et al., 2006; Lane et al., 2006; Mariotti and Fagherazzi, 2013). The impact of sea-level rise (SLR) on the sustainability of coastal wetlands is a worldwide concern (Simas et al., 2001; Van Wijnen and Bakker, 2001; Day et al., 2005; Swanson et al., 2013). With accelerated eustatic SLR (ESLR) more coastal wetlands will suffer increased flooding duration, erosion, and saltwater intrusion all of which affect vegetation health, growth and distribution, or lead to vegetation collapse, and eventually result in loss of wetlands (e.g., Day et al., 2005; Blankespoor et al., 2012). For coastal wetlands to be maintained or new wetlands to be built under future climate change and relative SLR (RSLR = ESLR + subsidence), surface elevation must increase via vertical accretion from transport, deposition and accumulation of both mineral sediment and organic matter at sufficient rates to offset RSLR (Mossa and Roberts, 1990; Day et al., 1997; Simas et al., 2001; Van Wijnen and Bakker, 2001; Lane et al., 2006; Paola et al., 2011; Callaway et al., 2012; Dean et al., 2012; Swanson et al., 2013). Therefore, coastal restoration and protection projects should consider the impact of RSLR in the assessment and prediction of the benefit and cost of restoration and protection efforts (Day et al., 2005; Blankespoor et al., 2012). River diversions can nourish wetlands with freshwater, sediment, and nutrients for decades, ultimately providing a lower cost and longer sustainability for created wetlands than methods such as dredged and pipelined sediment marsh creation (Day et al., 2005). This is because marshes created by those non-diversion methods tend to decay with the effect of RSLR immediately after placement (e.g., Orr et al., 2003; Day et al., 2005).

There have been limited studies on the impacts of sediment diversions on receiving basin surface elevation and vertical accretion in the context of future RSLR. The few existing studies provide critical information on diversion impacts, yet these studies focus on site-specific or project scales with intrinsic limitations for landscape-scale assessment (e.g., DeLaune et al., 2003; Lane et al., 2006; Day et al., 2013). Landscape-level assessments are critical to adaptively manage large sediment diversions over a broad coastal region (Allison and Meselhe, 2010; Allison et al., 2012; Teal et al., 2012). The 2012 Louisiana Coastal Master Plan modeling study provides an excellent opportunity to examine these issues on a landscape scale (Peyronnin et al., 2013). Potential diversion locations, discharge rates, and other features were incorporated and simulated with the Eco-Hydrology, Wetland Morphology, and Vegetation models under scenarios of future environmental changes (Couvillion et al., 2013; Meselhe et al., 2013; Visser et al., 2013). Numerical models of hydrodynamics, wetland morphology, and vegetation in the sediment-receiving basins offer an approach to adequately assess wetland geomorphology and ecosystem services across landscapes (Steyer et al., 2012; Couvillion et al., 2013; Rivera-Monroy et al., 2013). In this study, our overall objective is to use the outputs from model simulations of selected individual sediment diversion projects from the 2012 Coastal Master Plan wetland morphology modeling study (Steyer et al., 2012; Couvillion et al., 2013) to quantify diversion effects on landscape-scale surface elevation and vertical accretion in the Mississippi River Deltaic Plain under future environmental scenarios. Specifically, we address the following questions:

(1) Do sediment diversions promote vertical accretion and elevation gain on a landscape scale?
(2) What are the placement locations that best optimize land-building within the receiving hydrologic basin?
(3) What diversion discharge rates are necessary to achieve a landscape-scale elevation gain which keeps pace with RSLR, or reduces elevation loss to slow down wetland loss in the future?
(4) How are the magnitudes of elevation gain and vertical accretion affected by receiving basin characteristics?

## 2. Methods

### 2.1. Study area

The study area covers the Mississippi River Deltaic Plain along the southeast coast of Louisiana (Fig. 1). This region is formed by sediments from the Mississippi River and the Atchafalaya River (Day et al., 2000). Within this study area, there are six hydrologic basins, separated largely by current or abandoned distributary channels and their adjacent levee deposits (Day et al., 2000). Vegetation is classified into five zones seaward along a gradient of increasing salinity: forested wetlands, fresh, intermediate, brackish, and saline marshes. We focused our analyses on three major basins: Atchafalaya Delta, Barataria, and Breton Sound basins since a majority of sediment diversions in the 2012 Coastal Master Plan are proposed in these basins (Peyronnin et al., 2013).

### 2.2. The surface elevation model

We developed a spatial wetland morphology model for the 2012 Coastal Master Plan (http://www.coastalmasterplan.louisiana.gov/) (Steyer et al., 2012; Couvilion et al., 2013). The wetland morphology model has been calibrated and validated for vertical accretion using both long-term (e.g., $^{137}Cs$ dating from Piazza et al., 2011) and short-term (e.g., feldspar measurements from the Coast-wide Reference Monitoring System – CRMS, http://www.lacoast.gov/crms2/Home.aspx) field data as well as literature values (Steyer et al., 2012; Couvillion et al., 2013). The wetland morphology model is comprised of relative elevation and landscape change sub-models. The simulation results of these diversions at a spatial resolution of 30 m are used for analyses in this study. Herein we briefly describe the governing equations and assumptions of the surface elevation sub-model.

Wetland surface elevation dynamics is estimated using the following equation:

$$E_{yr2} = E_{yr1} + 0.01*(H - S) \quad (1)$$

Where $E_{yr2}$ is adjusted surface elevation at Year 2 (m NAVD 88); $E_{yr1}$ is surface elevation at Year 1 (m NAVD 88); $H$ is vertical accretion rate (cm $yr^{-1}$); $S$ is subsidence rate (cm $yr^{-1}$); and 0.01 is a conversion (cm to m) factor.

Vertical accretion ($H$) is estimated by:

$$H = \frac{Q_{sed} + Q_{org}}{10,000*BD} \quad (2)$$

where $Q_{sed}$ is mineral sediment accumulation rate (g $m^{-2}$ $yr^{-1}$), $Q_{org}$ is organic matter accumulation rate (g $m^{-2}$ $yr^{-1}$); the constant 10,000 is a conversion factor (from $m^2$ to $cm^2$); and BD is soil bulk density (g $cm^{-3}$). This equation was based on the assumption that vertical accretion can be described by accumulation of both mineral sediment and organic matter, and soil bulk density at equilibrium. If equilibrium cannot be reached, then representative

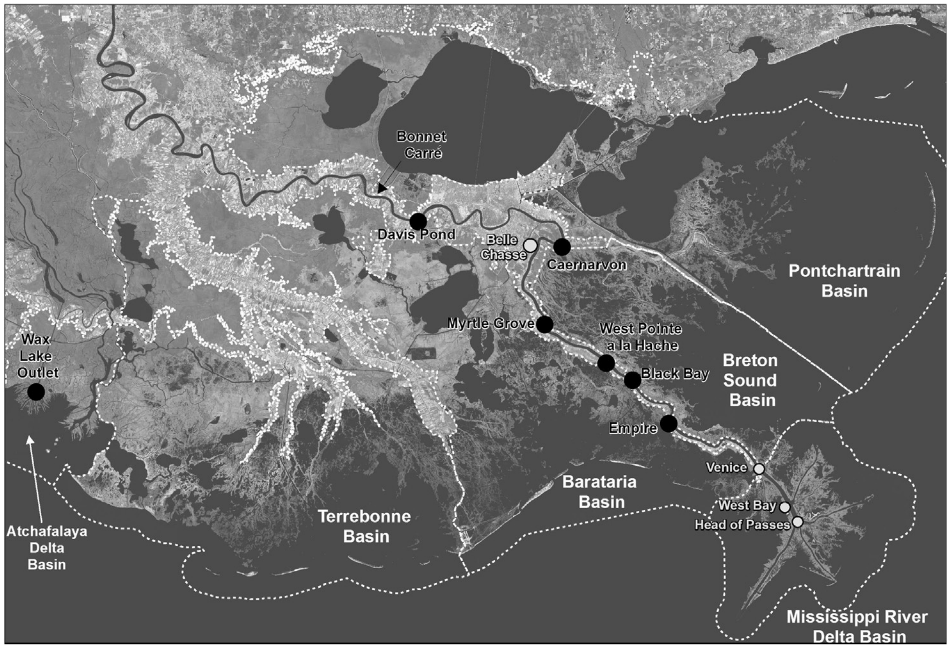


**Fig. 1.** Study area and selected sediment diversions along the lower Mississippi River and Atchafalaya River for the assessment of basin-wide elevation and vertical accretion.

