Wetlands
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WETLANDS AND CLIMATE CHANGE

# Modeled Sediment Availability, Deposition, and Decadal Land Change in Coastal Louisiana Marshes under Future Relative Sea Level Rise Scenarios

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**Abstract**
The ability, or lack thereof, for wetlands in coastal Louisiana to maintain elevation capital has been well documented in the literature to be a function of local and regional factors as well as environmental conditions. The Integrated Compartment Model (ICM) framework developed for the state of Louisiana's Coastal Master Plan models hydrologic, vegetation, and wetland elevation dynamics and captures regional and local dynamics of wetland elevation, inundation and sedimentation processes. It provides insights into the relative sensitivities of wetland evolution to environmental drivers under uncertain future environmental conditions. A systematic, and computationally efficient modeling exercise was conducted to test coastal marsh survival across a wide range of possible future relative sea level rise rate scenarios. Model results indicate a diverse response with respect to sediment deposition and marsh survival driven by regional subsidence rates and proximity to suspended sediment sources. Sediment poor regions of coastal Louisiana are particularly sensitive to relative sea level rise under all but the most optimistic of future sea level rise rates simulated. Coastal marshes with high sediment availability fare much better under most scenarios tested, despite high rates of relative sea level rise.

**Keywords** Sediment · Deposition · Numerical modeling · Sea level rise · Subsidence · Marsh collapse

## Introduction

Coastal Louisiana is home to a vast expanse of wetland ecosystems in a highly altered hydrologic landscape that is scattered with levees, shipping channels, oil and gas exploration and pipeline canals, has a history of subsurface fluid extraction and is also subjected to periodic tropical cyclones. Over 30% of all estuarine herbaceous marshes within the United States are located in the Louisiana coastal zone and over 25% of the wetlands within the coastal zone of Louisiana have been lost to open water in the past 85 years; a loss of more than 4850 km$^2$ of coastal wetlands from 1932 through 2010 (Couvillion et al. 2011). The magnitude and impacts of this historic wetland loss are well documented and are the result of multiple drivers including anthropogenic effects of levee and spoil bank construction and subsequent channelization of sediment supply, canal dredging, and subsurface fluid extraction (Jankowski et al. 2017; Peyronnin et al. 2013; Couvillion et al. 2011; Kolker et al. 2011; Blum and Roberts 2009; Morton et al. 2006; Day et al. 2000; Turner 1997; Chmura et al. 1992).

In addition to these anthropogenic influences, high historic rates of subsidence, present-day eustatic sea level rise (Watson et al. 2015; Yi et al. 2015) and predictions of future eustatic sea level rise an order of magnitude (or more) greater than present day rates (Sweet et al. 2017) indicate an uncertain future for coastal marsh survival. Due to spatial variability in hydrologic connectivity to fresh water and sediment sources and to other local factors, this uncertain future will vary both in magnitude and timing across coastal Louisiana marshes.

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The Chenier Plain in western Louisiana is located between Vermilion and Galveston Bays and is largely hydrologically isolated from riverine sources of suspended sediment in coastal Louisiana (McBride et al. 2007), whereas deltaic marshes still connected to the Mississippi and Atchafalaya Rivers, in the central and eastern parts of Louisiana, regularly receive high levels of suspended sediment concentrations (Reed 2002). In general, deltaic plain marshes are less hydrologically restricted, resulting in less "accretion deficit" than in the western Chenier Plain. Jankowski et al. (2017) calculated relative sea level rise from observed shallow subsidence and surface elevation change rates from several hundred monitoring locations in two distinct zones of coastal Louisiana, the Chenier Plain to the west of the state and the Mississippi River Delta to the east available from the Coast-wide Reference Monitoring System (CRMS). The location of these monitoring sites across the coast is based on a statistical design to ensure representation of different vegetation types (Steyer et al., 2003), with each site located away from major bayous and waterways, but adjacent to shallow open water to enable access (Folse et al. 2014). While site-specific local factors may influence measurements, as in any study, the large sample size and coast-wide distribution allow the data to provide an overview of conditions at the system scale. Despite higher rates of relative sea level rise in the Delta ($13.2 \pm 8.8$ mm/yr) than in the Chenier Plain ($9.5 \pm 6.3$ mm/yr), 65% of marshes within the Delta could keep pace with RSLR, whereas only 42% of sites in the Chenier Plain were able. These results were consistent with Cahoon (2015), where surface elevation table-marker horizons (SET) and corresponding tidal gauges were analyzed to determine local rates of RSLR. The SETs monitored local shallow subsidence and accretion, whereas the tide gauges measured water surface elevation and deep/crustal subsidence. While the coverage of the respective observation records varied and resulted in limitations to the conclusions able to be drawn, this analysis indicated that 58% of the wetland locations examined were accreting at rates unsustainable with respect to the calculated local RSLR rates which ranged from 0.1–29.4 mm/yr; values consistent with Jankowski et al. (2017).

This is consistent with both smaller scale field studies of specific sites and from larger scale (e.g. regional) modeling efforts. At the local scale, elevation, distribution of marsh sediments across the marsh profile, soil properties, shallow subsidence/compaction, and soil moisture all play a role in elevation change and accretion (Cahoon et al. 2011; Day et al. 2011). Baustian et al. (2012) used a field experimental approach to document the role of vegetation in promoting both accretion and elevation change in Louisiana marshes. In addition to these localized drivers, regional drivers such as overall sediment supply in the drainage basin and proximity to the suspended sediment distributary source are all sensitive drivers of marshes maintaining adequate elevation (Day et al. 2011; Blum and Roberts 2009; Temmerman et al. 2004). Episodic tropical cyclone events are also important drivers with respect to the spatial and temporal variability of wetland accretion characteristics (Bianchette et al. 2016; Baustian and Mendelssohn 2015; Tweel and Turner 2014; Cahoon et al. 1995; Baumann et al. 1984).

An extensive modeling effort has been undertaken to represent these local and regional processes in coastal Louisiana. These models have been used by coastal resources managers to simulate future wetland losses and land change in coastal Louisiana and to quantitatively assess a variety of potential restoration and protection projects (CPRA 2017; Peyronnin et al. 2013). An integrated modeling tool was developed to simulate long term hydrologic, vegetative, and wetland elevation dynamics for the entire Louisiana coastal wetland system across a variety of environmental conditions (White et al. 2017). It has been used to demonstrate, consistent with other studies (e.g., Chamberlain et al. 2018), that sustaining even part of the Louisiana coast under high sea-level rise rates is challenging (CPRA 2017), This singular modeling framework was used here to examine the relative impacts of regional subsidence, eustatic sea level rise, and sediment availability across coastal Louisiana. A variety of marsh sites across coastal Louisiana were selected for analysis and were examined to determine how each of these factors impacted the ability of marshes to maintain an elevation capital throughout a future 50-year period under a variety of relative sea level rise scenarios.

To simulate future landscape conditions with respect to marsh surface elevation, inorganic sediment supply to the marsh, and relative sea level rise, five scenarios representing different potential future environmental conditions were modeled within the coastal Louisiana region. The five future scenarios were all 50-years in duration and were applied to an identical initial landscape. Simulations using the scenarios are used to explore the role of local versus regional factors in determining coastal marsh survival in the face of sea level rise and to examine the impact that variability of RSLR rates and sediment availability had upon marsh inundation and the subsequent deposition of suspended inorganic sediments onto the marsh surface.

## Methodology

### Integrated Compartment Model

This analysis was conducted with the Integrated Compartment Model (ICM), a planning-level model that was developed by integrating into a single platform several models previously used for coastal zone planning and research within the state of Louisiana (White et al. 2017). The models that are included as subroutines within the ICM include a hydrologic and hydraulic model (Meselhe et al. 2013), a vegetation dynamics model (Visser and Duke-Sylvester 2017), a wetland morphology/elevation change model (Couvillion et al. 2013), as well a barrier island morphology model and several receptor models that summarize environmental conditions into numerous habitat indices and decision-making metrics.

### Hydrology

Hydrologic conditions are simulated within the ICM-Hydro subroutine. This subroutine is a link-node mass balance model capable of simulating: water level (stage), flow rate, salinity, water temperature, suspended sediment concentration, sediment deposition and resuspension within open water areas, sediment deposition on the marsh surface, and a variety of water quality/nutrient constituents (Meselhe et al. 2013; McCorquodale et al. 2017; White et al. 2017). The model is driven by boundary condition data representing tidal water levels and salinities as well as tributary inflows (and corresponding salinity, sediment, nutrient concentrations). Environmental forcing data representing rainfall, temperature, evapotranspiration, and wind are also required model inputs.

