Beneficial Use Decision Support for Wetlands: Case Study for Mobile Bay, Alabama

Kyle D. Runion[1]; Brandon M. Boyd[2]; Candice D. Piercy, M.ASCE[3]; and James T. Morris[4]

Abstract: The beneficial use of dredged material (BUDM) for wetland restoration improves coastal wetland resilience and conserves coastal natural infrastructure. Tools, such as biophysical models help coastal managers to assess habitat vulnerability and plan restoration. In this study, the Marsh Equilibrium Model (MEM) will be utilized combined with observed data to predict future conditions and evaluate potential marsh restoration via the BUDM in Mobile Bay, Alabama. A range of site conditions and restoration strategies will be considered and the impacts on dredged material management area (DMMA) volumes will be evaluated. Wetland restoration via thin-layer placement (TLP) of dredged material (DM) restores marsh elevation to combat sea level rise (SLR) and conserves fill capacity in DMMAs. A simplified mapping approach to assess this type of restoration will be demonstrated using wetland area and DM sources to determine the coastal United States wetland area to which it could be further applied. The mapping exercise revealed that 6,240 km^2 of US wetlands were suitable for restoration and sediment resources exist to conduct this type of restoration from navigational dredging. The further development of a spatial application of the MEM is needed to provide an operational tool for managers and refine these restoration estimates. **DOI: 10.1061/(ASCE)WW.1943-5460.0000650**.

Introduction

Wetlands are one of the most valuable ecosystems on the planet, which provide ecosystem services, such as flood control, shoreline stabilization and protection, and biodiversity support (Zedler and Kercher 2005). Historically, the extent of wetlands in the United States has declined to below half the area before European settlement, which is due to land use conversion for agriculture and development (Dahl 1990; Dahl et al. 1991) and is further projected to decline through conversion to open water faced with sea level rises [(SLRs) Craft et al. 2009]. Coastal wetlands exist at an elevation within the tidal range and naturally accrete or erode to maintain this elevation with changing sea levels (Redfield 1972; French 2006). With accelerated rates of SLRs, coastal wetlands that do not have sufficient sediment and space to migrate might transition to subtidal environments, which results in ecosystem services losses. The relative global salt marsh loss by 2100 is projected to be as high as 45%, although if provided with enough migration space and sediment supply the wetland extent could potentially expand (Craft et al. 2009; Schuerch et al. 2018). However, even under future scenarios where the wetland extent increases, widespread or complete local losses might occur in areas with negative sediment balances and a limited area for migration.

Wetland restoration is a long-standing practice that has recently become more prevalent in coastal management to protect and enhance ecosystem services (Patten 2006). Sediment is often needed in wetland restoration to nourish the wetland and increase the elevation (Weishar et al. 2005), especially in developed areas. Managers of coastal resources must balance the resources and need for sediment in wetland restoration. Integrating the beneficial use of dredged material (BUDM) via thin-layer placement (TLP) for wetland restoration into regional sediment management plans could generate restoration opportunities and improve management success (Khalil and Finkl 2009).

The BUDM could provide environmental benefits through ecosystem restoration and economic benefits through efficient resource allocation. Dredged material (DM) might be a valuable resource in coastal systems where opportunities for the BUDM exist (RSMW 2013). The practice of the BUDM was introduced in the 1970s (Montgomery and Griffis 1973) and through advances in technology, improvements in techniques, and an increase in need, has become more prevalent (EPA and USACE 2007). The USACE dredged approximately 160 million m^3 of material annually from navigation projects nationwide between 1998 and 2017 (USACE 2020a). In general, the majority of DM is suitable for beneficial use (IADC 2019), although approximately only 38% is used beneficially in the United States (Fig. 1; USACE 2020a). Material that is not used beneficially is generally placed within onshore dredged material management areas (DMMAs) or offshore ocean dredged material disposal sites (ODMDSs). DMMAs might occupy otherwise productive, valuable coastal land and require active management to maintain them (INA 2002). Placement in an ODMDS might require costly transport, degrade local habitats, and include uncertainty regarding the fate of placed material (Zimmerman et al. 2003; Noakes and Jutte 2006; Chen et al. 2018). The BUDM could reduce the volume of material placed in DMMAs or ODMDSs and provide ecological benefits.