BD values have to be derived from calibration process (Steyer et al., 2012).

Organic matter accumulation rate ($Q_{org}$) is estimated by:

$$Q_{org} = Q_{sed} * \frac{F_{org}}{F_{min}} \quad (3)$$

where $F_{org}$ is the fraction of organic matter mass in total soil mass at equilibrium, which is equivalent to organic matter content (OM%) divided by 100; and $F_{min}$ is the fraction of inorganic matter mass in total soil mass ($1 - F_{org}$) at equilibrium. This method assumes that site specific organic matter accumulation can be derived from the relationship between long-term mineral matter accumulation and organic matter accumulation at equilibrium, and when no organic matter accumulation occurs when mineral material accumulation is zero. As such, the model tends to underestimate observed accretion rates by approximately 22% (Couvillion et al., 2013). Vertical accretion rates could be underestimated in areas of low mineral sedimentation, but there is high organic accumulation due to significant contribution of vegetative growth to accretion (Nyman et al., 2006).

### 2.3. Individual sediment diversion projects

In this study, we selected ten sediment diversion projects (Table 1) to assess their impacts on wetland surface elevation and vertical accretion at basin (>1000 km$^2$) and sub-basin (>100 km$^2$) scales. Diversion projects discharge ranged from 142 to 7080 m$^3$ s$^{-1}$. We defined three scales of sediment diversions based on previous studies (Allison and Meselhe, 2010; Day et al., 2012; Meselhe et al., 2012; Allison et al., 2012, 2013): (1) large: diversion discharge >1416, up to 7080 m$^3$ s$^{-1}$; (2) medium: >283–1415 m$^3$ s$^{-1}$; and (3) small: ≤283 m$^3$ s$^{-1}$. See Peyronnin et al. (2013) and Louisiana Coastal Master Plan (2012, http://www.coastalmasterplan.louisiana.gov/) for details on design, assumptions and other characteristics of diversion projects.

### 2.4. Future environmental scenarios

In the 2012 Coastal Master Plan modeling study, a number of parameters with associated uncertainty were identified including ESLR, subsidence, hurricane/storm intensity and frequency, Mississippi River discharge, rainfall, evapotranspiration, Mississippi River nutrient concentrations (e.g., nitrogen and phosphorus) and marsh collapse thresholds (e.g., salinity and inundation regimes). Parameter uncertainty and range in the next 50 years (2010–2060) were determined from previous studies and best professional judgment for Louisiana coastal wetlands. Two future environmental change scenarios were selected: Moderate and Less Optimistic, and were used in the wetland morphology model simulations (Table 2).

### 2.5. Calculations of landscape effects

We calculated average surface elevation (m, NAVD 88) at the end of the simulation period (Year 2060) and changes with respect to the initial year (year 2010) across selected hydrologic basin and sub-basins where the individual sediment diversion structures are located. Surface elevation changes in 2060 between scenarios with diversions and future without action (FWOA) condition were also determined to assess the elevation changes due solely to diversion measures. The zonal statistics tool in ArcGIS was used to calculate the basin-wide and sub-basin-wide average surface elevation in 2010 and 2060 and the average vertical accretion during the 50 year modeling period.

The effects of sediment diversions on wetland surface elevation and vertical accretion were evaluated under the following criteria:

1) *Diversions and FWOA condition*: we selected diversions at Myrtle Grove in Barataria Basin, Caernarvon in Breton Sound Basin, and Wax Lake in Atchafalaya Delta Basin to compare basin-wide changes in average elevation and vertical accretion under FWOA and diversion conditions.
2) *Location effect*: we selected diversions in Barataria Basin (downriver order: Myrtle Grove, West Pointe a la Hache, and Empire) with the same discharge rate of 1416 m$^3$ s$^{-1}$ and in Breton Sound Basin (downriver order: Caernarvon and Black Bay) with the same discharge rate of 7080 m$^3$ s$^{-1}$ to examine basin-wide average elevation changes and vertical accretion rates over the 50 year modeling period (Fig. 1).

**Table 1**
Features of selected individual diversion projects in the 2012 Coastal Master Plan.

| Diversion | Basin | Description | Peak discharge ($m^3$ $s^{-1}$) |
|---|---|---|---|
| Wax Lake Delta | Atchafalaya Delta | Wax Lake Delta Diversion, 4248 $m^3$ $s^{-1}$ Capacity (60% Mississippi/40% Atchafalaya) | 4248 |
| Myrtle Grove | Barataria | Myrtle Grove Diversion, 7080 $m^3$ $s^{-1}$ Capacity (operation at capacity when Mississippi River flow exceeds 25,485 $m^3$ $s^{-1}$; operation at 1416 $m^3$ $s^{-1}$ for flows from 25,485 down to 16,990 $m^3$ $s^{-1}$; operation at 8% of river flow for river flows from 16,990 down to 5663 $m^3$ $s^{-1}$, no operation below 5663 $m^3$ $s^{-1}$) | 7080 |
| Myrtle Grove | Barataria | Myrtle Grove Diversion, 142 $m^3$ $s^{-1}$ Capacity (continuous operation at capacity for river flows above 5663 $m^3$ $s^{-1}$, no operation below 5663 $m^3$ $s^{-1}$) | 142 |
| Myrtle Grove | Barataria | Myrtle Grove Diversion, 1416 $m^3$ $s^{-1}$ Capacity (operation at capacity when Mississippi River flow exceeds 16,990 $m^3$ $s^{-1}$; operation at 8% of river flow from 16,990 down to 5663 $m^3$ $s^{-1}$, no operation below 5663 $m^3$ $s^{-1}$) | 1416 |
| West Point a la Hache | Barataria | West Pointe a la Hache Diversion, 1416 $m^3$ $s^{-1}$ Capacity (operation at capacity when Mississippi River flow exceeds 16,990 $m^3$ $s^{-1}$; operation at 8% of river flow from 16,990 down to 5663 $m^3$ $s^{-1}$, no operation below 5663 $m^3$ $s^{-1}$) | 1416 |
| Empire | Barataria | Empire Diversion, 1416 $m^3$ $s^{-1}$ Capacity (operation at capacity when Mississippi River flow exceeds 16,990 $m^3$ $s^{-1}$; operation at 8% of river flow from 16,990 down to 5663 $m^3$ $s^{-1}$, no operation below 5663 $m^3$ $s^{-1}$) | 1416 |
| Davis Pond | Barataria | Davis Pond Diversion, 302 $m^3$ $s^{-1}$ Capacity (operation of existing structure at capacity) | 302 |
| Caernarvon | Breton Sound | Caernarvon Diversion, 1416 $m^3$ $s^{-1}$ Capacity (operation at capacity when Mississippi River flow exceeds 16,990 $m^3$ $s^{-1}$; operation at 8% of river flow from 16,990 down to 5663 $m^3$ $s^{-1}$, no operation below 5663 $m^3$ $s^{-1}$) | 1416 |
| Caernarvon | Breton Sound | Caernarvon Diversion, 7080 $m^3$ $s^{-1}$ Capacity (70% Mississippi/30% Atchafalaya) (operation at capacity when Mississippi River flow exceeds 25,485 $m^3$ $s^{-1}$; operation at 1416 $m^3$ $s^{-1}$ for flows from 25,485 down to 16,990 $m^3$ $s^{-1}$; operation at 8% of river flow for river flows from 16,990 down to 5663 $m^3$ $s^{-1}$, no operation below 5663 $m^3$ $s^{-1}$ [to be modeled under 70/30 Mississippi/Atchafalaya allocation]) | 7080 |
| Black Bay | Breton Sound | Black Bay Diversion, 7080 $m^3$ $s^{-1}$ Capacity (60% Mississippi/40% Atchafalaya) (operation at capacity when Mississippi River flow exceeds 25,485 $m^3$ $s^{-1}$; operation at 1416 $m^3$ $s^{-1}$ for flows from 25,485 down to 16,990 $m^3$ $s^{-1}$; operation at 8% of river flow for river flows from 16,990 down to 5663 $m^3$ $s^{-1}$, no operation below 5663 $m^3$ $s^{-1}$ [to be modeled under 60/40 Mississippi/Atchafalaya allocation]) | 7080 |