The link-node structure of ICM-Hydro utilizes an idealized geometry of the estuary where each model node, or compartment (Fig. 1), represents a unit of open water surrounded by marsh area (and in some cases non-tidal upland drainage areas). Some model attributes are updated annually (e.g. open water bed elevation, marsh surface elevation, portion of compartment that is open water), while others remain constant throughout the simulation periods (e.g. surface roughness of the bed, surface roughness of the marsh).

### Vegetation

Annual land cover, represented by the relative abundance of vegetation species, is modeled within the ICM-LAVegMod vegetation modeling subroutine (Visser and Duke-Sylvester 2017). This vegetation model utilizes annual hydrologic parameters, as simulated by ICM-Hydro, and determines the relative likelihood that a wetland plant species currently on the modeled landscape would experience any mortality. The farther from a species' preferred hydrologic condition, the more rapid the mortality rate for the species. If a more suitable species' for the given hydrologic conditions is within a reasonable distance (defined as a function of a dispersal component of ICM-LAVegMod), the suitable species will establish on any newly bare ground (due to the aforementioned mortality), and the vegetation community will change. The vegetation model operates on an annual model time step and utilizes mean salinity during the growing season (May through August),

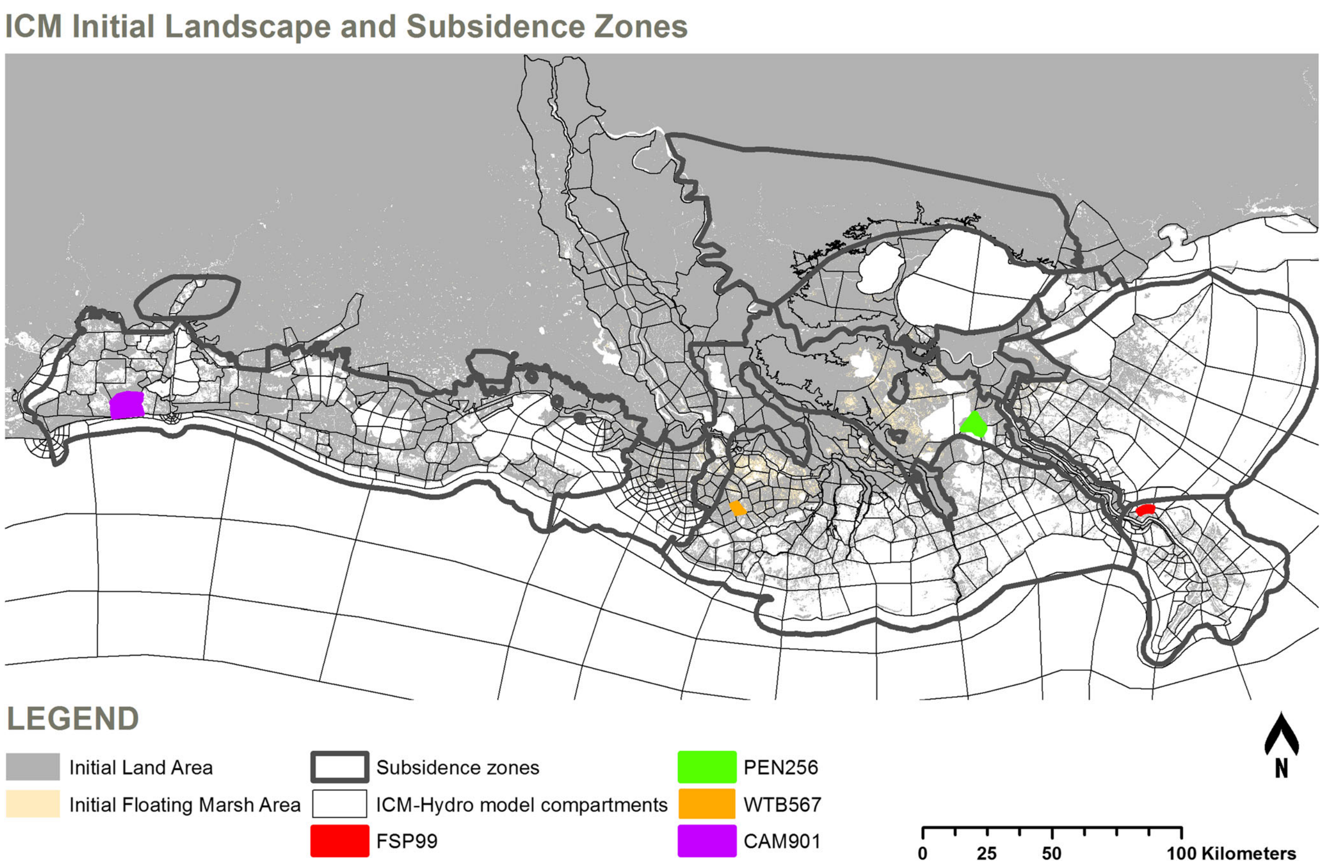


Fig. 1 Initial land/water landscape, ICM-Hydro model domain, study areas, and subsidence zones across coastal Louisiana

and variability of the water surface which is defined as the standard deviation of the water level during the year. Both factors are used to determine changes in vegetation, reflecting the damaging effect of 'stagnant' flooding conditions in some wetlands, especially forested wetlands (Conner et al. 2014; Shaffer et al. 2016). Once simulated, the numerous species modeled are lumped into vegetated habitat type (fresh forest, fresh marsh, intermediate marsh, brackish marsh and salt marsh) and the predominant type is assigned to the landscape for use in the subsequent ICM subroutine, ICM-Morph.

### Wetland Morphology

The wetland morphology subroutine, ICM-Morph, is a relative elevation model that simulates annual elevation change and marsh collapse over time as a function of dynamic variables modeled by the ICM-Hydro and ICM-LAVegMod subroutines: average and maximum annual water levels, maximum two-week mean salinity of the year, inorganic sediment deposition on the marsh edge and interior surfaces, and predominant vegetation type. There are three primary functions within ICM-Morph that determine the fate of wetlands within the model.

First, the elevation change of the marsh surface is a function of downward shifts due to subsidence and upward shifts due to vertical accretion (which includes both inorganic sediment deposition and organic matter accumulation). Inorganic sediment deposition is dynamically linked to the ICM-Hydro simulations. Organic matter accumulation rates are not dynamically calculated; instead, observed organic matter accumulation rates for different predominant vegetation types as measured in CRMS are included in the model. These organic rates vary spatially and by vegetation type, but do not change over time. The second primary function is the determination of new land areas (i.e., land gain); once the elevation of an open water area is 20 cm above the annual water surface elevation (due to sediment deposition), the open water area is no longer considered water but is classified as marsh. The third primary function within ICM-Morph is the wetland collapse (i.e., land loss) component of the model. A fresh marsh or fresh forest land area is converted to water if the area experiences an elevated salinity value for a period of at least two weeks. Salt tolerant marshes (intermediate, brackish and salt) will collapse into open water if the water level is persistently above an inundation depth tolerated by the predominant marsh type. The inundation tolerance levels for intermediate, brackish and salt marshes were developed from remote sensing imagery and a network of water level sensors across coastal Louisiana (Couvillion and Beck 2013). While salinity and inundation induced marsh collapse occur as dynamic responses to simulated depth, salinity, and sediment conditions, the model does not include dynamic processes to account for wave-induced erosion of the marsh edge. Rather, historic rates of marsh edge erosion were determined from satellite imagery and imposed as a temporally constant, yet spatially varied, linear erosive rate (Allison et al. 2017). The ICM-Morph subroutine and theory are described in depth in Couvillion et al. (2013) and White et al. (2017).

## Model Boundary Conditions

The model runs for all scenarios of this analysis utilized identical time series for tributary freshwater inflows to the upstream model boundary. The observed 50-year observed hydrograph for the Mississippi River at Tarbert Landing from 1964 through 2013 was repeated for the future 50-year simulations. River flow for this same time period for 36 tributaries to the coastal zone were developed from a combination of observed records and rating curves (Brown 2017). Suspended inorganic sediment concentrations were derived for the Mississippi River based upon separate sediment rating curves for sand and fines developed from field sampling conducted in the Mississippi River at Belle Chase (Allison et al. 2012). Gridded wind velocity and direction time series were compiled from the North American Regional Reanalysis climate dataset, time series of salinity concentrations, water and air temperature, and water quality nutrient (nitrogen and phosphorus) concentrations were developed from observed data samples (Brown 2017). The wind, temperature, salinity, and water quality time series were developed for the eight-year period used for model calibration/validation (2006–2013), and were repeated 6.25 times to compile a 50-year time series.