Modeling is useful to help resource managers predict the future state of coastal ecosystems (Konyha et al. 1995; Morris et al. 2002;

[1]Research Assistant, Dept. of Marine Science, Univ. of Texas Marine Science Institute, 750 Channel View Dr., Port Aransas, TX 78373-5015; formerly, Research Fellow, US Army Engineer Research and Development Center (ERDC), 3909 Halls Ferry Rd., Vicksburg, MS 39180-6199. ORCID: https://orcid.org/0000-0002-2582-1310. Email: kyle.runion@utexas.edu

[2]Research Oceanographer, Coastal and Hydraulics Laboratory, US Army ERDC, 3909 Halls Ferry Rd., Vicksburg, MS 39180-6199 (corresponding author). Email: brandon.m.boyd@erdc.dren.mil

[3]Research Environmental Engineer, Environmental Laboratory, US Army ERDC, 3909 Halls Ferry Rd., Vicksburg, MS 39180-6199. Email: candice.d.piercy@erdc.dren.mil

[4]Research Professor and Distinguished Professor Emeritus, Belle Baruch Institute for Coastal and Marine Science, Univ. of South Carolina, 712 Main St #607, Columbia, SC 29208-4111. Email: morris@inlet.geol.sc.edu

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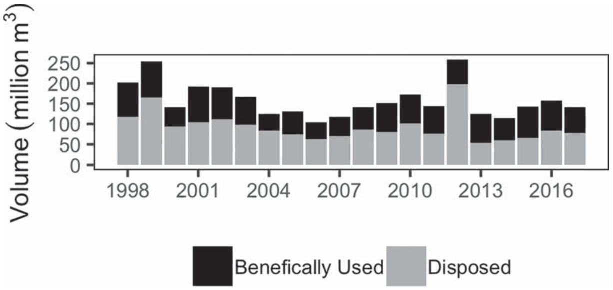

Fig. 1. Total beneficially used and disposed of US DM volumes from 1998 to 2017. (Data from USACE 2020a.)

Craft et al. 2009; Schile et al. 2014). Numerical modeling of physical characteristics, such as elevation allows managers to develop estimates of restoration need and potential. Mineral and organic contributions from suspended sediment and in situ biological production are critical to include, because marsh accretion depends on both sources to maintain elevation (Nyman et al. 1993; Turner et al. 2004; Mudd et al. 2010).

The Marsh Equilibrium Model (MEM) is a one-dimension numerical model that is used to estimate point vertical accretion through a mass balance approach (Morris et al. 2002; Morris et al. 2020). Vertical accretion is a function of organic and mineral inputs that alter elevation at the surface by a combination of deposition and organic contributions to soil volume via root and rhizome production and organic decay. Mineral deposition is defined as a capture efficiency of the suspended sediment concentration (SSC) and inundation status (defined as flooding frequency, fractional time flooded, and depth). Erosion is not considered, although it can be incorporated in combination with other models (Alizad et al. 2018). Vegetative characteristics, which are used to calculate biological processes, are defined by model inputs, such as growth rate limits, optimal growth elevation, and peak biomass concentration (Morris et al. 2016). The stable fraction of below-ground biomass is the only organic contribution to marsh elevation, because dead above-ground biomass in marshes is generally transported out of the marsh by the tides (Chambers et al. 1985; Bouchard and Lefeuvre 2000). The MEM was developed by Morris et al. (2002) and later refined (Morris et al. 2016; Morris et al. 2020). Previous studies demonstrated the utility of the MEM for wetland studies (Schile et al. 2014; Alizad et al. 2018). They are available in multiple computing environments (University of South Carolina 2010), and a Microsoft Excel interface with Visual Basic code runs in the background and provides accessibility and ease-of-use for end-users to assess wetland restoration via TLP.

