

Predicting landscape effects of Mississippi River diversions on soil organic carbon sequestration

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Abstract. Large Mississippi River (MR) diversions (peak water flow >1416 m³/s and sediment loads >165 kg/s) have been proposed as part of a suite of coastal restoration projects and are expected to rehabilitate and rebuild wetlands to alleviate the significant historic wetland loss in coastal Louisiana. These coastal wetlands are undergoing increasing eustatic sea-level rise, land subsidence, climate change, and anthropogenic disturbances. However, the effect of MR diversions on wetland soil organic carbon (SOC) sequestration in receiving basins remains unknown. The rate of SOC sequestration or carbon burial in wetlands is one of the variables used to assess the role of wetland soils in carbon cycling and also to construct wetland carbon budgets. In this study, we examined the effects of MR water and sediment diversions on landscape-scale SOC sequestration rates that were estimated from vertical accretion for the next 50 yr (2010–2060) under two environmental (moderate and less optimistic) scenarios. Our analyses were based on model simulations taken from the Wetland Morphology model developed for Louisiana’s 2012 Coastal Master Plan. The master plan modeled a “future-without-action” scenario as well as eight individual MR diversion projects in two of the hydrologic basins (Barataria and Breton Sound). We examined the effects that discharge rates (peak flow) and locations of these individual diversion projects had on SOC sequestration rates. Modeling results indicate that large river diversions are capable of improving basin-wide SOC sequestration capacity (162–222 g C·m⁻²·yr⁻¹) by up to 14% (30 g C·m⁻²·yr⁻¹) in Louisiana deltaic wetlands compared to the future-without-action scenario, especially under the less optimistic scenario. When large river diversions are placed in the upper receiving basin, SOC sequestration rates are 3.7–10.5% higher (6–24 g C·m⁻²·yr⁻¹) than when these structures are placed in the lower receiving basin. Modeling results also indicate that both diversion discharge and location have large effects on SOC sequestration in low-salinity (freshwater and intermediate marshes) as compared to high-salinity marshes (brackish and saline marshes).

Key words: Barataria Basin; Breton Sound Basin; Louisiana; Mississippi River; sea-level rise; sediment diversion; soil organic carbon sequestration; subsidence; vertical accretion.

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INTRODUCTION

Large Mississippi River (MR) diversions have been proposed for coastal restoration to rehabilitate and rebuild wetlands to alleviate significant historic wetland loss in coastal Louisiana (Day et al. 2009, Allison and Meselhe 2010, Allison et al. 2014). The Louisiana wetland loss crisis is mainly caused by the combination of eustatic sea-level rise (SLR), subsidence, and reduced sediment supply due to the construction of dams and levees along the MR (Blum and Roberts 2009). These dams and levees restrict the distribution of wetland-building mineral sediments and associated nutrients onto the deltaic plain. River diversions, akin to punching holes in existing levees, reintroduce freshwater and mineral sediments to degraded wetlands (Allison and Meselhe 2010, Allison et al. 2012, 2013, Kolker et al. 2012, Nittrouer et al. 2012) and, in the process, enhance marsh vertical accretion and surface elevation when sediment loads are sufficient (DeLaune et al. 2003, 2013, Lane et al. 2006, Day et al. 2011, Couvillion et al. 2013, Wang et al. 2014) which, in turn, could potentially mitigate the effects of climate change, specifically rising sea levels.

Other ecological benefits of freshwater and sediment diversions (hereafter, “diversions”) include removing elevated nitrates in river water before discharge into the Gulf of Mexico (DeLaune et al. 2005, Wang et al. 2011, Rivera-Monroy et al. 2013, VanZomerem et al. 2013), increasing marsh primary productivity (both aboveground and belowground; Twilley and Nyman 2005, Day et al. 2012), and, potentially, increasing rates of soil organic carbon (SOC) sequestration (DeLaune and White 2012, DeLaune et al. 2013). Soil organic carbon sequestration is defined as “the process of transferring CO₂ from the atmosphere into the soil of land unit through unit plants, plant residue, and other organic solids, which are stored or retained in the unit as part of the soil organic matter (SOM)” (Olson et al. 2014). Generally, coastal wetland ecosystems are known to sequester carbon efficiently because of their high rates of primary productivity and low rates of SOM decomposition as well as accumulating soil and sediment carbon 40 times faster than the average terrestrial forest (McLeod et al. 2011). This ecosystem service allows coastal wetlands to be

entered into the voluntary carbon market, once a SOC sequestration rate is quantified (Chmura et al. 2003, Mitra et al. 2005, Crooks et al. 2011, Callaway et al. 2012, DeLaune and White 2012, Pendleton et al. 2012, Mitsch et al. 2013). As it stands now, due to net wetland loss in the MR Deltaic Plain, the estimated rates of SOC loss range from 1000 to 2050 g C·m⁻²·yr⁻¹ for the period 1978–2000 (Markewich et al. 2007), while sequestration by vertical accretion occurs at a lower rate (100–380 g C·m⁻²·yr⁻¹; DeLaune and White 2012). However, little is known about the influence of large river diversions on landscape-level sequestration of SOC. One major question is whether large MR diversions can maximize SOC sequestration and land-building potential simultaneously.

In this study, our objective was to examine the effect of MR diversions on the capacity of Louisiana’s deltaic wetlands to sequester carbon in soils using a range of discharge rates and locations along the MR. Establishing discharge rates (including opening time and duration) and suitable locations for river diversion projects are the two major concerns in studying, planning, and implementing diversions to achieve maximum land building while simultaneously reducing flood risks to established wetlands (Day et al. 2012, Meselhe et al. 2012, 2013). Specifically, we evaluated SOC sequestration by vertical accretion and land area change under the influence of a series of individual proposed diversion projects from the lower MR in the Barataria and Breton Sound basins under future plausible environmental changes using simulation results of a Wetland Morphology model developed for the 2012 Coastal Master Plan (Steyer et al. 2012, Couvillion et al. 2013, Peyronnin et al. 2013, Wang et al. 2014). The Wetland Morphology model simulated multiple individual diversion projects for a 50-yr period (2010–2060) under future environmental conditions taking into account eustatic SLR, subsidence, MR discharge, and storm frequency and intensity (Peyronnin et al. 2013). The assessment of river diversion impacts on SOC sequestration in deltaic wetlands could provide critical information for the optimal design and implementation of future river diversion projects. Such information is crucial not only for coastal Louisiana, but also for other coastal regions in the world (e.g., the Yellow River Delta, China), where river diversions

are used as a technique for coastal restoration (Cui et al. 2009, Wang et al. 2011).