## Future Environmental Scenarios

Unlike the model boundary conditions described in the previous section, precipitation, evapotranspiration, subsidence, and eustatic sea level rise (ESLR) were adjusted for each model scenario. The process used to develop the scenarios is described in depth in Meselhe et al. (2017), Reed and Yuill (2017), Pahl (2017), and Habib et al. (2017). Changes in precipitation and evapotranspiration with the different scenarios were determined to have a relatively small impact upon future landscape change in coastal Louisiana, particularly when compared to the relative sea level rise tested here with various combinations of subsidence and ESLR (Meselhe et al. 2017b). Therefore, this analysis focused primarily on the difference in the relative sea level rise (RSLR) rates among the five scenarios modeled.

Three rates of ESLR (each with different acceleration values) were assumed for this analysis (Fig. 2): 0.43, 0.63, and 0.83 m from 2015 through the end of 2064, which correspond to 1.0, 1.5, and 2.0 m of ESLR by 2100 compared to 1992 sea level, respectively (Pahl 2017).

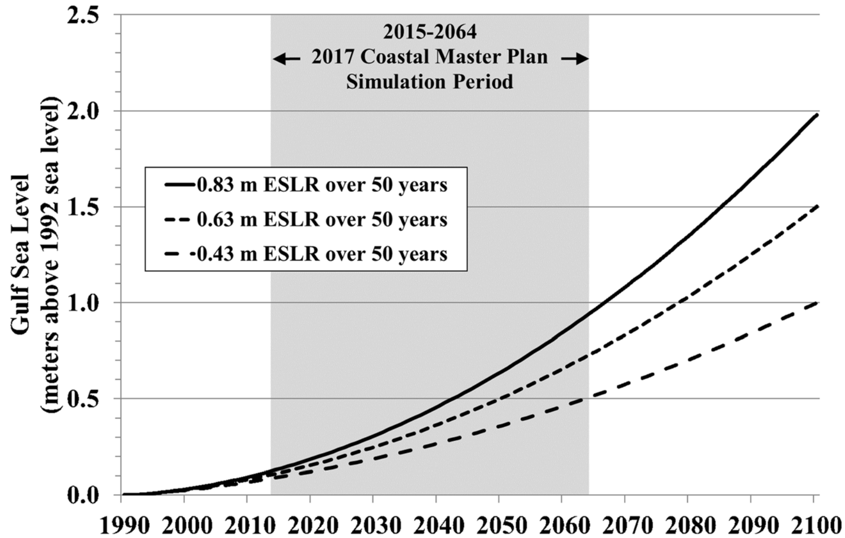


**Fig. 2** The three eustatic sea level rise scenarios used in this analysis

Relative sea level rise rates were assigned based upon these three ESLR rates and a combination of subsidence values, which varied spatially across the model domain. Previous studies have compiled subsidence measurements across coastal Louisiana and developed regional subsidence zones (Fig. 1), with a representative range of subsidence rates for each zone (CPRA 2012). The scenario analyses used here assigned spatially variable subsidence rates for each scenario by selecting the 20th, 35th, and 50th percentile values from across the range of observed data within each zone; each range was assumed uniformly distributed in calculating percentile values. For example, the Birdsfoot Delta subsidence zone had a range of observed subsidence rates between 15 and 35 mm/year; therefore, the 20th percentile value was equal to 19 mm/yr. (15 + 0.2*(35–15) = 19 mm/yr).

From the three ESLR rates and the three spatially varied subsidence rates, five distinct RSLR rates were developed. The low RSLR scenario (SA) combined the low ESLR rate (0.43 m/50-yr) and the low subsidence rate (20% above the minimum). The high RSLR scenario (SE) combined the high ESLR (0.83 m/50-yr) and the high subsidence rate (50% above the minimum). Three intermediate RSLR scenarios were developed from the medium ESLR rate (0.63 m/50-yr) and the low (20% above the minimum), medium (35% above the minimum) and high (50% above the minimum) subsidence rates (SB, SC, and SD, respectively). These five scenarios are summarized in Table 1.

## Study Area

For this analysis, four ICM-Hydro compartments were chosen to represent a variety of conditions across the entire coastal Louisiana model domain (Fig. 1). A compartment immediately adjacent to a Mississippi River delta distributary channel in Breton Sound near Bay Denesse/Old Fort St. Phillip (site FSP99) represented a location receiving a very high amount of freshwater and inorganic suspended sediments. Under initial conditions, this compartment was 8.9 km$^2$ in size, 61% open water with an average open water bed elevation of −1.12 m NAVD88 and an average marsh surface elevation of +0.45 m NAVD88.

The second location chosen (site PEN256) was in the upper portion of the marshes surrounding Barataria Bay, and was adjacent to the Gulf Intracoastal Waterway GIWW and The Pen, a large open water body near the town of Lafitte. This location represented a relatively higher flow regime, due to the presence of the GIWW, however the suspended inorganic sediment concentrations were lower than FSP99 due to isolation from the Mississippi River sediment loads. The 35.9 km$^2$ PEN256 compartment was 15% open water under initial conditions. The average elevation of the open water bed was −1.29 m NAVD88 and the marsh surface had an average elevation of +0.19 m NAVD88.

A third location (site WTB567) was selected in Western Terrebonne along Creole Bayou, north of Carencro Lake. The inorganic sediment concentrations available in this region were lower than in the Birdsfoot Delta, however the presence of the Atchafalaya River delta in the general area resulted in a slightly higher suspended sediment concentration than seen at PEN256. Under initial landscape conditions, this compartment was 13% open water with an average open water bed elevation of −0.05 m NAVD88, an average marsh surface elevation of +0.41 m NAVD88, and was 16.2 km$^2$ in area.

The fourth and final location chosen for this study was in the westernmost region of the model domain and represented a particularly low suspended inorganic sediment environment; site CAM901 was located in Cameron Meadows immediately north of Holly Beach and west of Mud Lake in between the Calcesieu and Sabine river outlets. This location was in the interior marsh along the Chenier Plain and received very little to no suspended inorganic sediments in the model

**Table 1** Relative sea level rise scenarios

| Scenario Code | Eustatic sea level rise (2015–2064) | Subsidence Rates | Description |
|---|---|---|---|
| SA | 0.43 m | 20% | Low |
| SB | 0.63 m | 20% | Intermediate-Low |
| SC | 0.63 m | 35% | Intermediate |
| SD | 0.63 m | 50% | Intermediate-High |
| SE | 0.83 m | 50% | High |

simulations. The CAM901 compartment was 6% open water, had a total area of 84.2 km$^2$ with an average open water bed elevation of −1.17 m NAVD88 and average marsh surface elevation of +0.60 m NAVD88 under initial conditions.

In addition to the varied suspended inorganic sediment environment at each of the four locations, the modeled subsidence rates for each location was also different; the range in subsidence rates used in this analysis are provided in Table 2, and the subsidence zones used are shown in Fig. 1.

### Inundation and Sediment Deposition Analysis

Marsh inundation was determined from the daily average water surface elevation for each of the four model compartments and the compartment's marsh area was considered inundated if the daily mean water surface was at or above the mean marsh surface elevation of the compartment. The surface elevation within the model was tracked at a 30-m resolution and updated annually to account for subsidence rates and vertical accretion, which was determined from both inorganic sediment deposition and organic matter accumulation, as described above. The mass of the sediment deposition was determined per unit area of marsh surface and accounted for inorganic sediment deposited from suspended sediments routed onto the marsh surface during inundation only. Model output from every fifth model year was used; all post-processing of model output data was conducted with Python 2.7.8 (Python, 2016), and utilized the NumPy (van der Walt et al. 2011) and ArcPy (ESRI 2017) libraries.

**Data Availability** The model input and output data generated for this analysis are archived and available upon request from the corresponding author or from CPRA.

## Results

### Model Calibration and Validation

A thorough model calibration and validation analysis was conducted as part of the model development process, as documented in Brown et al. (2017). Across the model domain, approximately 200 observation data points were used to calibrate and assess model performance with respect to flow rate, water level, salinity and total suspended solids (TSS) (model output of suspended inorganic sediment was compared to observed TSS data). The most sensitive model parameters which were used as the primary calibration parameters included: channel roughness for calibration of flow and water levels, diffusivity coefficients for salinity, and particle-specific calibration coefficients included in the sand and non-sand sediment distribution equations (McCorquodale et al. 2017).

The primary hydrologic parameter driving land elevation change within ICM-Morph, annual mean water level, was well validated with a root-mean-square-error of 8 cm during calibration and 7 cm during the validation period. Short term (e.g. daily) water levels were predicted with a root-mean-square-error of 12 cm and 14 cm for calibration and validation periods, respectively. Performance statistics for all calibrated and validated variables are provided in supplementary materials.