3) *Magnitude of discharge effect*: we selected Myrtle Grove in Barataria Basin and Caernarvon in Breton Sound Basin and used three diversion discharge rates in each basin: 142, 1,416, and 7080 $m^3$ $s^{-1}$ to examine basin-wide changes in elevation and vertical accretion under different diversion discharge rates.

4) *Receiving-basin effect*: we selected the Caernarvon diversions at two discharge rates: 1416 and 7080 $m^3$ $s^{-1}$ at each of three sub-basins in Breton Sound Basin (i.e., upper, middle, and lower Breton Sound Basins covering an area range of 395, 440, and 960 $km^2$). The three sub-basins have different topography/bathymetry, geometry, vegetation and soil properties. Thus, we were able to determine the spatial variations in sub-basin average elevation change and vertical accretion dynamics contrasting medium and large sediment diversions.

## 3. Results and discussion

### 3.1. Diversion vs. future without diversion

Model results indicate that the basin-wide average elevation gains during the next 50 years might be difficult to achieve, and if achievable, it would be far less than the ESLR under two future environmental scenarios (Table 3). For example, simulated elevation change over the 50 years under FWOA and diversion conditions tend to be negative (−0.01 to −0.30 m) except the Wax Lake diversion at 4248 $m^3$ $s^{-1}$ under Moderate Scenario (a slight elevation increase of 0.01 m, Table 3). These values indicate a trend of elevation loss (or elevation deficit) rather than elevation gain at a hydrologic basin scale, although a trend of elevation gain under diversion is possible at a local or project scale. A local or project scale assessment may give us biased estimates of diversion effects over a large region if the study sites selected are not well spatially distributed. Our high resolution (30-m) spatial modeling approach can help us to detect the spatial variability in sediment deposition, accretion and elevation change more accurately than a spatially-lumped modeling approach. Further, simulated landscape-scale vertical accretion rates (0.15–0.66 cm $yr^{-1}$) tend to be insufficient to keep pace with RSLR (0.74–2.0 cm $yr^{-1}$, Table 3). These results confirm the current elevation deficit leading to coast-wide wetland loss estimated by other studies including the Coast 2050 Report (Reed and Wilson, 2004), the Coastal Louisiana Ecosystem Assessment and Restoration Program (CLEAR, Twilley et al., 2008), and more recently, the 2012 Coastal Master Plan (Steyer et al., 2012; Couvillion et al., 2013). As mentioned before, the surface elevation model is conservative and tends to underestimate observed accretion rates (e.g., Nyman et al., 1990, 1993, 2006; DeLaune et al., 2003; Day et al., 2013).

Basin-wide elevation loss can be reduced by 0.02–0.16 m under a future with sediment diversion compared to the FWOA condition (Table 3). For example, the proposed Caernarvon diversion at 7080 $m^3$ $s^{-1}$ in the Breton Sound Basin could bring relative elevation gains of 0.16 m and 0.15 m at a basin scale, which are approximately 59% and 33% of ESLR (0.27 m and 0.45 m) for Moderate and Less Optimistic Scenarios, respectively (Table 3). Compared to FWOA, sediment diversions could increase basin-wide average vertical accretion rates from 2% to 31% with the highest increase occurring with large sediment diversions (Table 3). While basin-wide elevation loss is still occurring, there are large gains occurring in the areas closer to the diversion. The gains are only proportional to the sediments available. Thus, over a large area, the net outcome may be an elevation loss, even though the diversion results in land and elevation gain near the diversion location.

Model results indicate that under the moderate scenario, the Wax Lake diversion at 4248 $m^3$ $s^{-1}$, although smaller in diversion capacity compared to the Caernarvon at 7080 $m^3$ $s^{-1}$ in Breton Sound Basin, could increase basin-wide vertical accretion by ∼31% compared to ∼25% by the Caernarvon diversion (Table 3). The Wax Lake diversion discharge rate will most likely deliver more mineral sediments because during a limited period in a year (often <30

**Table 2**
Environmental uncertainty parameters and the two scenarios used in the model simulations.

| Environmental uncertainty | Plausible range | Moderate scenario | Less optimistic scenario |
|---|---|---|---|
| Sea level rise | 0.16–0.8 m over 50 years | 0.27 m over 50 years | 0.45 m over 50 years |
| Subsidence | 0 to 3.5 cm $yr^{-1}$; varies spatially | 0 to 1.9 cm $yr^{-1}$ (values vary spatially) | 0 to 2.5 cm $yr^{-1}$ (values vary spatially) |
| Storm intensity | Current storm intensities to +30% of current intensities | +10% of current intensities | +20% of current intensities |
| Storm Frequency | −20% to +10% of current storm frequency | Current storm frequency; (One Category 3 or greater storm every 19 yr) | +2.5% of current storm frequency; (One Category 3 or greater storm every 18 yr) |
| Mississippi River discharge | −7% to +14% of annual mean discharge; adjusted for seasonality | Mean annual discharge (15,121 $m^3 s^{-1}$) | −5% of mean annual discharge (14,413 $m^3 s^{-1}$) |
| Rainfall | Historical monthly range; varies spatially | Variable percentage of historical monthly mean | Variable percentage of historical monthly mean |
| Evapo-transpiration | Historical monthly range (+/−1 SD); varies spatially | Historical monthly mean (values vary spatially) | +0.4 SD from historical mean monthly (values vary spatially) |
| Mississippi River nutrient concentration | −45% to +20% of current nitrogen & phosphorus concentrations | −12% of current concentrations (mg/L)<br>Phosphorus = 0.19<br>Nitrite + Nitrate = 1.1<br>Ammonium = 0.038<br>Org. Nitrogen = 0.67 | Current concentrations (mg/L)<br>Phosphorus = 0.22<br>Nitrite + Nitrate = 1.3<br>Ammonium = 0.044<br>Org. Nitrogen = 0.77 |
| Marsh collapse threshold | Salinity (ppt)<br>Swamp: 4–7<br>Fresh Marsh: 6–8<br>Inundation (water depth, cm)<br>Intermediate Marsh: 31–38<br>Brackish Marsh: 20–26<br>Saline Marsh: 16–23 | Mid-range values of salinity and inundation result in collapse<br>Salinity (ppt)<br>Swamp: 6<br>Fresh Marsh: 7<br>Inundation (cm)<br>Intermediate Marsh: 34<br>Brackish Marsh: 23<br>Saline Marsh: 21 | Lower 25th percentile values of salinity and/or inundation ranges result in collapse<br>Salinity (ppt)<br>Swamp: 5<br>Fresh Marsh: 7<br>Inundation (cm)<br>Intermediate Marsh: 33<br>Brackish Marsh: 21<br>Saline Marsh: 18 |

days) the discharge in the lower Mississippi River exceeds 25,485 $m^3 s^{-1}$. The Atchafalaya Delta Basin, containing the Atchafalaya River delta and the Wax Lake delta, has been gaining wetlands for approximately the past 40 years (e.g., Blum and Roberts, 2009) at a rate of 1–3 $km^2$ per year (Allen et al., 2012). It is the only basin that has net wetland building even under the FWOA condition (Couvillion et al., 2013).