MATERIALS AND METHODS

Study area

The MR Deltaic Plain includes the Terrebonne, Barataria, Breton Sound, MR Delta, and Pontchartrain basins (Fig. 1). We focused our analyses on the coastal marsh within two major hydrological basins: Barataria and Breton Sound (Fig. 1). These locations were selected because the 2012 Louisiana Coastal Master Plan (<http://coastal.la.gov/a-common-vision/2012-coastal-master-plan/>) proposed a number of MR diversions in these two basins (Peyronnin et al. 2013). Vegetation across the region was classified into four types along a salinity gradient from low to high seaward in our model application: freshwater (0–0.5 practical salinity units [psu]), intermediate (0.5–5 psu), brackish (5–12 psu), and saline (12–20 psu) marshes (Stagg et al. 2016). The dominant species in these habitats are *Panicum hemitomon* and *Typha lancifolia*

(freshwater marsh), *Sagittaria lancifolia* and *Schoenoplectus americanus* (intermediate marsh), *Spartina patens* and *S. americanus* (brackish marsh), and *Spartina alterniflora* and *Juncus roemerianus* (saline marsh; Visser et al. 2003, Sasser et al. 2008).

Calculation of landscape SOC sequestration rates

In this study, we used the simulation results of a spatially explicit Wetland Morphology model to assess and predict the landscape effects of MR diversions on SOC sequestration under future environmental conditions. The Wetland Morphology model was one of the seven integrated, coast-wide predictive models that were developed in support of Louisiana's 2012 Coastal Master Plan (Peyronnin et al. 2013). The description of each predictive model and their integration appears in Appendix S1. Other models include the Eco-Hydrology, Barrier Shoreline Morphology, Vegetation, Ecosystem Services, Storm Surge and Wave, and Risk Assessment models (Appendix S1: Fig. S1). The Wetland Morphology model predicts coastwide land area and landscape configuration

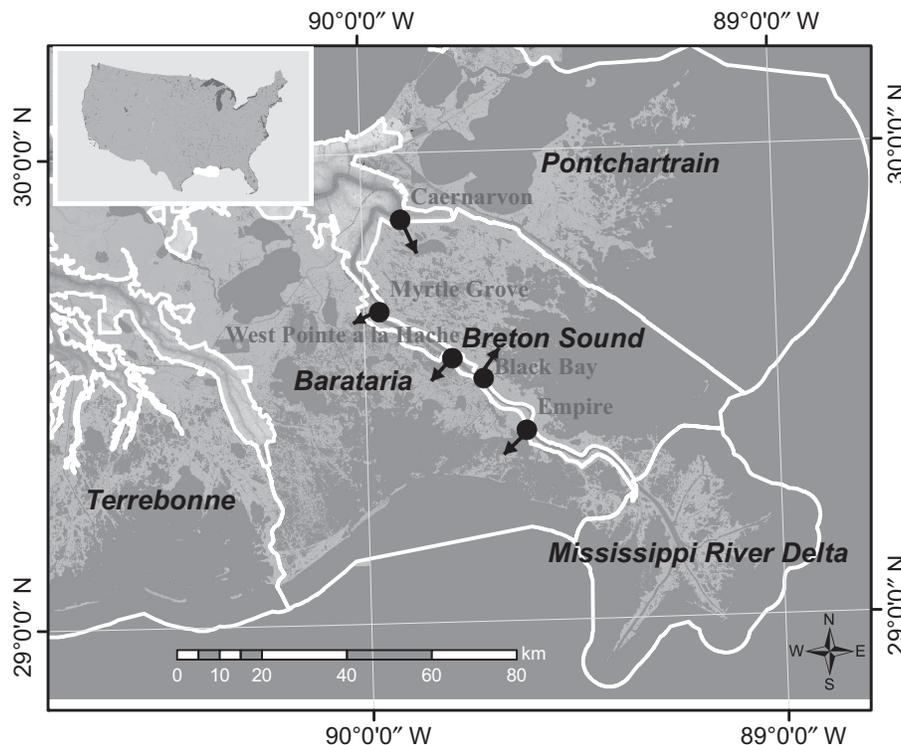


Fig. 1. Map of studied Louisiana deltaic wetlands and locations of selected diversions along the lower Mississippi River.

in response to surface elevation change, hurricanes, and implementation of protection and restoration projects. The model is driven by salinity, water level (stage), and sediment accumulation provided by the Eco-Hydrology model and plant community type and distribution from the Vegetation model. Other inputs for the Wetland Morphology model include historical land loss rates, wetland area, topography, bathymetry, land subsidence, and eustatic sea level. The outputs of the Wetland Morphology model include areas of land and water, vertical accretion, and surface elevation (Steyer et al. 2012). The Wetland Morphology model was calibrated and validated on long-term (decadal) vertical accretion derived from cesium-137 (^{137}Cs) dating of sediment cores from previous studies and the Coastwide Reference Monitoring System (CRMS; <http://lacoast.gov/crms2/home.aspx>). Appendix S1 also describes in detail the theory, assumptions, equations, inputs, outputs, calibration, and validation of the Wetland Morphology model.

The rate of SOC sequestration (ΔSOC) is estimated from model-simulated vertical accretion, depending on location, as:

$$\Delta\text{SOC} = \left(\frac{\text{BD} \times \text{OM} \times 0.01}{2.2} \right) \times H \times 10,000 \quad (1)$$

where ΔSOC is SOC sequestration rate ($\text{g C} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$), BD is soil bulk density (g/cm^3), OM is soil organic matter content (%), 2.2 is the organic carbon-to-organic matter conversion (OC-OM) factor, which was derived from CRMS data analysis (Steyer et al. 2012, Wang et al. 2016), and H is the rate of vertical accretion (cm/yr). In this study, SOC sequestration rates depend mainly upon the contribution of OM that is determined by the balance between plant growth (belowground) and OM decomposition in addition to inputs from other sources via river diversion. The OC-OM factor was derived from 60 soil cores collected during 2006–2007 to a depth of ~50 cm at 30 sites across coastal Louisiana (Piazza et al. 2011). The linear regression between OC and OM in coastal Louisiana soils using this data set is described by the following equation (Steyer et al. 2012):

$$\text{OC} (\%) = 0.4541 \times \text{OM} (\%) \quad (2)$$

$(n = 1142, R^2 = 0.93, P < 0.0001).$

The values of BD and OM were determined for each basin-vegetation type based on CRMS soil data (0–24 cm depth) and the set of 60 soil cores described above through a vertical accretion calibration process (Steyer et al. 2012). Bulk density and OM values vary correspondingly when vegetation types change in a particular basin as a result of fluctuations in salinity and flooding regimes (Visser et al. 2013).