### RSLR, Sediment Deposition and Land Area Change

Of the four compartments analyzed, FSP99 in the Birdsfoot Delta region was the only one with predicted gains in land area throughout the 50-year ICM simulations. Under all five scenarios, FSP99 indicated a slight decrease in land area throughout the first three decades (Fig. 3); however, due to continued access to high suspended sediment concentrations and deposition in the open water areas (Fig. 5), the land area increased under all five scenarios in the last two decades. In all but the

**Table 2** Study area descriptions and environmental conditions for each location

| ID | Description | Inorganic Sediment Environment | Subsidence Range |
|---|---|---|---|
| FSP99 | Marsh area adjacent to Bay Denesse near Old Fort St. Phillip in Breton Sound | High | 15–35 mm/yr |
| PEN256 | Marsh area bounded by the Gulf Intracoastal Waterway and The Pen near Lafitte in Upper Barataria | Medium-Low | 2–10 mm/yr |
| WTB567 | Marsh area along Creole Bayou north of Carencro Lake in Western Terrebonne | Medium-High | 6–20 mm/yr |
| CAM901 | Cameron Meadows west of Mud Lake and immediately inland from Holly Beach | Low | 1–15 mm/yr |

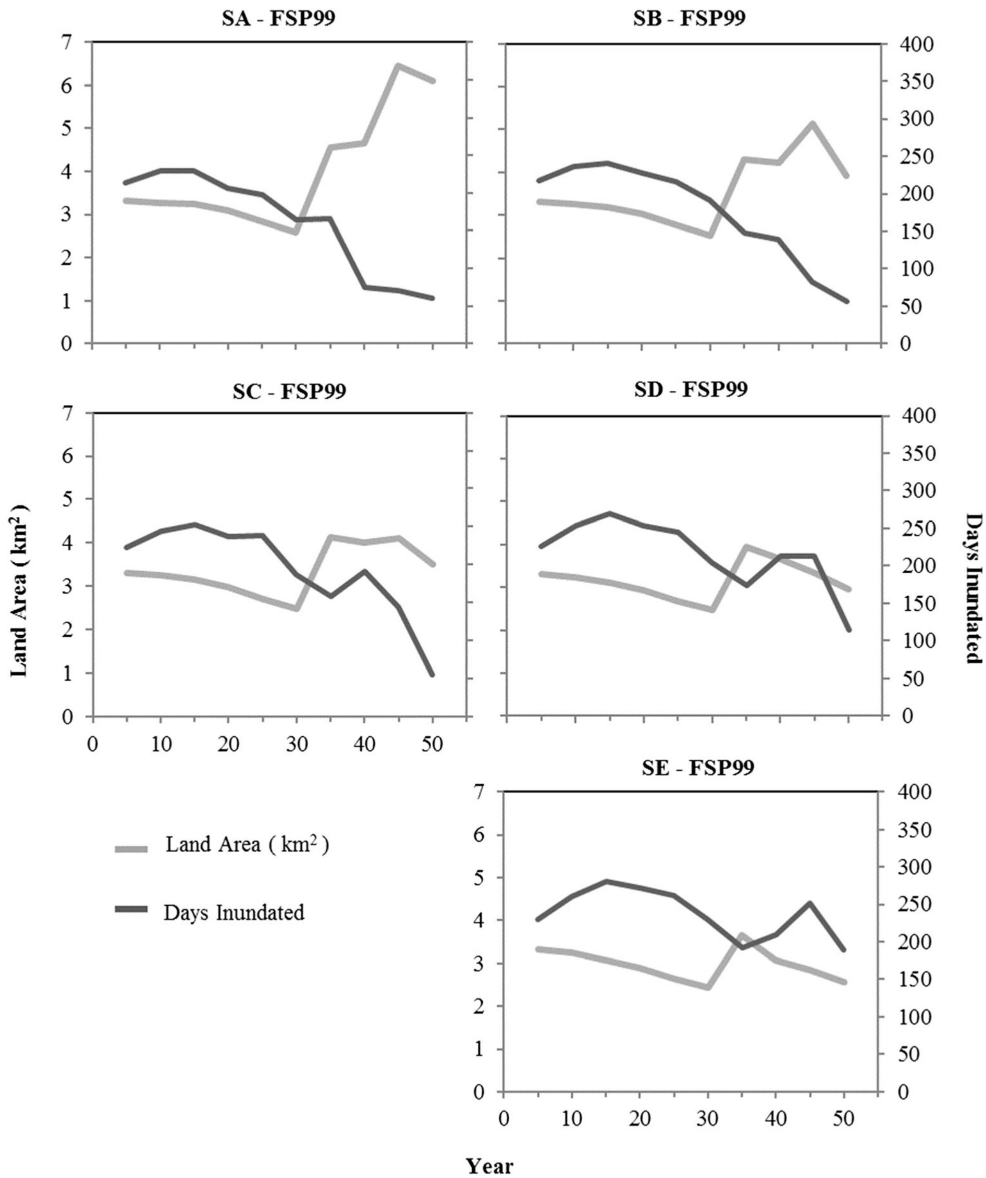


**Fig. 3** Change in land area and time inundated over future 50-year scenarios in the Birdsfoot Delta near Fort St. Phillip (FSP99) for Low RSLR (SA), Intermediate-Low RSLR (SB), Intermediate RSLR (SC), Intermediate-High RSLR (SD), and High RSLR (SE)

two most severe RSLR scenarios, the area of land at year 50 was greater than after just five years; under the Intermediate-High scenario (SD), there was no net change at the end of the simulation, and under the High RSLR scenario (SE), there was approximately 0.75 km$^2$ of net loss.

The FSP99 compartment was subjected to the highest RSLR rates within the ICM domain due to the high subsidence rates in the Birdsfoot Delta (Table 2); however, this compartment was predicted to have a decrease in inundation over time under all five scenarios (Fig. 3). This indicates that not only was the land area increasing under most scenarios, but the marsh surface was also accreting vertically at a pace faster than local RSLR. In addition to deposition in the open water area of the FSP99 compartment, the high concentrations of suspended inorganic sediment within the distributaries of the Birdsfoot Delta resulted in a consistent increase over time in the mass per unit area of sediment deposited on the marsh surface (Fig. 4). The increase in deposited sediments is gradual during the first two decades, but by year 30 the mass per unit area has increased dramatically from the magnitude of earlier decade deposition values. This is due to the location of the FSP99 compartment within the Birdsfoot Delta and the land change dynamics occurring in the areas between the Mississippi River and the FSP99 compartment. After the first 20 simulated years, the area immediately upstream of FSP99 (i.e. between FSP99 and the river) is slowly shoaling in the open water area. By year 30 under the Low RSLR scenario (Fig. 5) the area has filled in and is nearly all marsh with a large reduction in open water area. This sediment that had been depositing and

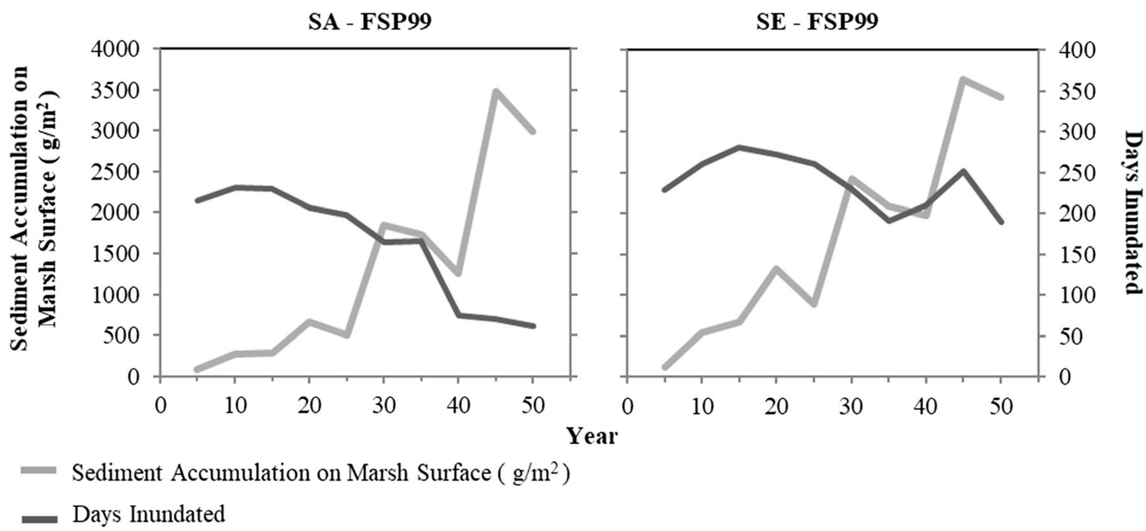


**Fig. 4** Mass of sediment deposited during year per unit area of marsh surface in FSP99 under the Low RSLR (SA, left) and High RSLR (SE, right) scenarios

shoaling the upstream compartment is now carried further downstream where larger sediment mass per unit area is depositing on the marsh surface of FSP99, regardless of the reduction in inundated time in the later decades.