In this study, modeling was conducted to estimate the potential for the BUDM in wetland restoration objectives at a case study in Blakeley Island, Mobile, Alabama, Site conditions were assessed through sample collection and analysis, modeling efforts identified restoration needs, and restoration opportunities were evaluated through spatial analysis. The case study demonstrates this approach, which could be replicated elsewhere. Finally, a US continental-scale Geographic Information System exercise revealed the BUDM potential and the extent to which this approach could be applied by determining suitable wetland areas in proximity to DM placement locations and the amounts of DMs that are available for restoration.

Site Description

Blakeley Island is located between the Mobile and Spanish Rivers in the Mobile Bay Estuary, Alabama. The island is composed of five DMMAs that occupy approximately 2.5 km^2 and approximately 5.5 km^2 of the salt marsh habitat (Fig. 2). The mean tide range at the nearby (approximately 3 km) Mobile State Docks, Alabama, National Oceanic and Atmospheric Administration (NOAA) gauge (Station ID: 8737048) is 0.45 m, and the rate of relative SLR for approximately the last 40 years is 4.18 ± 1.42 mm/year. Recently, the Mobile Bay, Alabama, watershed has become increasingly urbanized at the expense of upland forest habitat (Ellis et al. 2011), which potentially leads to increased SSCs (Walsh et al. 2005; Zeiger and Hubbart 2016). The SSC measured in the channel near Blakeley Island, Mobile, Alabama, from January to April 2017 was from 15 to 200 mg/L (Ramirez et al. 2018). Vegetation at the site is typical of upland wetland habitats and includes the invasive *Phragmites australis* (common reed), *Panicum virgatum* (switchgrass), *Typha latifolia* (common cattail), and *Baccharis halimifolia* (eastern baccharis; Berkowitz et al. 2018).

The Alabama State Port Authority and USACE are responsible for maintaining the federal navigation channels in Mobile Bay, Alabama. DM from the Mobile Bay River Channel totals approximately 2 million m^3 annually and varies in composition with fine-grained silts, soft clays, and sand (USACE 2019). Approximately half of the material (1 million m^3) is placed in the DMMAs and the remainder is placed at an ODMDS or used beneficially, typically in construction activities (RMG 2010; Parson et al. 2015; USACE 2019). Various management actions are utilized to increase DMMAs capacity, which includes removing material for placement elsewhere, rotating the use of DMMAs, and raising dike walls (RMG 2010; USACE 2019). With these practices, the life expectancy of the DMMA was estimated to exceed 20 years in 2019 (USACE 2019). Increasing the amount of wetland restoration conducted by the BUDM and TLP could reduce fill and further increase the capacity and lifespan of the DMMAs.

Methodology

Field Data Collection and Laboratory Analysis

Four soil cores were collected at varying elevation and vegetation types throughout the Blakeley Island marsh, Mobile, Alabama, in January 2020 (Fig. 2) to assess site conditions and inform the modeling exercise. Cores BI1a and BI2 were taken from the high marsh and BI3 and BI4 were taken from the low marsh; elevation data were not collected due to travel restrictions in 2020. Soil cores were each >60 cm in length and were collected via piston coring. In the laboratory, soil cores were sliced into 2 cm increments, dried, and milled. Water content was measured by weighing samples before and after drying at 100°C for 12 h. Organic content was determined via loss-on-ignition (i.e., Heiri et al. 2001), which was conducted by placing 4.000 ± 0.001 g of sample material in a 360°C muffle furnace for 3 h to combust organic material. Water, mineral, and organic content are presented as % mass.

Vertical profiles of cesium-137 (^{137}Cs) were examined to assess accretion rates (Ritchie and McHenry 1990). Activities of ^{137}Cs were determined at each 2 cm interval using a planar germanium detector (Ortec Model GEM-S7025P4, Oak Ridge, Tennessee) coupled to a multichannel analyzer (Ortec Model DSPEC-50, Oak Ridge, Tennessee). Activity profiles were incomplete due to time restraints. Radionuclide peaks might be affected by soil composition and physical processes that including postdepositional scavenging and bioturbation. The peak of ^{137}Cs activity was assumed to indicate the 1963 soil horizon due to the fallout of peak Northern Hemisphere nuclear weapon testing (Ritchie and McHenry 1990). Accretion rates