The landscape processes of vegetation type change, vertical accretion, wetland/water area change, and associated SOC sequestration were represented at a grid cell resolution of 500 m. We first calculated SOC density ($[\text{BD} \times \text{OM}]/2.2$) at each pixel (500-m resolution) for two time periods (2010–2035 and 2036–2060) based on the vegetation community distribution model output from the Vegetation model (Visser et al. 2013). We then estimated SOC sequestration rates for each diversion project and Future-Without-Action (FWOA) scenario under the two future environmental scenarios (moderate and less optimistic; see details in *Future environmental scenarios*) during the two periods by multiplying the derived SOC density by the vertical accretion rate from the Wetland Morphology model (Couvillion et al. 2013). Lastly, we used the areas of land and water distribution during the two periods simulated by the Wetland Morphology model (Couvillion et al. 2013) to define wetland areas across basins and vegetation types. These estimated areas served as the zones for the estimation of SOC sequestration rates in the selected basins (Barataria and Breton Sound) and vegetation types (freshwater, intermediate, brackish, and saline marshes) using the ESRI's ArcGIS zonal statistical analysis tool (Arc-Map 10.2.2.; ESRI, Redlands, California, USA).

Individual sediment diversion projects

We selected eight individual river diversion projects (Table 1) from a series of proposed diversion projects evaluated for the 2012 Coastal Master Plan to assess their effects on basin-wide and vegetation-based SOC sequestration rates. The discharge rates (Q : peak flow through the structure and channel) of these diversion projects range from 142 to 7080 m^3/s . Three scales of MR diversions were selected using the peak flow rate: (1) large: diversion discharge ≥ 1416 up to 7080 m^3/s ; (2) medium: >283 –1415 m^3/s ; and (3)

Table 1. Features of selected individual diversion projects in the 2012 Coastal Master Plan for the Barataria and Breton Sound basins.

Diversion	Description	Peak flow (m ³ /s)
Barataria		
Myrtle Grove	Myrtle Grove Diversion, 142 m ³ /s capacity (continuous operation at capacity for river flows above 5663 m ³ /s; no operation below 5663 m ³ /s)	142
Myrtle Grove	Myrtle Grove Diversion, 1416 m ³ /s capacity (operation at capacity when Mississippi River (MR) flow exceeds 16,990 m ³ /s; operation at 8% of river flow from 16,990 down to 5663 m ³ /s; no operation below 5663 m ³ /s)	1416
Myrtle Grove	Myrtle Grove Diversion, 7080 m ³ /s capacity (operation at capacity when MR flow exceeds 25,485 m ³ /s; operation at 1416 m ³ /s for flows from 25,485 down to 16,990 m ³ /s; operation at 8% of river flow for river flows from 16,990 down to 5663 m ³ /s; no operation below 5663 m ³ /s)	7080
West Point a la Hache	West Pointe a la Hache Diversion, 1416 m ³ /s capacity (operation at capacity when MR flow exceeds 16,990 m ³ /s; operation at 8% of river flow from 16,990 down to 5663 m ³ /s; no operation below 5663 m ³ /s)	1416
Empire	Empire Diversion, 1416 m ³ /s capacity (operation at capacity when MR flow exceeds 16,990 m ³ /s; operation at 8% of river flow from 16,990 down to 5663 m ³ /s; no operation below 5663 m ³ /s)	1416
Breton Sound		
Caernarvon	Caernarvon Diversion, 1416 m ³ /s capacity (operation at capacity when MR flow exceeds 16,990 m ³ /s; operation at 8% of river flow from 16,990 down to 5663 m ³ /s; no operation below 5663 m ³ /s)	1416
Caernarvon	Caernarvon Diversion, 7080 m ³ /s capacity (70% Mississippi/30% Atchafalaya; operation at capacity when MR flow exceeds 25,485 m ³ /s; operation at 1416 m ³ /s for flows from 25,485 down to 16,990 m ³ /s; operation at 8% of river flow for river flows from 16,990 down to 5663 m ³ /s; no operation below 5663 m ³ /s)	7080
Black Bay	Black Bay Diversion, 7080 m ³ /s capacity (60% Mississippi/40% Atchafalaya; operation at capacity when MR flow exceeds 25,485 m ³ /s; operation at 1416 m ³ /s for flows from 25,485 down to 16,990 m ³ /s; operation at 8% of river flow for river flows from 16,990 down to 5663 m ³ /s; no operation below 5663 m ³ /s)	7080

small: ≤ 283 m³/s (Wang et al. 2014). According to the diversion protocols described in Table 1, there are power function relationships between peak flow rates and annual total water amounts and between peak rates and sediment load; thus, we used peak flow rates in our model evaluation. The higher the peak flow rate, the higher the delivered water amount and sediment load. For example, annual total flows through the Caernarvon Diversion at Breton Sound Basin with diversion flow regimes of 142, 1416, and 7080 m³/s would be 4.5×10^9 , 38.4×10^9 , and 56.3×10^9 m³, respectively. Under these three diversion regimes, the annual total sediment loads would be 0.1, 1.2, and 2.1 million metric tons, respectively.