Our study suggests that sediment diversions have landscape benefits by mitigating wetland loss along the Louisiana coast in the coming decades. Previous studies have shown that the increase in vertical accretion is attributed to the direct addition of mineral sediment to the marsh surface as well as stimulated plant production (DeLaune et al., 2003; Day et al., 2013). Increases in aboveground and belowground plant production trap and hold mineral sediments on the marsh surface and increase soil organic matter accumulation (Teal et al., 2012; Day et al., 2013). Existing field studies have also shown the potential role of diversions in increasing vertical accretion (DeLaune et al., 2003; Lane et al., 2006; Day et al., 2012, 2013). DeLaune et al. (2003) used a combination of feldspar marker horizon (short-term: <2 yr) and $^{137}Cs$ dating (long-term) measurements at 20 sites to examine the influence of the Caernarvon Diversion on long-term and short-term vertical accretion in Breton Sound Basin. In their study multiple sites were grouped into upper and lower basins based on the distance to the currently in operation Caernarvon Diversion (capacity: 226 $m^3 s^{-1}$, operation range: 14–114 $m^3 s^{-1}$). Accretion rates were significantly higher with values ranging from 0.83 cm $yr^{-1}$ (long-term) to 1.72 cm $yr^{-1}$ (short-term) in the upper basin while in the lower basins rates values were from 0.66 cm $yr^{-1}$ (long-term) to 1.34 cm $yr^{-1}$ (short-term). Both short and long term estimations

**Table 3**
Simulated basin-wide surface elevation change and vertical accretion rates with river diversions and future without action (FWOA) under two environmental change scenarios.

| Basin | Discharge ($m^3 s^{-1}$) | Elevation (m, NAVD 88) | | | | Accretion | | RSLR (ESLR + subsidence) (cm $yr^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| | | 2010 | 2060 | Net change (2060-2010) | Net change (Diversion-FWOA) | Average (cm $yr^{-1}$) | Change % [(diversion-FWOA)/FWOA] | |
| Moderate Scenario | | | | | | | | |
| Barataria | FWOA | −1.62 | −1.73 | −0.11 | | 0.51 | | 1.24 |
| | Myrtle Grove (142) | −1.62 | −1.71 | −0.09 | 0.02 | 0.52 | 1.55 | 1.24 |
| | Davis Pond (302) | −1.62 | −1.69 | −0.06 | 0.05 | 0.52 | 1.41 | 1.24 |
| Breton Sound | FWOA | −1.26 | −1.43 | −0.17 | | 0.53 | | 1.14 |
| | Caernarvon (7080) | −1.26 | −1.27 | −0.01 | 0.16 | 0.66 | 24.71 | 1.14 |
| Atchafalaya Delta | FWOA | 2.90 | 2.83 | −0.06 | | 0.15 | | 0.74 |
| | Wax Lake (4248) | 2.90 | 2.91 | 0.01 | 0.07 | 0.19 | 30.79 | 0.74 |
| Less Optimistic Scenario | | | | | | | | |
| Barataria | FWOA | −1.62 | −1.90 | −0.27 | | 0.56 | | 2.00 |
| | Myrtle Grove (142) | −1.62 | −1.88 | −0.25 | 0.02 | 0.58 | 3.09 | 2.00 |
| | Davis Pond (302) | −1.62 | −1.85 | −0.23 | 0.04 | 0.58 | 3.16 | 2.00 |
| Breton Sound | FWOA | −1.26 | −1.56 | −0.30 | | 0.54 | | 1.80 |
| | Caernarvon (7080) | −1.26 | −1.41 | −0.16 | 0.15 | 0.65 | 20.76 | 1.80 |
| Atchafalaya Delta | FWOA | 2.90 | 2.76 | −0.14 | | 0.15 | | 1.20 |
| | Wax Lake (4248) | 2.90 | 2.89 | −0.01 | 0.13 | 0.18 | 21.98 | 1.20 |

Note: simulated elevation change, adjusted by vertical accretion and subsidence, should be compared to ESLR; vertical accretion should be compared to RSLR for wetland sustainability assessment.

represented increases of approximately 28% and 20%, respectively. Further mineral sediment accumulation in the upper basin averaged 1985 g $m^{-2}$ $yr^{-1}$ compared to 572 g $m^{-2}$ $yr^{-1}$ in the lower basin. This major spatial difference in annual accumulation is due to cumulative input of sediment from the diversion as indicated by increased soil bulk density which went from 0.11 g $cm^{-3}$ to 0.30 g $cm^{-3}$ (DeLaune et al., 2003). Similarly, organic matter accumulation also increased in the upper basin (937 g $m^{-2}$ $yr^{-1}$) compared to the lower basin (566 g $m^{-2}$ $yr^{-1}$) as a result of enhanced vegetation growth and productivity (DeLaune et al., 2003). Day et al. (2013) reported that the highest vertical accretion rate (1.24 cm $yr^{-1}$, feldspar measurement during 2006–2007) was also found at a site nearest the Caernarvon diversion which was receiving sediment directly from the diversion. Although no significant correlation between accretion and belowground productivity was observed, the near site had a much greater net belowground productivity (14,485 g $m^2$ $yr^{-1}$) than another sampling site located further down the diversion (4776 g $m^2$ $yr^{-1}$) (Day et al., 2013). Yet, these field data cannot be compared directly with our simulated basin-wide elevation and vertical accretion values because it is difficult to extrapolate site-specific rates to the landscape level rates estimated by our model. In addition, higher ESLR (0.54 and 0.9 cm $yr^{-1}$ for Moderate and Less Optimistic scenarios) rather than current ESLR ($\sim$0.31 cm $yr^{-1}$ or less) rates were used in model simulations.

### 3.2. Location effect

Model results indicate that when river sediment is diverted at the same discharge rate, the location of the proposed diversion structure plays a major role in defining changes in average elevation and accretion rates at the basin-wide scale. A trend of decrease in diversion benefits is observed from Myrtle Grove, West Pointe a La Hache, and Empire down the lower Mississippi River (Fig. 1). Placing the diversion at a discharge rate of 1416 $m^3$ $s^{-1}$ next to Myrtle Grove located within the Barataria Basin would prevent elevation loss by 0.04 m under both Moderate and Less Optimistic scenarios as compared to an elevation loss of 0.03 m at other locations (Fig. 2). This difference in diversion placement demonstrates that other factors such as spatial variability in initial elevation, bathymetry, and a network of distributaries within the Barataria Basin would also account for the difference in the realized basin-wide elevation change. These simulations of basin-wide vertical accretion rates tend to increase from $\sim$6% to $\sim$12% when compared to a FWOA condition (Fig. 2). Nevertheless, these simulation results in the Barataria Basin do not show a clear trend when assessing diversion location effect. This result reflects the spatial variations in complex sedimentary processes from river sediment extraction to sediment deposition and accumulation in soils.

If a large sediment diversion were to be placed in Breton Sound Basin, placing the diversion at or near existing Caernarvon structure would have a larger positive effect on reducing an elevation deficit than placing the diversion down the Mississippi River at Black Bay (Figs. 1 and 2). Increases in basin-wide average elevation compared to FWOA could be 0.16 m and 0.08 m under Moderate and Less Optimistic scenarios, respectively. The simulated basin-wide average vertical accretion rate represented an increase of >20% as compared to the FWOA condition. However, we did not identify a clear decreasing trend in vertical accretion rates from the Caernarvon diversion down to the Black Bay diversion as expected (Fig. 2). Although changes in accretion tend to be similar at both Caernarvon and Black Bay ($\sim$24%) under the moderate scenario and smaller at Caernarvon than at the Black Bay under the less optimistic scenario, placing a large sediment diversion at Caernarvon, instead of at Black Bay, would almost double the effect of reducing basin-wide average elevation loss.