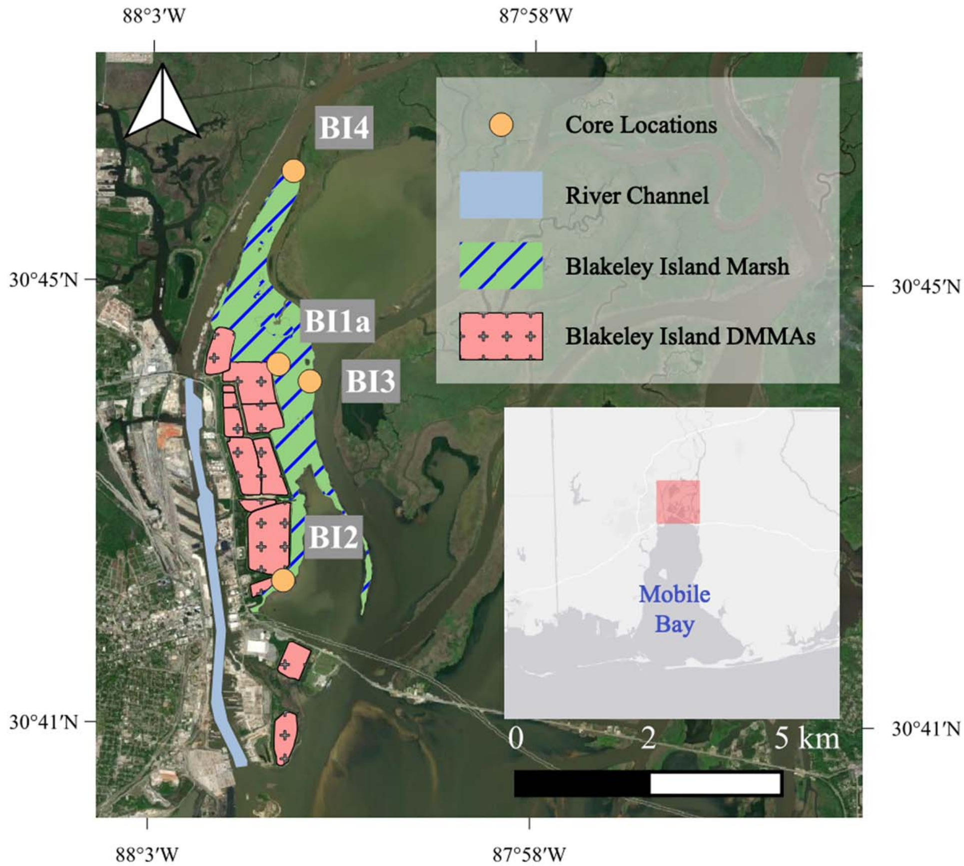

Fig. 2. Map of Mobile Bay River Channel and Blakeley Island, Mobile, Alabama, DMMAs, marsh, and soil core locations. (Sources: Esri, HERE, Garmin, OpenStreetMap, Maxar, Earthstar Geographics, USDA FSA, USGS, Aerogrid, IGN, IGP.)

using the ^{137}Cs method can be calculated using

$$a = \frac{d}{y - 1963} \tag{1}$$

where a = accretion rate (cm/year); d = depth of ^{137}Cs peak (cm); and y = year of core collection.