Future environmental scenarios

A number of uncertainty parameters were identified in the 2012 Coastal Master Plan modeling study: eustatic SLR, subsidence, hurricane/storm intensity and frequency, MR discharge, rainfall, evapotranspiration, MR nutrient

concentrations, and marsh collapse thresholds (Peyronnin et al. 2013). The ranges in uncertainty parameters in the next 50 yr (2010–2060) were determined from previous studies and best professional judgment (Table 2). Two future environmental change scenarios were selected: (1) *moderate* and (2) *less optimistic* (Couvillion et al. 2013, Meselhe et al. 2013, Visser et al. 2013). Full details on the plausible range of each uncertainty parameter under each scenario are described in Peyronnin et al. (2013) and Wang et al. (2014). In particular, eustatic SLR rates over the 50-yr simulation period were non-linear and resulted in 0.27 and 0.45 m of sea-level change, respectively. In the case of the moderate and less optimistic scenarios, subsidence rates varied spatially in the range of 0–1.9 cm/yr and 0–2.5 cm/yr. Consequently, the time-averaged rates of relative SLR (RSLR = eustatic SLR + subsidence) for Barataria Basin and Breton Sound Basin were 1.24 and 1.14 cm/yr under the moderate scenario and 2.00 and 1.80 cm/yr under the less optimistic scenario, respectively (Wang et al. 2014). As a

Table 2. Environmental uncertainty parameters and the two scenarios used in the 2012 Louisiana Master Plan model simulations.

Parameter	Plausible range	Moderate scenario	Less optimistic scenario
Sea-level rise	0.16–0.8 m over 50 yr	0.27 m over 50 yr	0.45 m over 50 yr
Subsidence	0–3.5 cm/yr; varies spatially	0–1.9 cm/yr (values vary spatially)	0–2.5 cm/yr (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 (MR) discharge	–7% to +14% of annual mean discharge; adjusted for seasonality	Mean annual discharge (15,121 m ³ /s)	–5% of mean annual discharge (14,413 m ³ /s)
Rainfall	Historical monthly range; varies spatially	Variable percentage of historical monthly mean	Variable percentage of historical monthly mean
Evapotranspiration	Historical monthly range (± 1 SD); varies spatially	Historical monthly mean (values vary spatially)	+0.4 SD from historical mean monthly (values vary spatially)
MR nutrient concentration	–45% to +20% of current nitrogen and phosphorus concentrations	–12% of current concentrations (mg/L) Phosphorus = 0.19 Nitrite + nitrate = 1.1 Ammonium = 0.038 Organic nitrogen = 0.67	Current concentrations (mg/L) Phosphorus = 0.22 Nitrite + nitrate = 1.3 Ammonium = 0.044 Organic nitrogen = 0.77
Marsh collapse threshold	Salinity (psu) Swamp: 4–7 Fresh marsh: 6–8 Inundation (water depth, cm) Intermediate marsh: 31–38 Brackish marsh: 20–26 Saline marsh: 16–23	Mid-range values of salinity and inundation result in collapse Salinity (psu) Swamp: 6 Fresh marsh: 7 Inundation (cm) Intermediate marsh: 34 Brackish marsh: 23 Saline marsh: 21	Lower 25th percentile values of salinity and/or inundation ranges result in collapse Salinity (psu) Swamp: 5 Fresh marsh: 7 Inundation (cm) Intermediate marsh: 33 Brackish marsh: 21 Saline marsh: 18

comparison, the average RSLR in coastal Louisiana based solely upon tide gauge trends at Grand Isle, Louisiana, during 1947–2006, was 0.92 cm/yr (Couvillion and Beck 2013). These rates would be higher if wetland submergence were included (Cahoon 2015).

Assessment of diversion effects on landscape SOC sequestration rates

The effects of sediment diversions on SOC sequestration were evaluated under the following criteria.

Discharge rate effect.—We selected Myrtle Grove in Barataria Basin and Caernarvon in Breton Sound Basin and used three master plan diversion peak flow rates in each basin: 142, 1416, and 7080 m³/s as well as the FWOA condition to examine the basin-wide and vegetation type-based average SOC sequestration rates. Because historical flows from existing diversions at Davis Pond in Barataria and Caernarvon in Breton

Sound basins were incorporated in both FWOA and master plan diversion conditions (Meselhe et al. 2013), the diversion discharge rates used in our analysis do represent FWOA water flows into the two basins.

Location effect.—We selected diversions in Barataria Basin with the same discharge peak flow rate of 1416 m³/s (downriver order: Myrtle Grove, West Pointe a la Hache, and Empire) and in Breton Sound Basin with the same discharge rate of 7080 m³/s (downriver order: Caernarvon and Black Bay) to examine basin-wide and vegetation type-based average SOC sequestration rates over the 50-yr simulation period (Fig. 1).

Statistical analysis

We conducted a three-way ANOVA with hydrologic basin, future environmental scenario, and diversion discharge and all possible interactions as explanatory variables for SOC sequestration rates in Barataria and Breton Sound basins. We also

conducted a three-way ANOVA with vegetation type, future environmental scenario, and diversion discharge and their interactions on SOC sequestration rates. A three-way ANOVA was also used to examine the effects of diversion location, vegetation types, and future environmental scenario on SOC sequestration rates. Data were square-root-transformed to meet normality and homoscedasticity assumptions. The SAS 9.3 software package (SAS Institute, Cary, North Carolina, USA) was used for the statistical analyses. All the tests were two-tailed based on type III sums of squares and considered significant at $P < 0.05$.

RESULTS

Discharge rate effect

Our results indicated that simulated SOC sequestration rates varied significantly ($P < 0.001$) with hydrologic basin, future environmental scenario, diversion discharge, and their interactions (Table 3). The highest average simulated SOC sequestration rates within Barataria Basin (mean \pm standard error; moderate: 168 ± 1.0 g C·m⁻²·yr⁻¹,

Table 3. Statistical result of the effects of hydrologic basin, future environmental scenario, and diversion discharge on simulated SOC sequestration rate.

Factor	df	Type III SS	F	P
Basin	1	20,265.48	1438.15	***
Environmental scenario	1	66,914.92	4748.65	***
Discharge	3	20,681.75	489.23	***
Basin \times environmental scenario	1	27,918.03	1981.22	***
Basin \times discharge	2	20,452.09	725.70	***
Environmental scenario \times discharge	3	31,780.32	751.77	***
Basin \times environmental scenario \times discharge	2	14,302.72	507.50	***

Note: SOC, soil organic carbon; SS, sums of squares; df, degrees of freedom.