In the westernmost compartment, CAM901, the land area and the number of days inundated respond consistently across all scenarios except the lowest RSLR case (SA), where the land area remains nearly constant throughout all five decades despite an increase from only 11 inundated days at year 5 to 177 inundated days during year 50 (Fig. 6). All other scenarios had more than 300 inundated days by year 50 and experienced much greater land loss area than the lowest scenario; nearly half of the land area was lost by year 50 under the Intermediate scenario and essentially all of the land was lost to open water by year 50 under the High scenario.

Except for the Low scenario, land area at CAM901 was seen to decrease in all scenarios, with a distinct acceleration once the marsh surface was inundated for 200 days in a year or more. Under the Intermediate-Low scenario, this 200-day threshold occurred around year 40, prior to which the land area had held relatively constant in CAM901. Once the 200-day inundation threshold is exceeded, this compartment experiences an ever-increasing amount of wetland collapse. This increasing marsh collapse with respect to increasing inundation is consistent with salt marsh stability under increasing inundation depths (Morris et al. 2002).

As the marsh surface is inundated nearly 100% of the time and loss occurs, there is an increase to the mass per unit area of deposited inorganic sediments upon the marsh surface in CAM901 (Fig. 7). This is due to two complementary factors. First, as the water levels increase and inundation is more persistent on the marsh surface, a longer period of inundation results in a longer period of time for suspended sediments to settle onto the marsh surface; thus, increasing the mass load of sediment. Concurrently, the area of marsh surface over which the sediments are settling has been reduced, further increasing the load per unit area. Even if the mass loading remained constant over time, the area available for deposition was decreasing, which would still result in a larger mass loading *per unit area* of the marsh surface. While the trend of sediment deposition per unit area increase is abrupt in the last decade at CAM901, the overall magnitude of the deposition mass per unit area is still extremely low for when compared to other model locations.

The PEN256 compartment in the upper portions of the Barataria basin demonstrates very similar land loss temporal patterns as the Chenier Plain compartment. While the hydrology of these two locations are dissimilar (PEN256 is bisected by the GIWW and has access to fresh water inflows, CAM901 is generally isolated and adjacent to the Gulf of Mexico), they have very similar subsidence rates and are limited in sediment availability within the model (Table 2). The PEN256 compartment is relatively stable with respect to land area in the first few decades, however, once the average marsh surface elevation is inundated by the daily mean water level approximately 80% of the time (~300 days), the marsh area begins to persistently decrease through time across scenarios (Fig. 8).

The Western Terrebonne location, WTB567, experienced higher subsidence rates than either CAM901 or PEN256, however the proximity to the Atchafalaya River Delta and the second-most sediment availability of the four locations analyzed, resulted in a relatively resilient land area under all scenarios (Fig. 9). Under the three low and medium subsidence scenarios (SA, SB, SC), the land area within WTB567

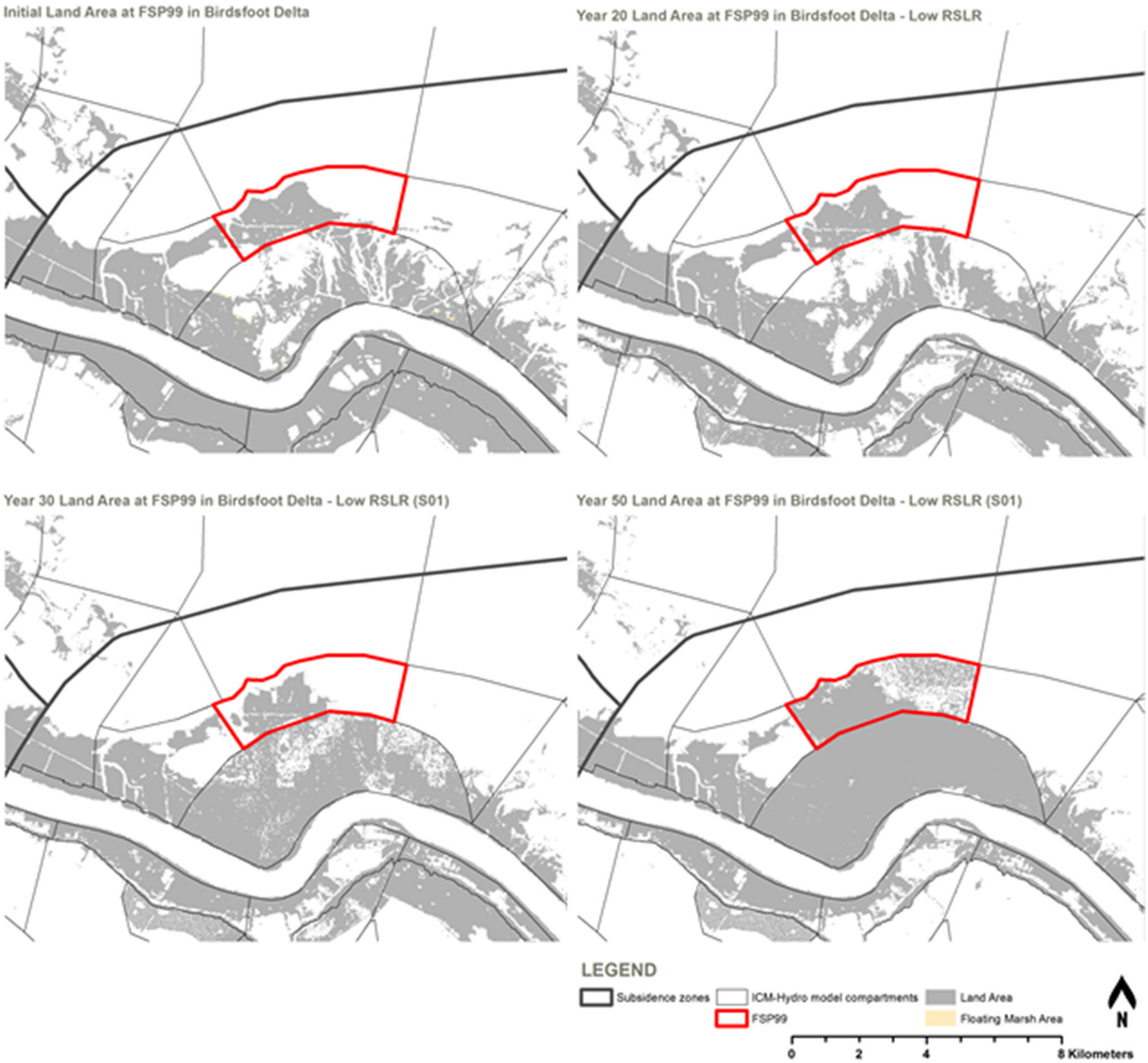


**Fig. 5** Land change in the Birdsfoot Delta near Fort St. Phillip (FSP99) over time under the Low RSLR scenario (SA)

remained essentially constant until year 50 despite ever-increasing periods of inundation due to the assumed RSLR scenarios. It was not until the Intermediate-High and High RSLR scenarios, both of which assumed the highest subsidence rate values, that substantial land loss occurred in this compartment.

## Discussion

### Model Performance and Limitations

The ICM was developed by integrating legacy models used to examine the long-term trends and physical processes important for coastal restoration decision-making in coastal Louisiana. Rather than using a "bathtub model" approach where projected rates of sea level rise are more-or-less imposed upon present-day landscapes (Poulter and Halpin 2008), the ICM simulates the response of the land surface to future hydrologic changes. The ICM, as developed and used, provides a planning-level tool which aimed to incorporate the primary physical drivers of vegetation change and wetland sustainability across the entire coastal zone of Louisiana over multi-decadal timescales. The nature of such a model limits applicability to examination of large-scale spatial and temporal trends under an array of assumed future relative sea level rise scenarios. With that said, this analysis was focused on five distinct locations across the model domain with the