Model Evaluation of Future Marsh Conditions

This study utilized the MEM version 8.6 with a TLP feature to model 27 distinct scenarios that were based on Blakeley Island, Mobile, Alabama, conditions with three different inputs for each SLR projection, SSC, and initial marsh elevation over a 100-year timeframe (Table 1). A range of inputs for the variables generated an array of end states to forecast conditions over a landscape and account for uncertainty in projections, such as SLR and dynamic conditions, such as SSCs. The SLR projections used in this study were derived from USACE low, medium, and high curves at the nearby Dauphin Island, Alabama, NOAA gauge (approximately 50 km; Station ID: 8735180; USACE 2017). Inputs for the SSC in the model were based on local assessments by Ramirez et al. (2018) and scaled as demonstrated by Schile et al. (2014). Finally, initial (time zero) marsh elevation was based on a tuning of model parameters that used organic matter and elevation data from a nearby study at Weeks Bay, Alabama (Morris et al., unpublished data, 2016). The three elevations selected resemble marshes at Weeks Bay, Alabama, below, near, and above mean sea level (MSL) and were within elevation limits for vegetative growth. The medium initial marsh elevation was set so that the model could generate organic content similar to that at Weeks Bay, Alabama, and the high initial elevation was set to above mean high water (MHW) based on existing Weeks Bay elevations. Other physical inputs (twentieth-century rate of SLRs, initial sea level, and mean tidal amplitude) and all biological inputs (maximum growth rate limit, optimal elevation, peak biomass concentration, maximum root depth, and organic matter decay rate) were provided for various regions in the model; those for Weeks Bay, Alabama, were used as a proxy for conditions at the Blakeley Island marsh, Mobile, Alabama, and were consistent throughout the model scenarios (Morris et al., unpublished data, 2016, Alizad et al. 2018; Table S1). The optimal elevation was defined as the elevation at which primary productivity was at its maximum, which resulted in increased accretion rates by accumulating below-ground biomass. The results of the modeled marsh elevation are reported in cm in the MSL. Model initialization generated measurements of the initial

Table 1. Values for model input variables

Value range	SLR (cm/century)	SSC (mg/L)	Marsh elevation (MSL)	Placement activity
Low	30	23.75	−5	15 cm every 10 years
Medium	61	47.50	8	—
High	161	95.00	50	30 cm every 20 years
Source	USACE (2017)	Ramirez et al. (2018)	Morris et al., unpublished data, 2016	—

Note: Low, medium, and high values were determined based on the literature to capture various potential scenarios.

organic matter and accretion rates gave inputs about site conditions, such as tide range and past rates of SLRs. These initial data were compared with observed measurements from the soil cores as a measure of validation for the model.

The MEM's TLP capability was used to evaluate two potential restoration strategies (15 cm TLP every 10 years and 30 cm TLP every 20 years) that each resulted in 150 cm of cumulative TLP over 100 years. The two strategy scenarios utilized a high SLR, low SSC, and low initial elevation as model inputs. These inputs led to the largest elevation deficit and therefore estimated the maximum potential for the BUDM. TLP in the MEM was defined as the realized elevation after 1 year of settling, consolidation, and loss; it directly affects elevation and above-ground biomass and indirectly impacts inundation and vegetative productivity. Given a placement thickness over the area of wetland at Blakeley Island, Mobile, Alabama, a volume of sediment that was required for TLP was calculated. For this study, the DM that was used for TLP was assumed to be sourced solely from the collection of DMMAs.

Determination of Wetland BUDM Potential through Spatial Analysis

The total wetland area broadly suitable for beneficial use was assessed for proximity to DM sources and reported at four spatial scales to assess the larger potential for the BUDM within Blakeley Island and Mobile Bay, Alabama, the state of Alabama, and coastal continental United States that excluded the Great Lakes states. The BUDM placement was assumed to be feasible for wetlands that met the prescribed criteria regardless of potential physical and legal access constraints. DM placement locations were used as a proxy for DM sources; the BUDM can be conducted as a multistep process where the material is placed at a location and later remobilized for placement. Publicly available wetland data was sourced from the US Fish and Wildlife Service National Wetland Inventory [(NWI) USFWS 2020], and DM placement data was sourced from USACE (2020b). The suitable wetland area was limited to the NWI land use class of "Estuarine and Marine Wetland" as a proxy for wetlands that were vulnerable to SLR. Preexisting BUDM placement areas (e.g., beach nourishment or bank stabilization) or those that would be unavailable for placement (e.g., capped or restricted) were classified as unsuitable and not considered DM sources. The placement proximity around DM sources was limited to a 5 km radius: the maximum distance material can be pumped before supplemental booster pumps are required (USACE 2015).