*** $P < 0.001$.

$n = 10,325$; and less optimistic: 252 ± 1.4 g C·m⁻²·yr⁻¹, $n = 9433$) were observed for the sediment diversion with a peak flow rate of 1416 m³/s under both the moderate and less optimistic scenarios (Fig. 2a). Compared to the rates under the FWOA condition and the moderate scenario (162 ± 1.07 g C·m⁻²·yr⁻¹, $n = 9699$), the

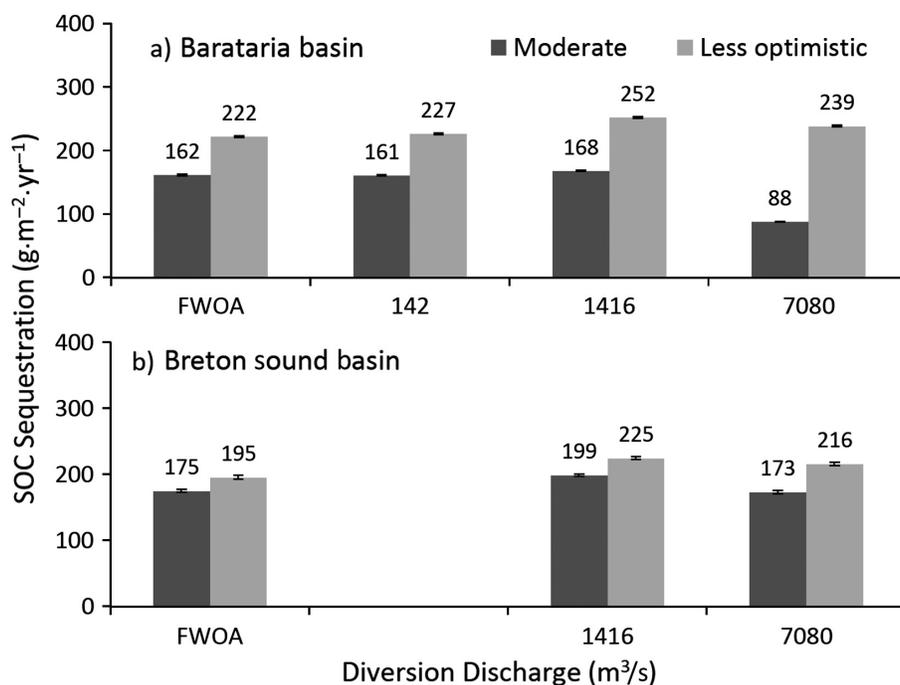


Fig. 2. Simulated soil organic carbon (SOC) sequestration rates with varying diversion discharge rates in the Barataria and Breton Sound basins under moderate and less optimistic scenarios. Means (± 1 standard error) are significantly different ($P < 0.001$) among diversion discharge and future environmental scenario combinations.

simulated SOC sequestration rates increased by 3.8% at a 1416 m³/s discharge, whereas simulated rates decreased by 0.6% and 45.5% when 142 and 7080 m³/s discharge rates were used. In contrast, simulated SOC sequestration rates increased with discharge rates of 142 (2.1%), 1416 (13.7%), and 7080 m³/s (7.5%), compared to rates under the FWOA and the less optimistic scenarios (222 ± 1.3 g C·m⁻²·yr⁻¹, *n* = 8914).

Similarly, within the Breton Sound Basin, the highest averaged SOC sequestration rates were observed for the diversion with the peak flow rate of 1416 m³/s under both scenarios (moderate: 199 ± 2.0 g C·m⁻²·yr⁻¹; less optimistic: 225 ± 2.3 g C·m⁻²·yr⁻¹; Fig. 2b). In the case of the FWOA condition under the moderate scenario (SOC sequestration rate: 175 ± 2.2 g C·m⁻²·yr⁻¹), the simulated rate of SOC sequestration increased by 13.7% applying the 1416 m³/s discharge, while the rate decreased by 1.1% using the 7080 m³/s discharge rate. Further, SOC sequestration rates increased by 15.4% and 10.8% using the 1416 and 7080 m³/s discharge rates as input when compared to simulated SOC sequestration rates under FWOA condition and the less optimistic scenario (i.e., 195 ± 2.8 g C·m⁻²·yr⁻¹).

Simulated SOC sequestration rates varied significantly as a result of interactions (*P* < 0.001) among vegetation type, environmental scenario, and diversion discharge (Table 4). Plots of simulated SOC sequestration rates across vegetation types under various discharge rates and environmental scenarios in Barataria Basin and Breton

Table 4. Statistical results of the effects of vegetation type, environmental scenario, and diversion discharge on simulated SOC sequestration rate.

Factor	df	Type III SS	<i>F</i>	<i>P</i>
Vegetation type	3	346,317.78	9928.71	***
Environmental scenario	1	29,669.47	2551.82	***
Discharge	3	29,230.39	838.02	***
Vegetation type × environmental scenario	3	7352.89	210.80	***
Vegetation type × discharge	9	27,529.09	263.08	***
Environmental scenario × discharge	3	19,783.86	567.19	***
Vegetation type × environmental scenario × discharge	9	17,711.46	169.26	***

Note: SOC, soil organic carbon; SS, sums of squares; df, degrees of freedom.

*** *P* < 0.001.

Sound Basin are shown in Appendix S2. In Barataria Basin, brackish marsh soils had the highest SOC sequestration (374 ± 3.4 g C·m⁻²·yr⁻¹) under diversion water flow of 1416 m³/s in the moderate scenario followed by saline and intermediate marsh soils (280 ± 2.7 g C·m⁻²·yr⁻¹ and 276 ± 3.6 g C·m⁻²·yr⁻¹, respectively). Freshwater marsh soils showed the lowest SOC sequestration rates (166 ± 0.7 g C·m⁻²·yr⁻¹) under the flow of 1416 m³/s (Appendix S2: Fig. S1a).

Under the less optimistic scenario, SOC sequestration capacity in Barataria Basin changed in response to the salinity gradient. Saline marsh soils showed the highest SOC sequestration rates (350 ± 3.1 g C·m⁻²·yr⁻¹), followed by brackish and intermediate marsh soils (296 ± 4.5 and 282 ± 1.3 g C·m⁻²·yr⁻¹); the lowest SOC sequestration capacity (177 ± 1.4 g C·m⁻²·yr⁻¹) was registered in the freshwater marsh soils under diversion water flow of 1416 m³/s (Appendix S2: Fig. S1a). Unlike the basin-wide increase in SOC sequestration capacity under the less optimistic scenario, the 1416 m³/s diversion scenario resulted in decreasing SOC sequestration rates in brackish (-3.4%) and saline marshes (-23.5%) compared to the FWOA condition. Further, freshwater and intermediate marshes sequestered more carbon than saline and brackish marshes in Barataria Basin when the total area for each vegetation category was considered (Fig. 3a). Indeed, freshwater marshes (1373–1723 km²) contributed 53–66% of the total annual sequestered soil carbon under the moderate scenario while intermediate marshes (941–991 km²) contributed 54–62% of the total annual carbon sequestration under the less optimistic scenario (Fig. 3a).