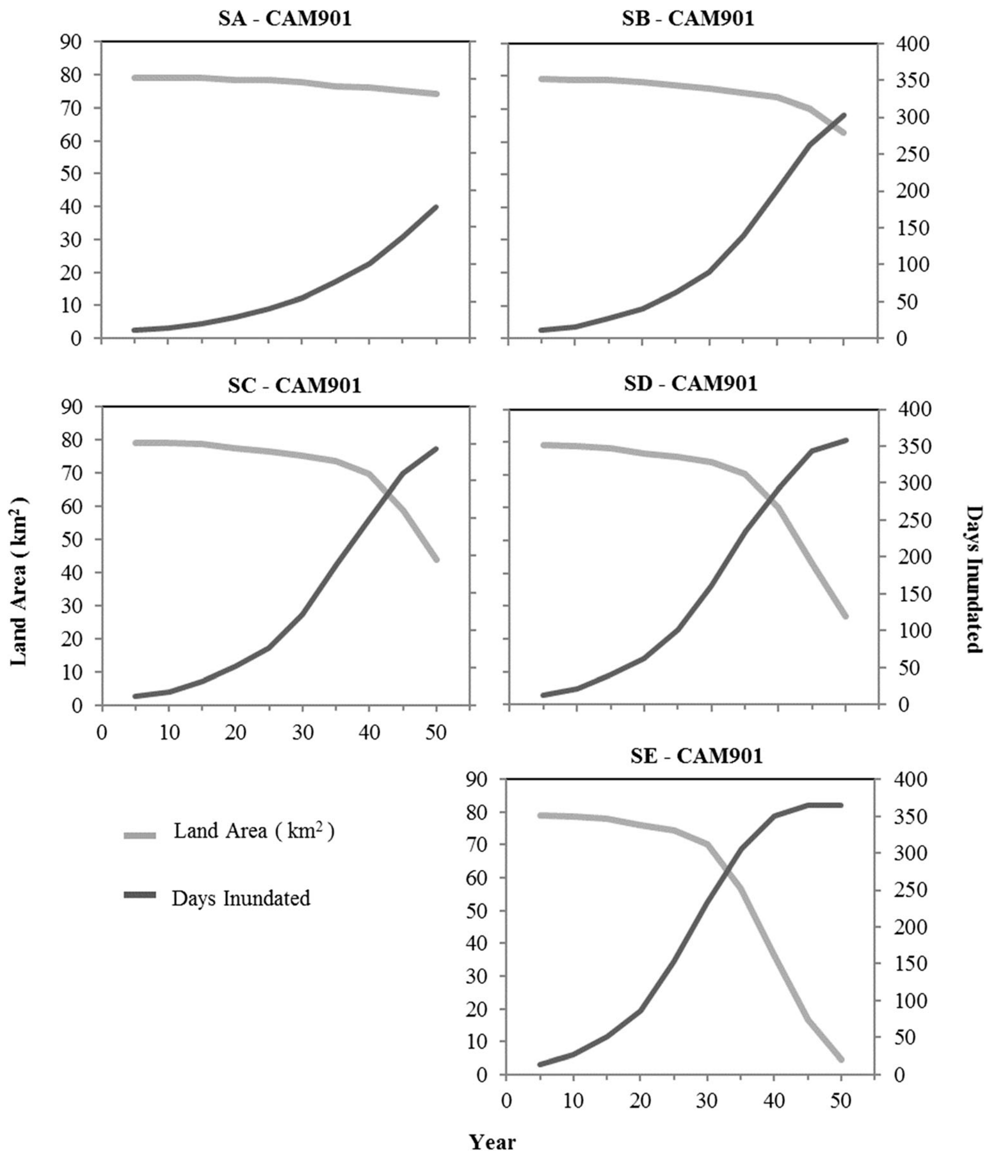


**Fig. 6** Change in land area and time inundated over future 50-year scenarios in the Chenier Plain near Cameron Meadows (CAM901) for Low RSLR (SA), Intermediate-Low RSLR (SB), Intermediate RSLR (SC), Intermediate-High RSLR (SD), and High RSLR (SE)

intent to examine the variability in modeled processes and to compare the modeled system's sensitivity to environmental drivers across the entire model domain. By comparing these modeled trends to literature, this analysis examined the model performance with respect to previous observations and studies which ranged from small-scale field experiments to basin-scale geospatial analyses. Further discussion of model uncertainty and limitations is provided in supplementary materials.

## Influences on Land Loss

Despite uncertainty surrounding the exact future landscape throughout coastal Louisiana, the ICM appears to reasonably capture dynamics of wetland collapse across a wide range of RSLR scenarios at the four locations selected to reflect an array of inundation and sediment deposition patterns into the future. The complex temporal patterns of land area change and inundation periods in the Birdsfoot Delta indicate that if a consistent suspended sediment supply is available (all five scenarios used the same Mississippi River hydrograph and sediment rating curve) upstream shoaling and delta building eventually impacts downstream marsh and open water areas. Under a low RSLR scenario (SA), substantial land area was gained by deposition in open water and enough shoaling occurred to maintain land building regardless of RSLR. This is consistent with observations in the Birdsfoot Delta by White (1993) of vegetation colonization of accreting mudflats and the findings of Cahoon et al. (2011) who identified three distinct stages to wetland formation in a crevasse splay in the Birdsfoot Delta based on field studies: sediment infilling, vegetative colonization, and development of a mature wetland

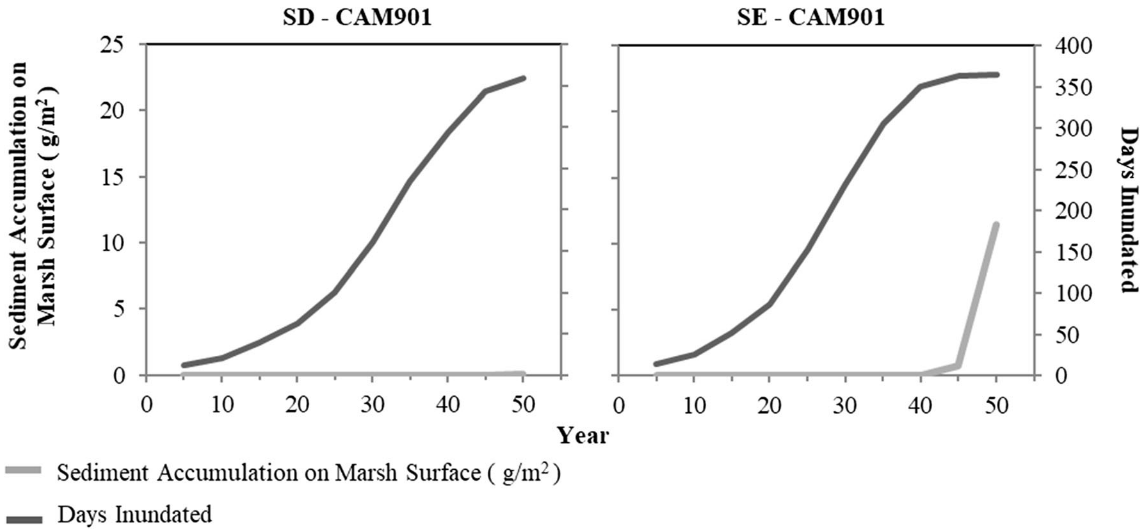


**Fig. 7** Mass of sediment deposited during year per unit area of marsh surface in CAM901 under the high subsidence rate scenarios: Intermediate-High RSLR (SD, left) and High RSLR (SE, right)

community. Under all other scenarios, the increased marsh surface deposition occurring after upstream shoaling and delta building indicates that while land gain from shoaling in the Birdsfoot Delta could potentially expand the delta footprint within the vicinity of FSP99 under lower RSLR scenarios, this effect will likely be limited if higher RSLR rates occur in later decades. The general trend of maintaining marsh area while not drastically changing the hydroperiod of the FSP99 compartment is consistent with recent observations under current RSLR conditions indicating most marsh sites examined near the Mississippi Delta experience vertical accretion rates that are adequate in maintaining viable marsh area in light of RSLR (Jankowski et al. 2017).

The relatively stable marsh area modeled in Western Terrebonne is due to a consistent supply of sediment available for deposition onto the marsh surface, due to the proximity to the Atchafalaya River delta, consistent with the findings of Twilley et al. (2016) who found an overall retreat of the 50% land/water isopleth of 17-km in the Terrebonne basin. This was compared to a retreat of only 22-m in the Atchafalaya basin over the same period (1932–2010). The WTB567 site is located on the westernmost edge of Terrebonne and receive a sediment signal from the proximity to the Atchafalaya River. Unlike FSP99, WTB567 was exposed to a high suspended sediment concentration continually reaching the marsh surface. As inundation increased over time, the mass of sediment depositing per unit area increased proportionally (Fig. 10). Under the High RSLR scenario (SE), there was a collapse of marsh area in the last decade (Fig. 9), although the mass of sediment inundating the marsh continued to be relatively constant across scenarios due to the proximity to the Atchafalaya River delta. Therefore, when the marsh area receiving the deposited sediments drastically decreased, the mass loading per unit area experienced a sharp increase (Fig. 10). However, under this High RSLR scenario, the increase in sediment load per unit area did not appear to be enough to adequately maintain the remaining marsh land area over the last decade as the land loss in WTB567 continued until the end of the 50-year simulation. This trend of increased sediment loading as the marsh is rapidly degrading is consistent with field observations of large increase in sediment deposition on the surface of a degrading marsh in eastern Terrebonne due to elevation loss and fragmentation (Day et al. 2011). The proportional increase in sedimentation with increased inundation frequency is consistent with higher accretion values in low marsh and open water as compared to high marsh and forested zones in a sediment-rich marsh in an active crevasse splay in the Birdsfoot Delta (Cahoon et al. 2011). The inorganic deposition from suspended sources may increase as the marsh platform is lower in the tidal frame, however without additional increases in organic matter accumulation, the total vertical accretion may still be inadequate to counteract RSLR (Baustian et al. 2012).