This exercise was conducted at four spatial scales using the following steps: (1) compile state wetland and DM placement data; (2) limit data to suitable criteria of wetland and placement type; (3) generate a 5 km placement buffer around DM sources; and (4) calculate the wetland area within a 5 km placement buffer. Fig. 3 shows the results of this workflow. Using a TLP scenario that totaled 150 cm over 100 years (as employed in the modeling case study for Blakeley Island, Mobile, Alabama), the placement areas at each scale were used to calculate the volumes of DM that could be beneficially placed.

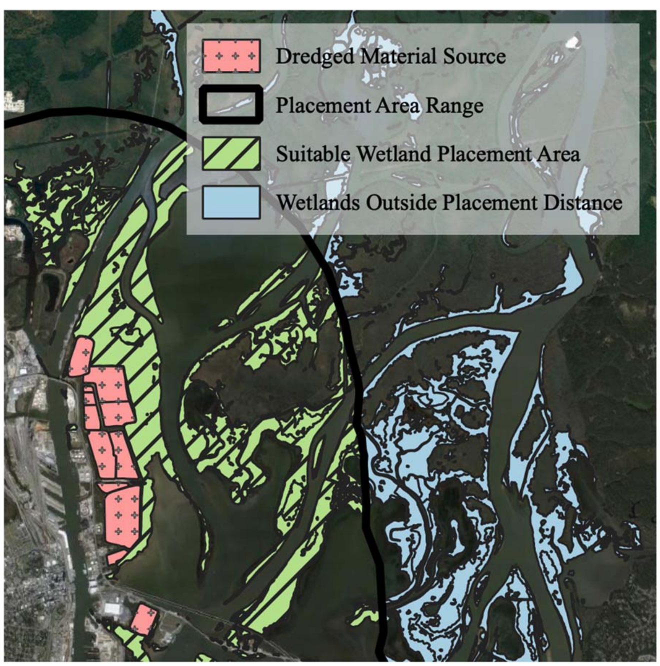

Fig. 3. Depiction of the potential wetland beneficial use area exercise process near Blakeley Island, Mobile, Alabama. Placement area range delineates all area within 5 km of DM source areas. Wetlands are shown as areas within this range (suitable wetland placement area) and areas outside this range (wetlands outside placement distance). (Sources: Esri, HERE, Garmin, OpenStreetMap, Maxar, Earthstar Geographics, USDA FSA, USGS, Aerogrid, IGN, IGP.)

Results

Measured Marsh Soil Properties and Accretion

Blakeley Island, Mobile, Alabama, marsh soil had a high water content and the dried material consisted of largely mineral material with some substantial organic material stocks (Fig. 4). The soil water content was from 59% to 93%. For the dried material, the organic content was from 3% to 39% and the mineral fraction was from 61% to 97%. The median soil organic matter (SOM) was 9.9%. Cores varied in water, mineral, and organic content; BI1a and BI2 from the high marsh had a lower water content than

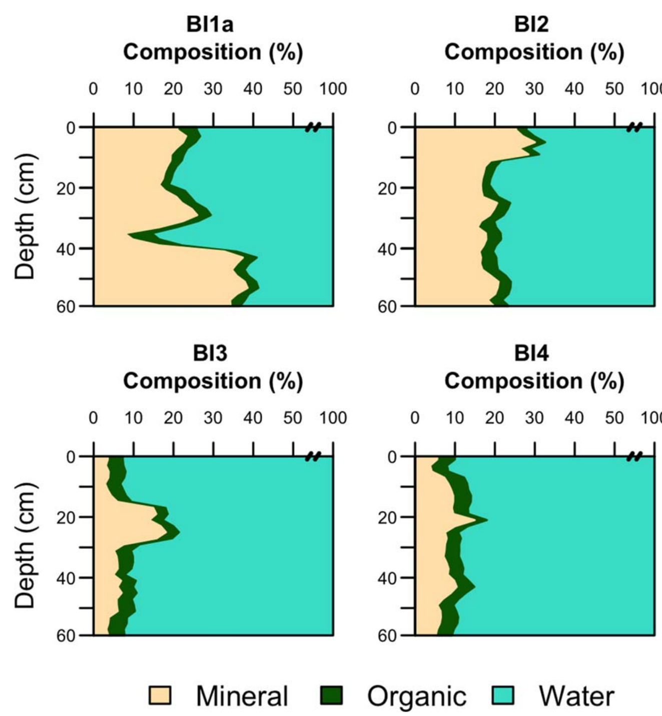

Fig. 4. Physical soil composition of each core from 0 to 60 cm.