In the case of Breton Sound Basin, a river diversion of 7080 m³/s resulted in an increase in SOC sequestration in freshwater marsh when compared to the FWOA scenario (Appendix S2: Fig. S1b). The increase in simulated SOC sequestration rates per marsh type was 37.8% under the moderate scenario and 37.6% under the less optimistic scenario. Similar to the case in Barataria Basin, freshwater marshes in Breton Sound Basin (116–242 km²) were also critical contributors (up to 55%) to total carbon sequestered, especially under medium- to large-scale diversions, although brackish marshes (20–249 km²) contributed more carbon under FWOA (up to 70%) and with small freshwater flow (Fig. 3b). These

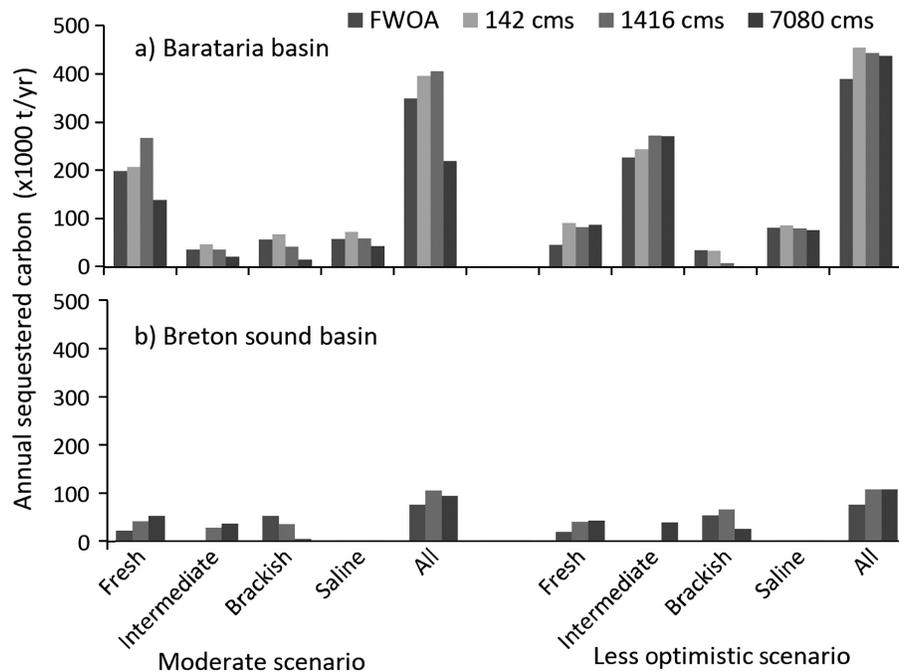


Fig. 3. Simulated annual total sequestered soil carbon ($\times 1000$ t/yr) within different marsh types with varying diversion discharge rates under moderate and less optimistic scenarios (cms = m^3/s).

simulation results for Breton Sound showed a larger effect of MR diversion on SOC sequestration in low-salinity (freshwater and intermediate marshes) than in high-salinity marshes (brackish and saline marshes).

Location effect

Simulated basin-wide SOC sequestration rates varied with the diversion structure location. The highest basin-wide SOC sequestration rates (168 ± 1.0 $\text{g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ and 252 ± 1.4 $\text{g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ under the moderate and less optimistic scenarios, respectively) were obtained when placing the diversion at or near Myrtle Grove in the upper receiving basin in Barataria Basin (Fig. 4a). Placing a diversion with a capacity flow of 1416 m^3/s near West Pointe a la Hache and Empire resulted in reduction in SOC sequestration ranging from 3.2% to 9.4% (159 ± 0.9 $\text{g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ and 162 ± 1.1 $\text{g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ under the moderate scenario and 231 ± 1.3 $\text{g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ and 228 ± 1.3 $\text{g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ under the less optimistic scenario) compared to the case when the diversion structure was placed next to Myrtle Grove (Fig. 4a). Placing a diversion of 7080 m^3/s near Black Bay in

the lower receiving basin in the Breton Sound Basin resulted in an increase in SOC sequestration rates by 7.5% and 1.0% under the moderate (i.e., 186 ± 2.5 $\text{g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) and less optimistic scenarios (i.e., 218 ± 2.5 $\text{g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) when compared to building the diversion structure at or near Caernarvon (173 ± 2.5 $\text{g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ and 216 ± 2.5 $\text{g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ under the two scenarios; Fig. 4b).

Simulated SOC sequestration rates varied significantly ($P < 0.001$) with diversion structure location, vegetation type, environmental scenario, and their interactions in Barataria Basin (Table 5) and Breton Sound Basin (Table 6). The effect of diversion location on carbon sequestration rates varied with the type of vegetation present within each of the two hydrological basins. Plots of simulated SOC sequestration rates across vegetation types under different diversion structure locations and environmental scenarios in Barataria Basin and Breton Sound Basin are shown in Appendix S2: Fig. S2. Placing the 1416 m^3/s diversion at or near Empire in the lower receiving basin in Barataria Basin slightly increased SOC sequestration rates in saline marsh soils under the