The net volume of sediment supply received from the river is closely related to location as is sediment deposition, retention and accumulation by the receiving wetland vegetation, when present. Previous studies have shown that sediment supply follows a decreasing availability along the lower Mississippi River due to the presence of dams in the upper Mississippi Basin that influence water flow and associated sediment (Blum and Roberts, 2009; Allison and Meselhe, 2010; Allison et al., 2012). One of the focus areas for the implementation of sediment diversions proposed in the 2012 Coastal Master Plan is the lower Mississippi River at the stretch between the Belle Chasse area and the Head of Passes reach (Fig. 1) (Allison and Meselhe et al., 2012; Allison et al., 2012). A detailed suspended sediment budget analysis for the lower Mississippi-Atchafalaya River in flood years during the period of 2008–2010 (Allison et al., 2012) suggests that approximately 45% of the annual water and 43% of the sediment passing Belle Chasse was diverted throughout the exits above Head of Passes. Further, most of the sediment (mainly sand) was lost to channel aggradation that may cause shoaling due to the reduction in stream power (Allison et al., 2012). In fact, sediment transport through these proposed diversions below Venice would be reduced and limited to high flow discharge phases (Allison and Meselhe et al., 2012), resulting in a relatively small proportion of the upstream sediment load available for coastal restoration at locations near the Gulf of Mexico.

The West Bay Sediment Diversion located below Venice (Fig. 1) is designed to deliver sediment, especially sand, to the open water in West Bay in order to re-build land (Kolker et al., 2012; Teal et al., 2012). Kolker et al. (2012) found that between 2003 and 2009, the West Bay sediment diversion resulted in sediment accumulation rates as high as 3 cm $yr^{-1}$ thus matching or exceeding the low-end estimated regional RSLR (2.6 cm $yr^{-1}$), but not the upper predicted RSLR rate (3.4 cm $yr^{-1}$). Based on these rates, it would take a few decades to observe the formation of sub-aerial land in West Bay due to the deep water depth (4.6 m), open geometry, high bottom slope, relative high land subsidence ($\sim$3.5 cm $yr^{-1}$), and low hydraulic head available to move sediment out of the river (Allison and Meselhe et al., 2012; Dean et al., 2012; Kolker et al., 2012). Using two geometric models, the truncated cone geometry (uniform depth) and uniform width models, Dean et al. (2012) showed that diversions above Myrtle Grove would be favorable for building new wetlands but unfavorable below this location. Our analyses of the effects of location on the effectiveness of sediment diversions provide supporting evidence of the reduced diversion benefits (i.e., reducing elevation loss) at the lower Mississippi River region.

### 3.3. Magnitude of discharge effect

Model results show that basin-wide average elevation and vertical accretion rates would increase with the magnitude in river discharge at Myrtle Grove (Barataria Basin) and Caernarvon regions (Breton Sound Basin) under both Moderate and Less Optimistic scenarios (Fig. 3). The Barataria basin-wide average elevation loss would be reduced by 0.02 m, 0.04 m, and >0.07 m when discharge increased from 142 to 1416 to 7080 $m^3$ $s^{-1}$ (Fig. 3). Breton Sound basin-wide average elevation loss would be reduced by 0.07 m and 0.15 m when discharge increased from 1416 to 7080 $m^3$ $s^{-1}$ (Fig. 3). As expected, accretion rates tend to increase with the increase in diversion discharge, i.e., the higher the discharge, the higher the positive effect of the diversion. In addition, due to the area difference in the two basins (the Barataria Basin is larger than Breton Sound Basin), under the same large-scale diversion discharge

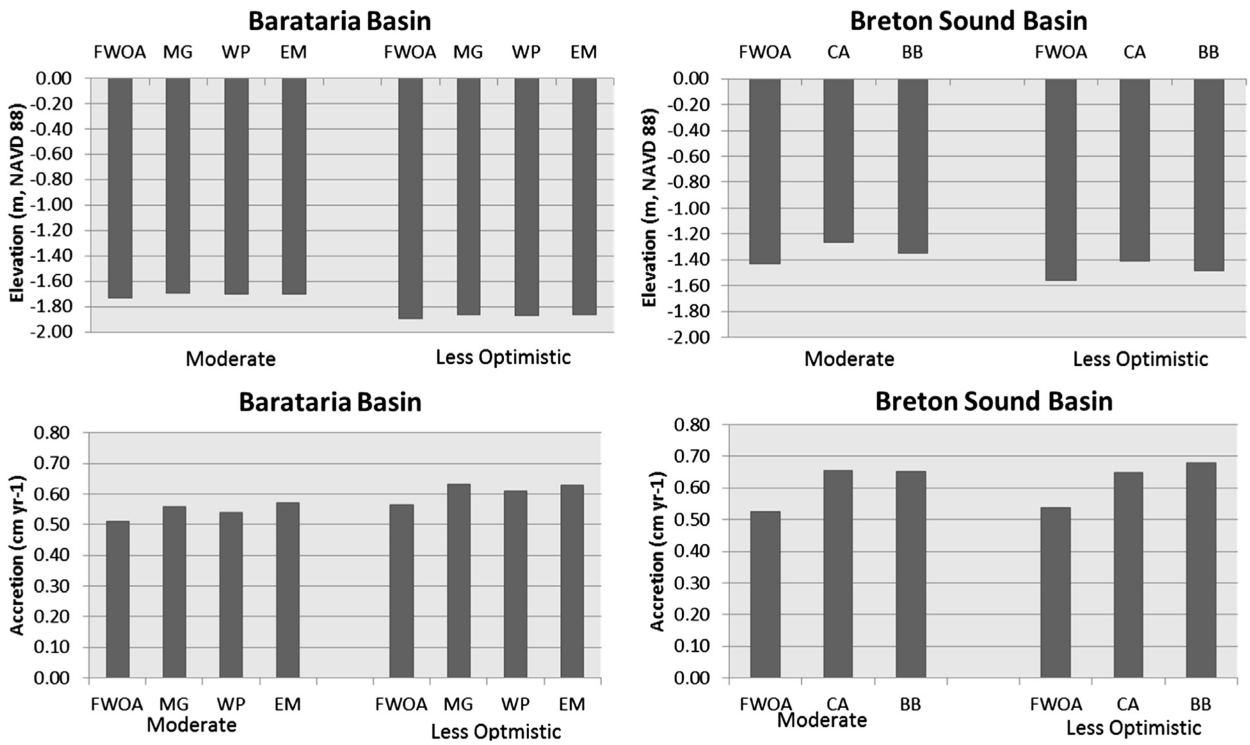


**Fig. 2.** Simulated basin-wide surface elevation at the end of simulations (Year 2060) and vertical accretion when diversions are placed at different locations but within the same hydrologic basins under two environmental change scenarios (note: FWOA = future without action; MG = Myrtle Grove; WP= West Pointe a la Hache; EM = Empire; CA= Caernarvon; BB= Black Bay. Subsidence rates for Barataria and Breton Sound basins in the model are 0.7 and 0.63 cm $yr^{-1}$ under Moderate Scenario, and 1.1 and 0.9 cm $yr^{-1}$ under Less Optimistic Scenario, respectively).

(7080 $m^3$ $s^{-1}$), large diversions in Barataria Basin would not produce the similar basin-wide average elevation gain (0.07–0.1 m compared to 0.15–0.16 m in Breton Sound Basin). As mentioned previously, even large diversions at 7080 $m^3$ $s^{-1}$ could not support basin-wide accretion rates (≤0.7 cm $yr^{-1}$) sufficient to keep pace with RSLR (>1.0 cm $yr^{-1}$) (Fig. 3).