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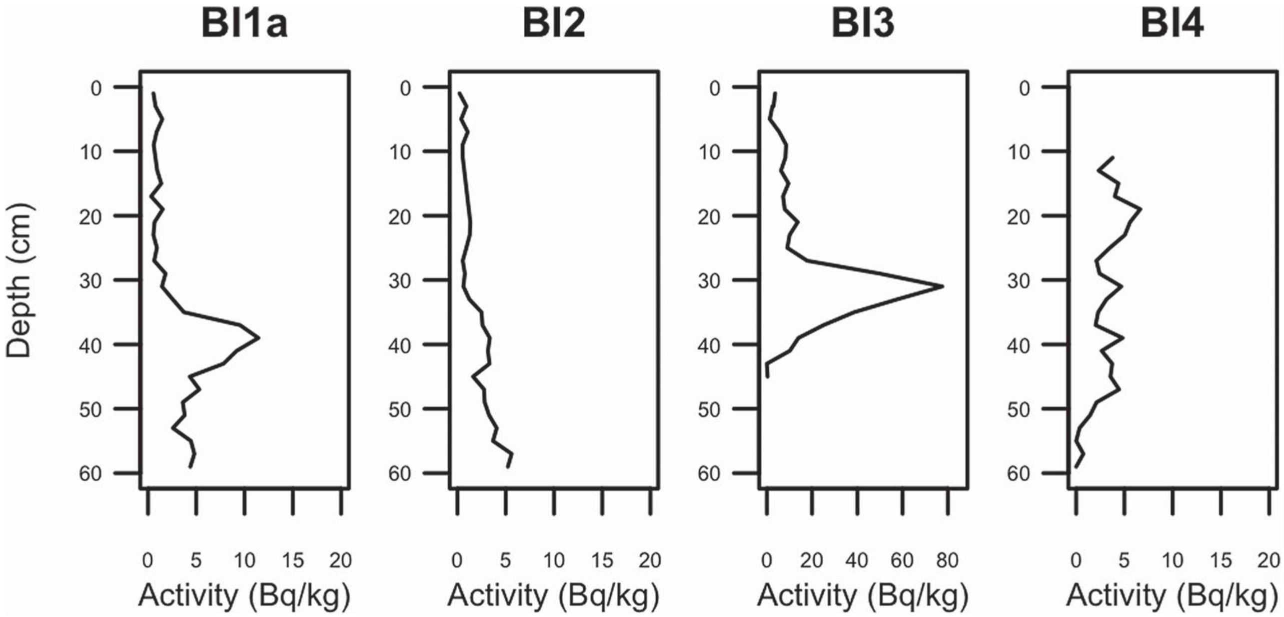

Fig. 5. ^{137}Cs Activity (Bq/kg) of each core from 0 to 60 cm by 2 cm sample interval. Note that the horizontal scales differ.

those from the low marsh. The organic matter was higher in BI3 and BI4, the low marsh cores.

Gamma spectroscopy revealed peaks of ^{137}Cs in cores BI1a and BI3 at 39 and 31 cm, which resulted in average accretion rates of 0.68 and 0.54 cm/year, respectively (Fig. 5). Peak activity was 11.4 and 77.5 Bq/kg, respectively, and the average sample uncertainty was 0.8 Bq/kg; uncertainty was not shown in Fig. 5 for legibility. The ^{137}Cs peaks were not visually identified in the BI2 or BI4 cores. Their absence might be due to the core depth not being sufficient to capture the 1963 horizon or processes, such as postdepositional scavenging of ^{137}Cs (Benninger et al. 1975) or erosion and removal of ^{137}Cs (Ritchie and McHenry 1990), which resulted in the lack of a measurable peak. A ^{137}Cs peak <60 cm, the deepest sample examined, would equate to a minimum average accretion rate of 1.1 cm/year. Sediment accretion rates in marsh environments might vary spatially with changes in microtopography (Kearney et al. 1994); however, such a comparably high accretion rate was assumed to be unlikely. The marsh substrate and coring technique limited core depth to approximately 60 cm.