The model results in the upper portion of Barataria basin at PEN256 show remarkably consistent behavior across the three intermediate scenarios, all of which were subjected to the same ESLR rate of 0.63-m over 50 years (Fig. 8). This location had both the smallest range and smallest magnitude of subsidence rates examined, and as a result inundation and land loss behavior is primarily a function of assumed ESLR rates in this region of the model. The sensitivity to ESLR is

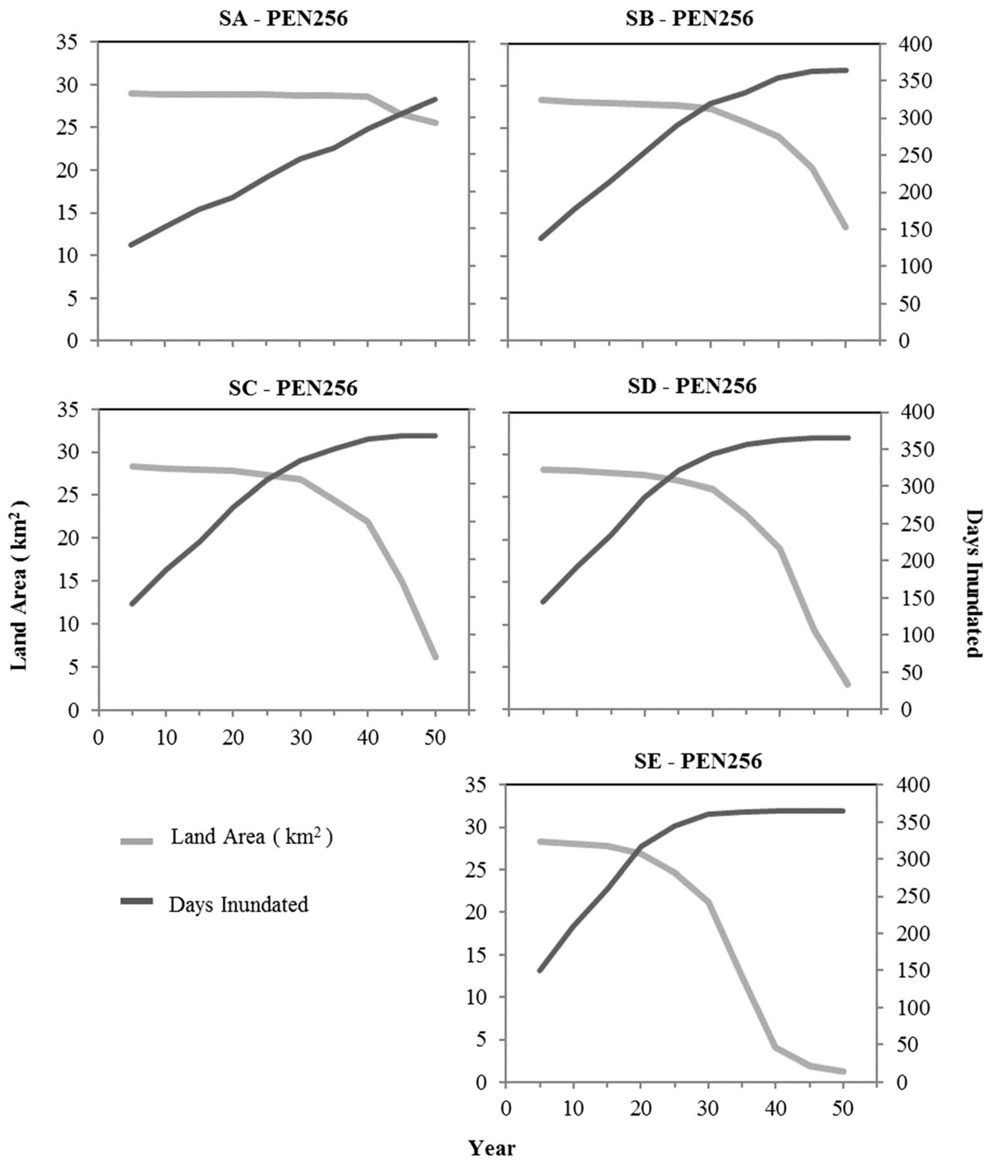


**Fig. 8** Change in land area and time inundated over future 50-year scenarios in upper Barataria near Lafitte (PEN256) for Low RSLR (SA), Intermediate-Low RSLR (SB), Intermediate RSLR (SC), Intermediate-High RSLR (SD), and High RSLR (SE)

likely responsible for the acceleration of both inundation and land loss during later decades, as the assumed ESLR rates increase over time. This location is also in a low sediment environment; only in the last decade of the most severe RSLR scenario (SE), does PEN256 experience an annual sediment deposition rate greater than 100 g/m$^2$. The overall sedimentation rate on the marsh surface at PEN256 is an order of magnitude less than the rates seen in the Birdsfoot Delta at FSP99 and less than half of the rates seen near the Atchafalaya Delta at WTB567. Therefore, even though inundation increases with increased severity of RSLR at the PEN256 site, the low sediment environment appears to result in no clear benefit from the increased inundation; overall rates of land loss increase in time across all RSLR scenarios.

The inundation/land area behavior across the modeled scenarios also provides insights into the relative sensitivity to subsidence and ESLR (e.g., global mean sea level rise) in a low sediment and low subsidence environment. At CAM901 in the Chenier Plain, if actual subsidence over the next 50-years were to occur at a rate near lower end observations and low rates of ESLR occur (SA), the land area at year 50 within this model compartment will be nearly unchanged. The model results show only a slight increase in the loss rate during the last simulated decade if a moderate rate of ESLR is experienced (SB) (Fig. 6). If subsidence were to occur at higher rates, inundation behavior would not change dramatically under a moderate ESLR rate. However, a substantial increase in the land loss rate would occur (SC and SD, as compared to SB in Fig. 6). If subsidence would occur at the most rapid rates, there would be slightly more land loss under a high rate of ESLR as compared to a moderate rate (SE vs. SD), however the behavior is remarkably similar