Meselhe et al. (2012) found that given the same design involving diversion alignments and intake location, the higher the discharge of the diversion (425, 1275 and 2124 $m^3$ $s^{-1}$ at Myrtle Grove in Barataria Basin), the higher the sediment/water ratio (0.6, 0.93 and 1.12). This result implies that more riverine sediment can be captured and transported to the wetland surfaces. Data from monitoring stations along the Mississippi River also show that total suspended sediment (sand and mud) load increases with river discharge (e.g., Allison and Meselhe, 2010), with higher loads on the rising limb than the falling stage (Snedden et al., 2007). Sediment supply in the receiving basin is consistently greater during winter and spring (December to May) due to the combined effects of river discharge and re-suspension of sediments strongly influenced by meteorological conditions. During this period, winter cold-front passages serve as another factor enhancing sediment transport to coastal wetlands (Mossa and Roberts, 1990; Snedden et al., 2007; Day et al., 2013).

Diversion discharge should be high enough to ensure sheet flow to both transport and deposit sediment on the interior marsh surface and allow for vertical accretion (Snedden et al., 2007; Day et al., 2009, 2013). The discharge threshold to enhance vertical accretion was estimated at 100 $m^3$ $s^{-1}$ in the Caernarvon diversion region (Snedden et al., 2007). Below this threshold sheet flow in the upper estuary cannot be created during a diversion event; instead, sediment in diverted flow would be exported or deposited in channels or ponds (i.e., Bayou Mandeville and Delacroix Canal, Fig. 4) and not on the marsh surface (Snedden et al., 2007). Pulses of high discharge not only deliver large quantities of sediment to the Breton Sound estuary, but also provide a transport mechanism for river sediments to reach the marsh interior regions where mineral deposition is needed to offset RSLR (Snedden et al., 2007; Day et al., 2009).

Model results suggest that small diversions (<142 $m^3$ $s^{-1}$) in the Barataria Basin would produce limited basin-wide relative elevation gain (≤0.02 m) and low vertical accretion (<2%) under the two future environmental scenarios over the next 50 years (Fig. 3). This scenario is the result of reduced sediment supply reaching interior marshes (Lane et al., 2006; Snedden et al., 2007; Day et al., 2009). The Caernarvon diversion footprint (peak flow = 226 $m^3$ $s^{-1}$) is estimated to be within a 6-km radius from the diversion structure and closest to the edge of the channels. This footprint covers an area of ~57 $km^2$ and represents only 5.2% of the total area in Breton Sound estuary (~1100 $km^2$ of fresh, brackish, and saline marshes) (Wheelock, 2003; Snedden et al., 2007; Day et al., 2009, 2013). The delineation of the Breton Sound estuary in this study follows the Eco-Hydrology model boundary conditions used to simulate regional hydrological patterns (Fig. 4; ~1800 $km^2$) (Meselhe et al., 2013). Overall, previous studies indicate that only about 10–20% of the total sediment load directly reaches marsh surfaces in the upper Breton Sound Basin under current Caernarvon diversion operations (Lane et al., 2006; Day et al., 2009), but some sediments are likely delivered to the marsh surface by subsequent winter storms (Reed, 1989). Current annual sediment delivery rate (~$1.0 \times 10^5$ tons per year) from the Caernarvon diversion to the Breton Sound Basin is insufficient to offset the present rate of RSLR. However, sediment loads during spring pulses are able to reach about 10–15 km down the estuary (Lane et al., 2007). Therefore, if maximum relative elevation gain

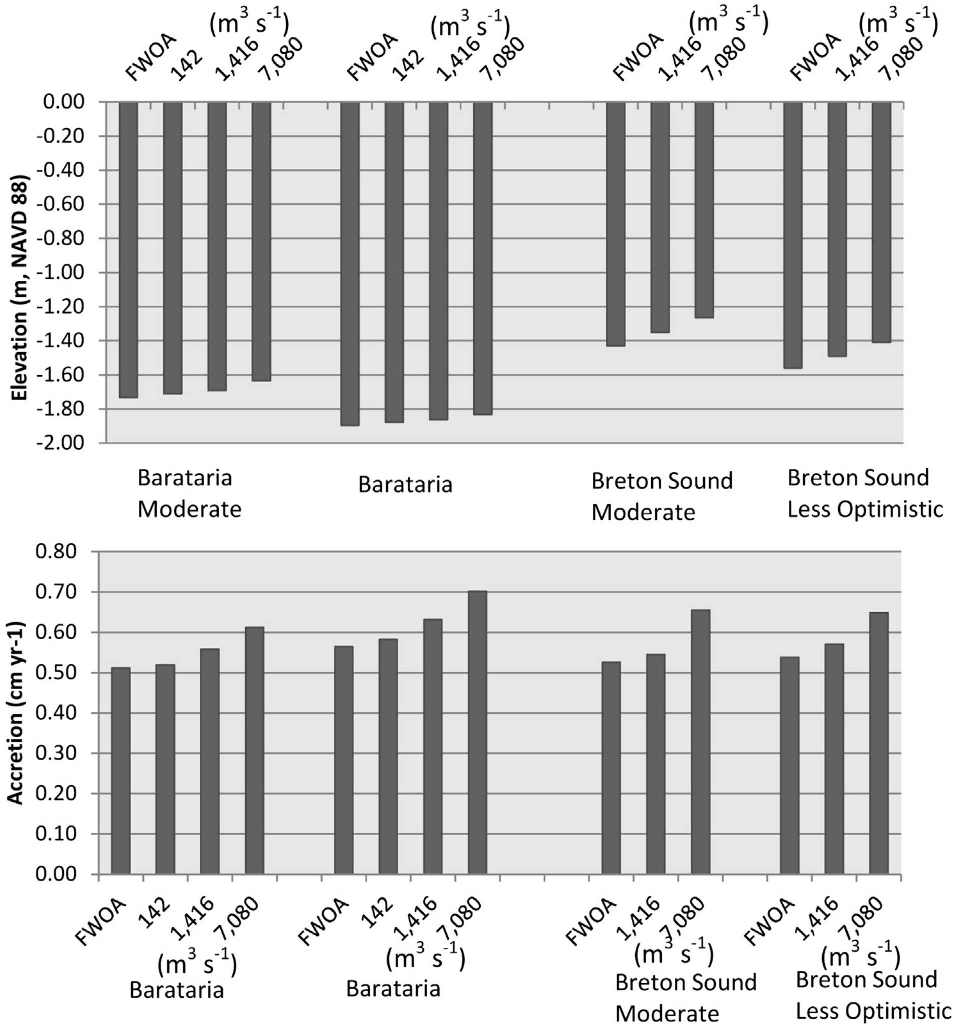


**Fig. 3.** Simulated basin-wide surface elevation at the end of simulations (Year 2060) and vertical accretion under different sizes of diversion discharge in Barataria and Breton Sound basins under two environment change scenarios (note: FWOA = future without action. Refer to Fig. 2 for subsidence rates used in the model for the two basins).

across the entire Breton Sound Basin is targeted, then large pulsed sediment diversions are needed.

The observed sediment delivery and accumulation which occurred at the Bonnet Carré Spillway after the opening during the 2011 Mississippi River Flood illustrates coastal land-building potential using large sediment diversions from the Mississippi River (Allison et al., 2012; Day et al., 2012; Nittrouer et al., 2012). Large sediment diversions could lead to higher rates of vertical accretion and elevation gain compared to wetlands that do not receive periodic input of Mississippi River water (Day et al., 2012). Therefore, the periodic, large diversion of river sediment can be effective in sustaining existing coastal wetlands. Day et al. (2012) found that the Bonnet Carré Spillway, as an example of a large diversion (peak discharge = 4500–9000 $m^3$ $s^{-1}$), led to higher vertical accretion rates ($^{137}Cs$ measurement: 2.6–2.8 cm $yr^{-1}$) in cypress swamp wetlands in the spillway than wetlands at LaBranche which is isolated from periodic sediment inputs from the Mississippi River water. Similar high accretion rates were observed in wetlands (0.43–1.4 cm $yr^{-1}$) isolated from sediment inputs from Lake Pontchartrain. Accretion in wetlands receiving large river diversion can keep up with not only current RSLR (>1 cm $yr^{-1}$), but also projected high RSLR (1.5–2.0 m) by 2100 based on a projected ESLR range of 0.4–1.0 m (1.5–2.5 cm $yr^{-1}$) (e.g., Day et al., 2012).