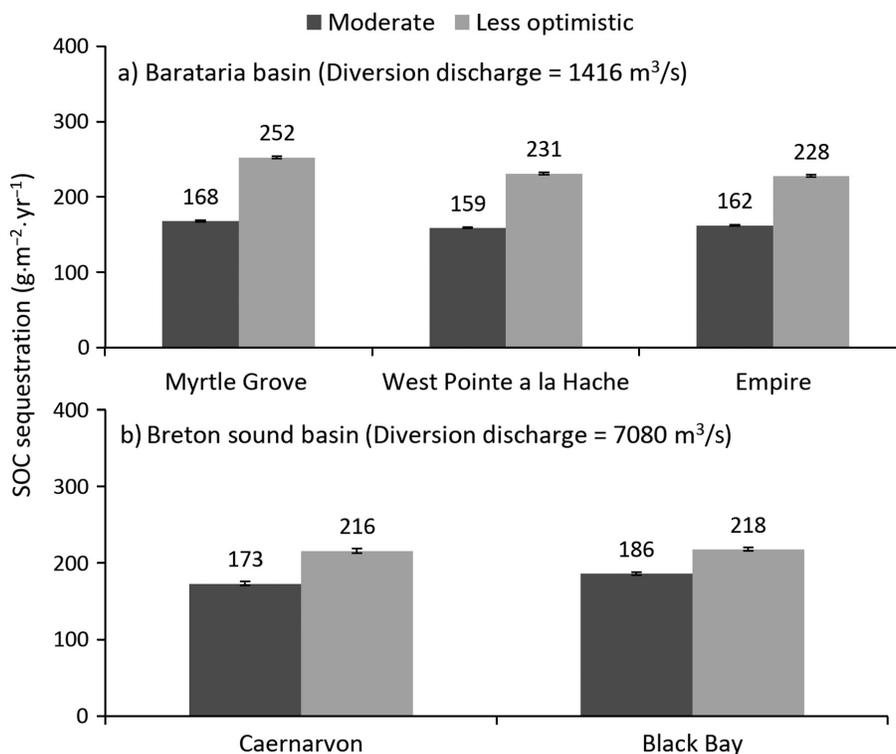


Fig. 4. Simulated soil organic carbon (SOC) sequestration rates under moderate and less optimistic scenarios when placing diversion structures at Barataria Basin (with diversion discharge of 1416 m³/s) and Breton Sound Basin (with diversion discharge of 7080 m³/s) at different locations. Means (± 1 standard error) are significantly different ($P < 0.001$) among diversion location and future environmental scenario combinations.

Table 5. Statistical results of the effects of diversion location, vegetation type, and environmental scenario on simulated SOC sequestration rate in Barataria Basin.

Factor	df	Type III SS	F	P
Vegetation type	3	289,712.37	10,384.90	***
Environmental scenario	1	240.38	25.85	***
Location	2	5318.96	285.99	***
Vegetation type \times environmental scenario	3	6223.75	223.09	***
Vegetation type \times location	6	2880.69	51.63	***
Environmental scenario \times location	2	57.87	3.11	*
Vegetation type \times environmental scenario \times location	6	2653.17	47.55	***

Note: SOC, soil organic carbon; SS, sums of squares; df, degrees of freedom.
* $P < 0.05$, *** $P < 0.001$.

Table 6. Statistical results of the effects of diversion location, vegetation type, and environmental scenario on simulated SOC sequestration rate in Breton Sound Basin.

Factor	df	Type III SS	F	P
Vegetation type	3	8629.18	335.75	***
Environmental scenario	1	722.56	84.34	***
Location	1	445.08	51.95	***
Vegetation type \times environmental scenario	3	761.16	29.62	***
Vegetation type \times location	3	4955.04	192.79	***
Environmental scenario \times location	1	45.48	5.31	*
Vegetation type \times environmental scenario \times location	3	646.37	25.15	***

Note: SOC, soil organic carbon; SS, sums of squares; df, degrees of freedom.
* $P < 0.05$, *** $P < 0.001$.

moderate scenario ($284 \pm 2.3 \text{ g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) and in brackish marsh soils under the less optimistic scenario ($309 \pm 3.2 \text{ g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) compared to placing the diversion next to Myrtle Grove ($280 \pm 3.4 \text{ g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ for saline marsh and $296 \pm 4.5 \text{ g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ for brackish marsh; Appendix S2: Fig. S2a). This is in contrast with the decreasing basin-wide SOC rates with locations at Myrtle Grove, West Point a la Hache and Empire (Fig. 4a). In the case of Breton Sound Basin, placing a $7080 \text{ m}^3/\text{s}$ large diversion at Caernarvon resulted in higher SOC sequestration rates for freshwater ($220 \pm 2.2 \text{ g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ and $229 \pm 2.4 \text{ g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) and intermediate ($245 \pm 3.6 \text{ g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ and $329 \pm 3.6 \text{ g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) marsh soils when compared to placing the diversion at or near Black Bay under the moderate and less optimistic scenarios (Appendix S2: Fig. S2b). In contrast, installing the $7080 \text{ m}^3/\text{s}$ river diversion at or near Black Bay resulted in increased SOC sequestration rates for brackish marshes ($243 \pm 2.2 \text{ g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ and $277 \pm 2.1 \text{ g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) compared to placing the diversion at Caernarvon ($215 \pm 7.9 \text{ g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ and $223 \pm 2.4 \text{ g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) under the two scenarios (Appendix S2: Fig. S2a). In addition, relatively stable SOC sequestration rates were estimated for saline marsh soils (~ 130 and $144 \text{ g C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ under the two future scenarios; Appendix S2: Fig. S2b). These simulation results underscore the significant impact of diversion location on basin-wide and marsh type-specific SOC sequestration rates in Louisiana deltaic wetland soils. Locations of large diversions affect to a larger degree SOC sequestration in freshwater, intermediate, and brackish marshes than in saline marshes.

DISCUSSION

Our results show that increasing discharge from 142 to $1416 \text{ m}^3/\text{s}$ could significantly enhance SOC sequestration rates in Barataria and Breton Sound basins. However, the benefit in soil carbon gain due to a large diversion would decline as discharge rate increases beyond a threshold. This threshold appears between 1416 and $7080 \text{ m}^3/\text{s}$ (Figs. 2, 3) depending on a hydrologic basin's geomorphological features and change in environmental conditions (e.g., salinity, inundation, and temperature). The diminishing marginal benefit of large diversions on soil carbon sequestration is