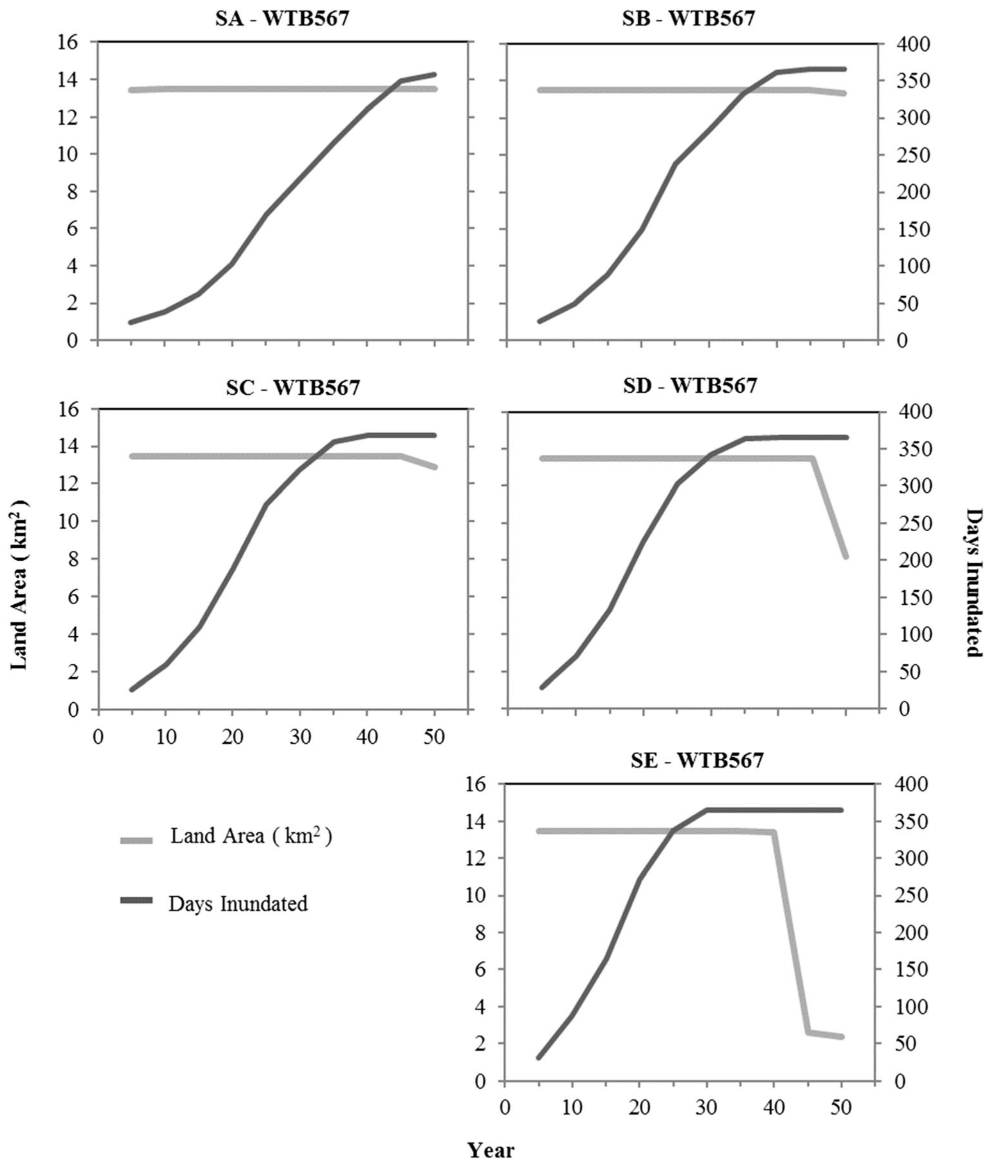


**Fig. 9** Change in land area and time inundated over future 50-year scenarios in Western Terrebonne (WTB567) for Low RSLR (SA), Intermediate-Low RSLR (SB), Intermediate RSLR (SC), Intermediate-High RSLR (SD), and High RSLR (SE)

with respect to land loss rates between these high subsidence scenarios at CAM901. While the lowest rate of RSLR indicated only a slight decrease in land area over time, all other scenarios indicated large loss rates. This is consistent with the findings from recent data collection efforts (Jankowski et al. 2017; Bianchette et al. 2016), in which a larger portion of marsh locations in the Chenier Plain are at an accretion deficit than in the Mississippi Delta, and are therefore more susceptible to RSLR-induced land loss.

## Conclusions

This analysis has demonstrated the utility of integrated modeling approaches in providing insights on how coastal land loss may respond to changing future conditions. The existing spatial variation in factors such as subsidence and sediment availability across coastal Louisiana provide a context for understanding and then simulating and validating complex feedbacks among driving processes. The multidecadal simulations described here, using multiple scenarios of future conditions, show how areas of relative landscape stability under existing conditions can dramatically change. Due to the spatially varied subsidence observations used in this modeling analysis, the most sediment rich locations within the coastal zone, near the Mississippi and Atchafalaya deltas, were also subjected to the highest rates of relative sea level rise. The location in Western Terrebonne maintained existing marsh area for nearly the entire 50-year simulation under all but the highest RSLR scenario due to high sediment deposition rates on the marsh surface but eventually experienced degradation. The location in the

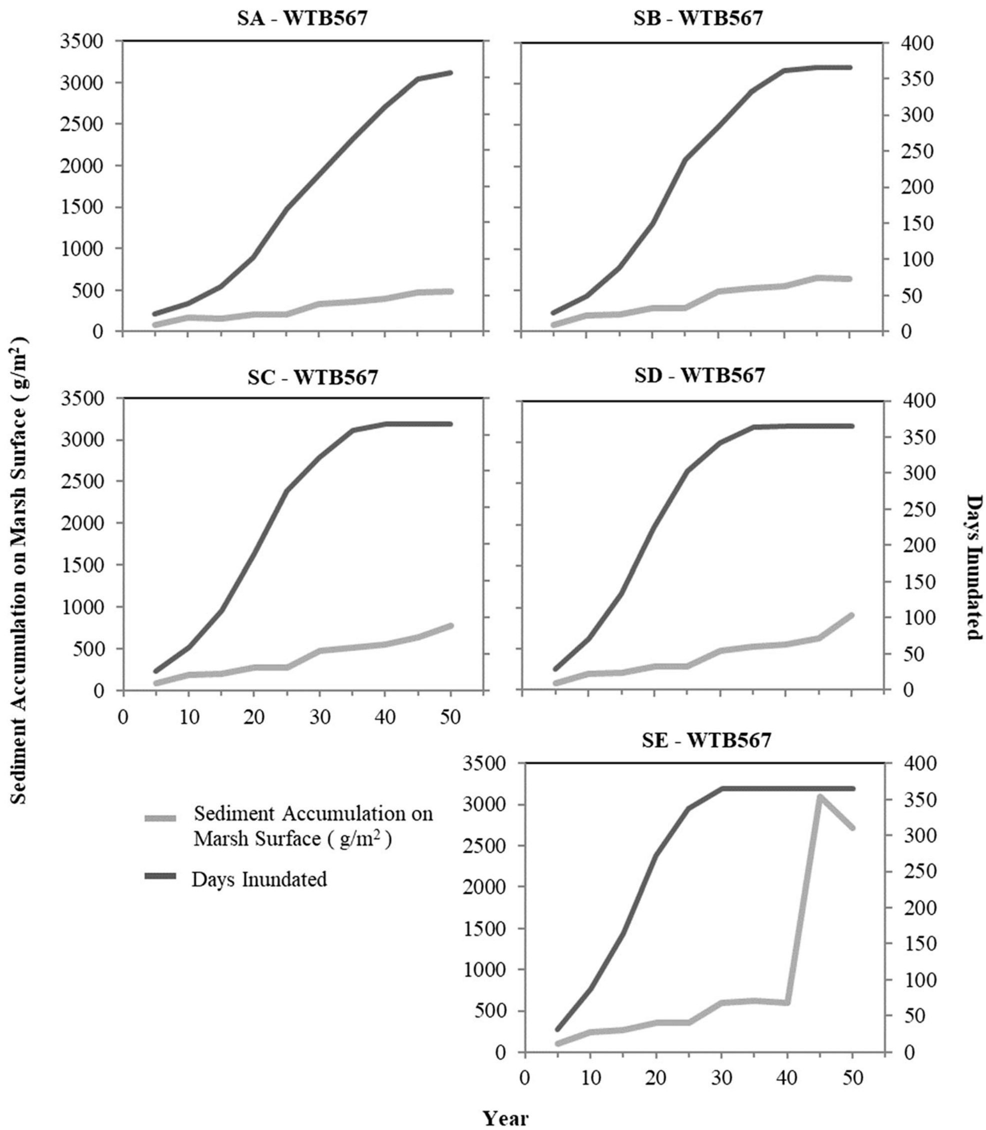


**Fig. 10** Sediment deposition during year per unit area of marsh surface in Western Terrebonne near Carencro Lake (WTB567) for Low RSLR (SA), Intermediate-Low RSLR (SB), Intermediate RSLR (SC), Intermediate-High RSLR (SD), and High RSLR (SE)

Birdsfoot Delta increased the area of marsh over the simulation period under all but the highest RSLR scenario due to both deposition on the marsh surface and shoaling and eventual land building in the open water areas. Further analysis of this type could be used to identify specific 'tipping points' beyond which marshes in different locations will be unable to survive.

For areas without sediment input, model results can be used to anticipate rates of change. The two locations with poor sediment availability, in upper Barataria and in the Chenier Plain, showed persistent loss of marsh area over time regardless of RSLR scenario modeled. While the rate and magnitude of these losses varied by location and scenario, the trend was consistent. The best-case scenario of those modeled for these two compartments was the Low RSLR scenario, which still resulted in at least some land loss by the latter model decades. Areas such as this, where time is limited may be the focus of 'triage' type restoration planning where models can be used to identify what, if anything, can be done to improve sustainability.

In addition to the sediment deposition, inundation, and land change results presented here, the vegetation dynamics and a variety of habitat and ecosystem services within coastal Louisiana are also simulated by the ICM. The ability to quickly and systematically conduct scenario analyses with a physically based numerical model of the Louisiana coastal zone that captures wetland elevation dynamics and delta building (albeit in a coarse resolution), will allow coastal zone managers and researchers the ability to further assess the relative sensitivities of coastal wetlands to any array of known and unknown future environmental and physical perturbations.

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