### 3.4. Receiving-basin effect

Medium and large sediment diversions at Caernarvon could produce elevation gains of 0.26 m and 0.63 m for the upper Breton Sound estuary. Model results indicate elevation gains at or greater than ESLR (0.27 m) over the next 50 years under the moderate scenario (Fig. 5). The 7080 $m^3$ $s^{-1}$ diversion could even increase elevation by 0.30 m for the middle Breton Sound estuary (Fig. 5), which is sufficient to keep pace with ESLR (0.27 m). Sub-basin-wide average accretion rates under this same diversion flow would be 1.36 and 0.98 cm $yr^{-1}$, representing increases of ~135% and 109% for the upper and middle Breton Sound estuaries, respectively (Fig. 5). Simulated vertical accretion rate for the upper estuary is higher than RSLR (1.1 cm $yr^{-1}$), and the simulated accretion rate for the middle estuary is close to the RSLR (1.04 cm $yr^{-1}$).

Under the less optimistic scenario, even a 7080 $m^3$ $s^{-1}$ diversion could not increase elevation to keep pace with ESLR (0.45 m) over the next 50 years (Fig. 5). Vertical accretion rates increased from 0.93 cm $yr^{-1}$ under the medium diversion (1416 $m^3$ $s^{-1}$) to 1.24 cm $yr^{-1}$ under the large (7080 $m^3$ $s^{-1}$) diversion for the upper Breton Sound estuary, yet this value was lower than expected RSLR (1.78 cm $yr^{-1}$). Simulation results also reveal that for the lower Breton Sound estuary under both future scenarios, potential

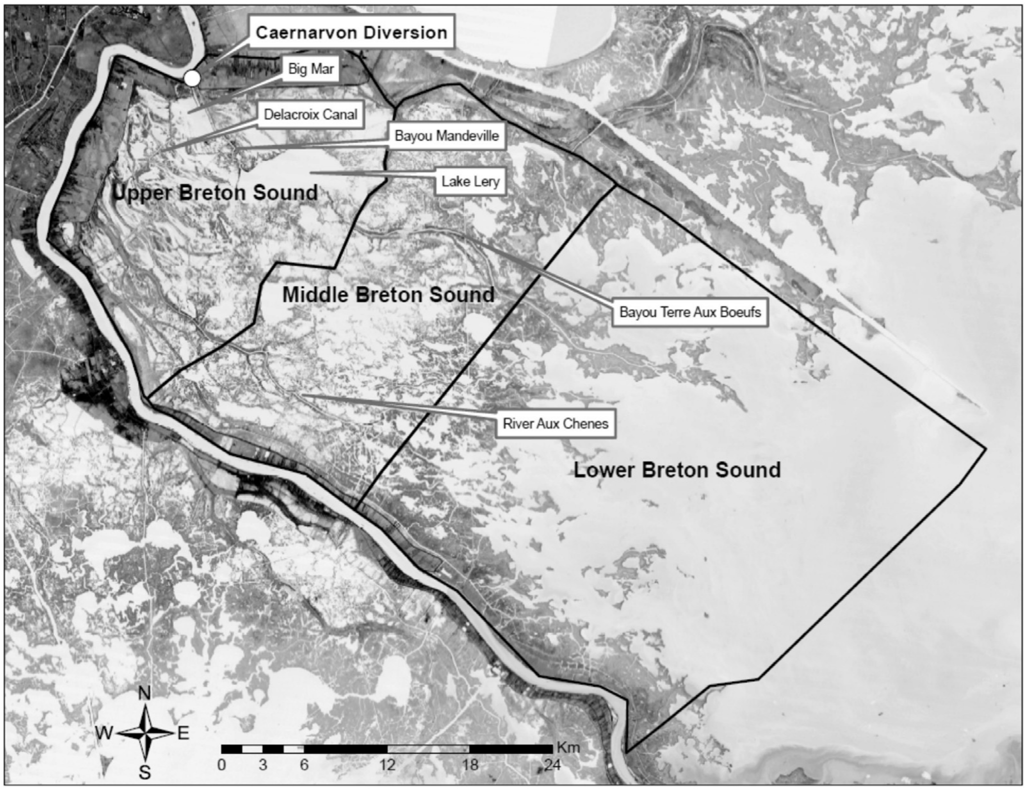


**Fig. 4.** Selected sediment diversions to Breton Sound estuary for sub-basin-scale analysis.

diversions could result in elevation loss from 0.01 to 0.08 m when compared to the FWOA condition (Fig. 5).

Sediment deposition and accumulation patterns within the receiving-basin depend on several factors including distance from the diversion structure, proximity to major water ways, presence of barriers to flows, topography, bathymetry, geometry, and openness to the ocean and to wind fetch (DeLaune et al., 2003; Lane et al., 2006; Day et al., 2012, 2013; Teal et al., 2012). For example, the 2010 baseline bathymetry and topography were substantially different among the three sub-basins. The percent land for the upper, middle and lower Breton Sound sub-basins were 62%, 47% and 20% and mean elevations were 0.22 m, 0.05 m and −0.90 m (NAVD 88), respectively. Our simulations indicate that diversions could reduce vertical accretion rates by 10–26% at the lower Breton Sound Basin compared to the FWOA condition (Fig. 5). This significant reduction is primarily due to the extraction of a larger amount of sediments from the Mississippi River that are delivered to and deposited in the upper and middle Breton Sound. In contrast, a reduced sediment load is potentially delivered to and deposited in the lower Breton Sound estuary under the FWOA condition (Meselhe et al., 2012). This scenario shows that the large sediment volume from a Mississippi River diversion would deposit and accumulate in the upper and middle estuaries rather than the lower parts of the hydrological basin. For example, previous work shows that >4 $km^2$ of new wetlands have been created in the upper Breton Sound estuary since 2005 due to mineral sediment input from current river diversion (Henkel et al., 2011). Yet, lower landscape-scale vertical accretion and elevation gains are usually observed in the lower Breton sound region and in estuaries near the Gulf of Mexico due to a reduction in sediment supply, a deeper water column, lower percentage of vegetated area, and less than 50% in sediment retention rates (Blum and Roberts, 2009; Paola et al., 2011; Allison et al., 2012; Couvillion et al., 2013).

### 3.5. Future studies

This work is the first step toward forecasting the effects of individual sediment diversion projects on landscape-scale wetland surface elevation and vertical accretion dynamics for coast-wide restoration of the Mississippi delta. Model results indicate that river diversions, especially large river diversions, could significantly reduce the landscape-scale elevation deficit by substantial increases in vertical accretion, thus mitigating further wetland loss. Nevertheless, our results are considered firs-rate estimates and need further experimental validation, particularly for large sediment diversions, due to trade-offs when using large river diversions for sediment delivery. Even if we could capture most of the sediment from the diverted river (sediment-to-water ratio >1; Meselhe et al., 2012), and deposit these materials to support accretion, we have to consider other ecological, economical and social factors involved in management decisions. From an ecological perspective, potential adverse impacts of such large river sediment diversions are large nitrogen and phosphorus loads to estuaries that might cause eutrophication, harmful algal blooms, hypoxia/dead zones, and reduced root/shoot ratio. Other concerns include changed fish and wildlife habitats and reduced oyster growth and high mortality due to low salinity levels (Snedden et al., 2007; Day et al., 2009; LaPeyre et al., 2009; Twilley and Rivera-Monroy, 2009; Zhang et al., 2012). The engineering designs have to consider factors involving both the water and sediment sources (river) and receiver (wetland: marsh interior and open water). Such factors include location in relation to the river sand bar, intake angle, channel length, width, depth, bottom slope, shape, guide levee (Dean et al., 2012; Meselhe et al., 2012), and topography and bathymetry of the receiving-basin (DeLaune et al., 2003; Couvillion et al., 2013).