primarily attributed to changes in vegetation structure (e.g., species composition, spatial distribution) as a result of the direct changes in salinity and hydroperiod regimes associated with large river diversions (Visser et al. 2013). Visser et al. (2013) found that brackish marsh area would shrink and saline marsh area would remain relatively stable, while areas of freshwater and intermediate marshes would expand with restoration including river diversions and SLR over the next 50 yr. The rate of SOC sequestration in this study was calculated as the product of OC density and vertical accretion (Eq. 1). Thus, estimated SOC sequestration rates depend largely upon the OC density regulated by the type of wetland vegetation growing in situ especially if communities are dominated by wetlands with high peat production as is the case of intermediate (mean OC density = $0.041 \text{ g}/\text{cm}^3$), brackish ($0.039 \text{ g}/\text{cm}^3$), and saline ($0.036 \text{ g}/\text{cm}^3$) marshes (Morris et al. 2013, Wang et al. 2016). Indeed, the lowest OC density has been reported for freshwater marshes ($0.028 \text{ g}/\text{cm}^3$) based on the Louisiana CRMS soil data (over the 0 – 24 cm depth) compiled during 2006–2009 (Wang et al. 2016). This difference in SOC densities was explicitly included in the Wetland Morphology model, which assigned SOC values to the four marsh categories included in our simulations. The interaction between SOC density and plant composition is clearly observed when large diversions (i.e., 1416 to $7080 \text{ m}^3/\text{s}$) promote the conversion of non-freshwater marshes to freshwater marshes as a result of low surface water and porewater salinity (DeLaune et al. 2003). Once freshwater wetlands are dominant, total carbon sequestration decreases on a per unit area basis. Large diversions (i.e., $7080 \text{ m}^3/\text{s}$) could lead to a significant decrease in the percentage of SOC density when marshes switch from brackish (48%) and intermediate (28%) marshes to freshwater marshes while vertical accretion tended to increase ($<20\%$) under the $7080 \text{ m}^3/\text{s}$ diversion (Wang et al. 2014).

Further, marsh plant productivity also tends to have a parabolic relationship with water level or elevation (Morris et al. 2002, Mudd et al. 2009, Kirwan et al. 2012) with maximum growth and production at the peak of the parabola. In coastal Louisiana, relatively high plant productivity indicated by high Normalized Difference Vegetation Index was found to be at an elevation relative to

mean water level: 4.7–19.0 cm for intermediate marsh, 12.6–26.8 cm for brackish marsh, and 16.3–31.9 cm for saline marsh, respectively (Couvillion and Beck 2013). This relationship between productivity and elevation indicates optimal water depths for marsh plant productivity, and once these optimal depths are exceeded, plant growth and biomass significantly decrease, likely resulting in a decrease in SOM accumulation. For instance, both aboveground biomass and belowground biomass of *Spartina alterniflora* and *Spartina patens* were found to decrease significantly in response to increased flooding in Breton Sound Basin (Snedden et al. 2015).

The location of a diversion structure relative to the coastline and the river watershed also plays a critical role in SOC sequestration. This role is further influenced by the discharge rate regime and the in situ geomorphological properties of the receiving hydrologic basin (e.g., configuration of land and water areas, vegetation distribution, topography, and bathymetry). A representative example of this effect on SOC rates in our modeling exercise is the diversion placed near Myrtle Grove in Barataria Basin that used a peak water flow of 1416 m³/s (a large diversion). High SOC sequestration rates (Fig. 4a) correlated with the highest vertical accretion and reduction in elevation loss when placing the 1416 m³/s diversion at or near Myrtle Grove (Wang et al. 2014). In contrast, when placing the diversion structure and setting a flow rate of 7080 m³/s (a mega-diversion) within Breton Sound Basin at or near Caernarvon, SOC sequestration was not the highest at the basin-wide level (Fig. 4b) although this large diversion at this location could lead to the highest vertical accretion (>0.7 cm/yr) and reduction in wetland surface elevation loss compared to FWOA (Wang et al. 2014). Previous studies show that a diversion at an upriver location would reduce the energy, water, and sediment capture at downriver distributaries (Allison and Meselhe 2010, Allison et al. 2013, Meselhe et al. 2013). Normally, along the upper → middle → lower estuary gradient within a hydrologic basin, the land-to-water ratio decreases while the percentage of vegetated marsh area decreases, and marsh elevation decreases while water depth increases. All of these factors contribute to the lower retention rates of delivered sediment and decreased vertical accretion (Couvillion et al.

2013, Wang et al. 2014). Even with relatively higher OC densities (Wang et al. 2016), SOC sequestration in brackish and saline marshes would decrease because of lower vertical accretion in the lower basin (Wang et al. 2014).

Overall, the discharge and location effects of MR diversion projects identified by this study underscore the need to evaluate management priorities in obtaining desired ecosystem services from carbon sequestration under brackish or freshwater dominated marshes characterized by significant mineral sediment input that promotes vertical accretion in the MR Delta Plain.

CONCLUSIONS

Landscape-level SOC sequestration rates (both basin-wide and vegetation type averaged) under three MR sediment diversion discharge rates (peak flow: 142, 1416, and 7080 m³/s) and under different diversion structure locations along the lower MR were evaluated using simulation results of a Wetland Morphology model developed, calibrated, and validated for the Louisiana's 2012 Coastal Master Plan. A diversion with a water discharge rate of 1416 m³/s and placed in the upper reach of the lower MR resulted in the highest SOC sequestration at the landscape level. Simulation results indicate that large MR diversions (peak flow ≥1416 m³/s and sediment loads >165 kg/s) are capable of improving landscape-scale SOC sequestration capacity in Louisiana deltaic wetlands. Additionally, large diversions could help mitigate wetland salinity stress (salinization) due to saltwater intrusion from SLR and land subsidence (Herbert et al. 2015), thus improving SOC sequestration capacity in freshwater marshes.

Additional individual diversion projects with large discharge rates ranging from 2000 to 6000 m³/s should be considered in future feasibility modeling studies to explore the specific discharge thresholds in specific basins, vegetation types, and future environmental conditions including a range of relative SLR rates. Since most existing river diversions are small scale (≤283 m³/s) and sea level is rising at an accelerating rate induced by climate change (Williams 2013), large diversions would be required if soil carbon sequestration capacity in Louisiana deltaic wetlands is to be enhanced or maintained under future climate and environmental change.

Since SOC sequestration rates may decrease once a potential threshold of discharge is exceeded, it is paramount to evaluate the economic and ecological consequences due to the decline of diversion benefit in sequestering carbon via vertical accretion. Model results imply that the diversion discharge threshold, if present, would vary with basin, vegetation type, future environmental conditions, and possibly location of diversion structure as well.

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DATA AVAILABILITY

Data associated with this paper have been deposited in USGS ScienceBase at <https://doi.org/10.5066/f72r3pww>

SUPPORTING INFORMATION

Additional Supporting Information may be found online at: <http://onlinelibrary.wiley.com/doi/10.1002/ecs2.1984/full>