Our results are best used in combination with examinations of the engineering designs and tests of large sediment diversions that

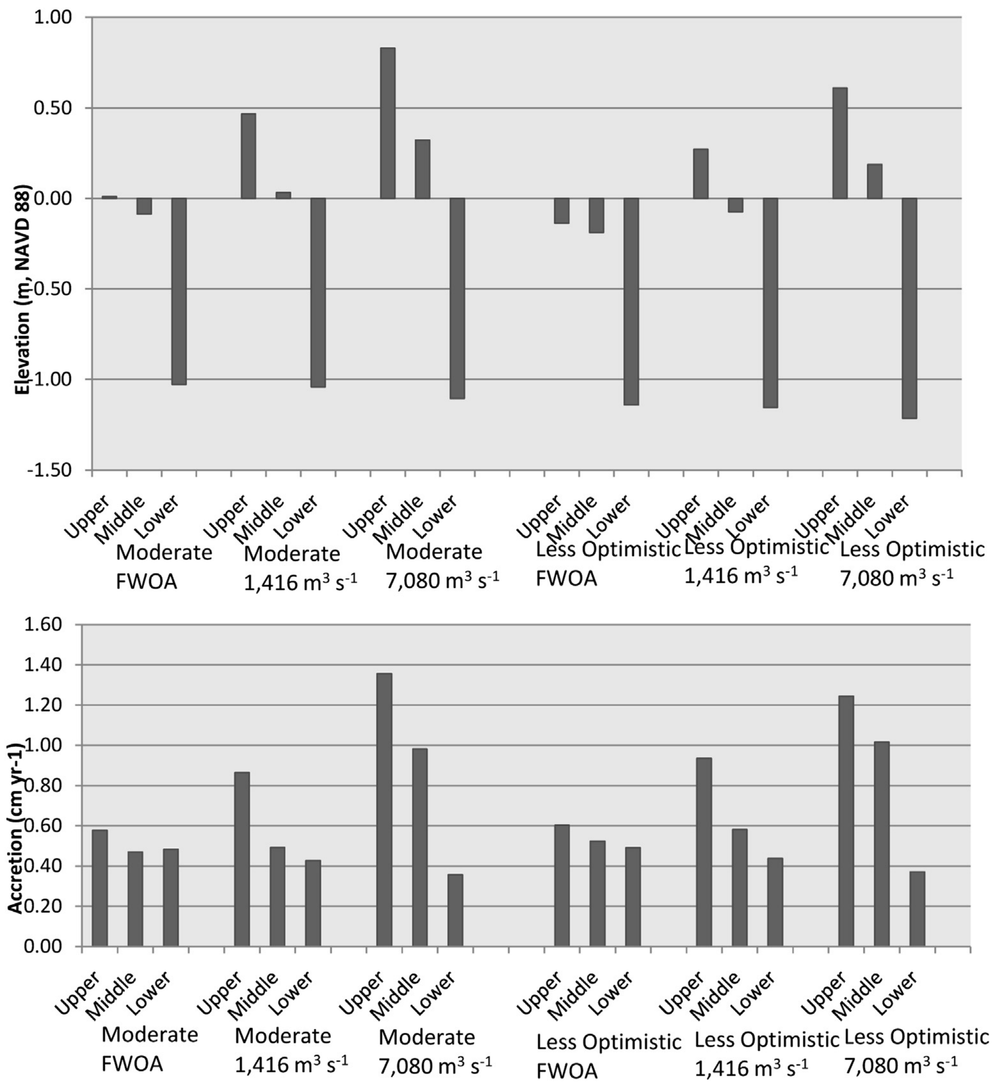


**Fig. 5.** Simulated sub-basin-wide surface elevation at the end of simulation period (Year 2060) and vertical accretion under selected medium (1416 $m^3 s^{-1}$) and large (7080 $m^3 s^{-1}$) scale diversions in Breton Sound basin under two environmental change scenarios (note: FWOA = future without action; subsidence rates for Upper, Middle, and Lower Breton Sound in the model are 0.56, 0.50, and 0.49 cm $yr^{-1}$ under Moderate Scenario, and 0.88, 0.75, and 0.73 cm $yr^{-1}$ under Less Optimistic Scenario, respectively).

target maximum optimal extraction of sediment from diverted river water and sediment using hydrodynamic and sediment transport numerical models (Allison and Meselhe, 2010; Rego et al., 2010; Meselhe et al., 2012). Additionally, a more intensive field sampling of sediment delivery and deposition in receiving wetlands is needed to detect landscape level effects and impacts of sediment diversions on elevation and vertical accretion dynamics.

## 4. Conclusions

We present a comprehensive modeling analysis of the effects of individual diversion projects on landscape-scale surface elevation and vertical accretion in the Mississippi River Deltaic Plain under future environmental conditions. Although coastal Louisiana will continue to lose wetlands, large sediment diversions (>1500 $m^3$ $s^{-1}$) could significantly reduce the landscape-scale elevation deficit, thus slowing further wetland loss. Our modeling results show that large sediment diversions could contribute sediments to maintain basin-wide or sub-basin-wide elevation by 16–82 cm over the next 50 years (0.32–1.64 cm $yr^{-1}$) compared to a future without action (FWOA) condition. The substantial increase in vertical accretion (basin-wide: 31% and sub-basin-wide: 135%) from diverted water and sediment is responsible for this reduction in elevation loss. Large-scale sediment diversions along the lower Mississippi River are expected to influence a larger area of coastal wetlands compared to small diversions. Our model probably underestimates the effects of river diversions on marsh vertical accretion because it does not allow for accretion without mineral sedimentation. This constrain is due to the fact that diversions lower salinity stress over a much larger area than they could increase mineral sedimentation, and also because coastal wetlands can accrete via vegetative growth (Nyman et al., 2006).

The zone of diversion influence (i.e., footprint) is a dynamic concept and is expected to extend beyond current project boundaries that are delineated based on existing small diversions. When river diversion effects are examined at a sub-basin scale (>100 $km^2$), elevation gain in excess of RSLR could be achieved in wetlands in proximity to the diversion structure. In the case of the proposed large sediment diversion (7080 $m^3$ $s^{-1}$) at Caernarvon, wetlands in both the upper- and middle- Breton Sound Basin could be maintained under the moderate scenario as a result of vertical accretion (1.36 and 0.98 cm $yr^{-1}$) in excess of or close to RSLR (1.10

and 1.04 cm $yr^{-1}$). The higher elevation gain than RSLR rates at a sub-basin scale implies that large sediment diversions could build new land at a larger geographical region under rising sea-level and subsidence. This result is promising since presently there is no other effective restoration technique that can restore wetlands to keep pace with RSLR across coastal Louisiana. Overall, the maximum benefits of sediment diversions on reducing elevation loss could be reached when large sediment diversions are placed in the upper region of the lower Mississippi River between the City of New Orleans and upstream of the Empire Lock.

Achieving a maximum reduction in elevation deficit or elevation gain by sediment transport and deposition under large sediment diversions does not necessarily imply similar maximum ecological benefits. Other components associated with river diversions such as water and nutrient loads could affect estuarine salinity, hydroperiod (depth, frequency and duration), soil fertility and soil strength, thus affecting ecosystem services (e.g., soil organic carbon sequestration and denitrification potential) as well as growth and productivity of flora and fauna (e.g., LePeyre et al., 2009; Twilley and Rivera-Monroy, 2009; Teal et al., 2012; Rivera-Monroy et al., 2013). Therefore, further work is needed to assess the ecological and economic effects of medium- to large sediment diversions on estuarine ecosystem services at landscape scales in coastal Louisiana.

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