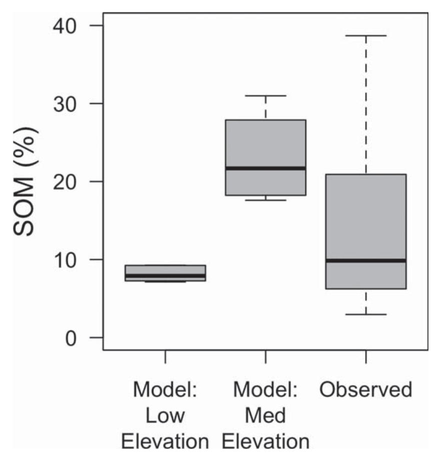

Fig. 6. SOM from cores (uncorrected loss-on-ignition) and MEM results in two of the three initial elevations: low and medium. The high initial elevation model SOM was approximately 90% for all scenarios and is not shown.

Modeling Case Study

Soil Formation and Accretion

Model validation that used modeled, and SOM and accretion rates resulted in good agreement between the model and observed conditions. The SOM was lower in the observed (9.9%) than the initialized model outputs (40.2%; Fig. 6). Out of all the variables, the initial marsh surface elevation had the largest effect on SOM. At the low initial marsh elevation, the median SOM was 8.2%; at the medium initial marsh elevation SOM was 23.0%, and at the high initial marsh elevation SOM was 89.5%. In the model initialization of scenarios with elevations at or above MHW, organic matter production and decay reached equilibrium at an organic matter content of 89.5%. SOM was higher at the medium initial elevation scenarios than at the low initial marsh elevation scenarios, because reduced inundation time allowed for increased vegetative growth. The relationship between elevation and organic matter in the model differed from that observed in the soil cores. Organic matter in the high marsh cores (BI1a and BI2; 7.1%) was lower than in the

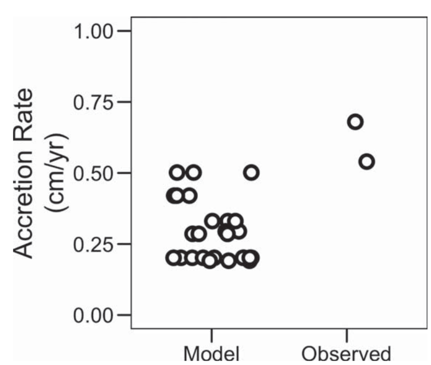

Fig. 7. Accretion rates from soil cores and the 27 model (MEM) scenario initializations.

low marsh cores (BI3 and BI4; 21.4%). The observed accretion rates averaged 0.61 cm/year and were higher than initial modeled accretion rates that averaged 0.29 cm/year (Fig. 7). In the MEM, high SSCs and low SLR conditions led to higher accretion rates, given increased rates and opportunities for sedimentation; initial modeled accretion rates in these scenarios most closely matched the observed accretion rates.

Elevation and Above- and Below-Ground Biomass

Marsh elevation and above- and below-ground biomass are the MEM outputs of interest when evaluating marsh resilience. The marsh elevation was modeled over time for 27 model scenarios (three rates of SLR, three SSCs × 3 elevations) and is shown in Fig. 8. The modeled marsh elevation after 100 years was from −111 cm MSL to 42 cm MSL. The largest elevation deficit relative to MSL was generated by the high SLR, low SSC, low initial marsh elevation scenario, and the largest surplus was obtained from the scenarios of low SLR and high starting marsh elevation. The final modeled above-ground biomass between the scenarios was between the minimum and maximum allowed within the model (0–2,500 g/m^2) and peaked when the marsh was at the optimal elevation (Fig. 8, Figs. S1 and S2). The scenario with the largest elevation deficit (high SLR, low SSC, and low initial marsh elevation) resulted in the lowest concentrations of above-ground biomass. Above-ground biomass fell to zero in model year 22 of this scenario, which signaled a marsh collapse; a fate shared later in the model timespan in

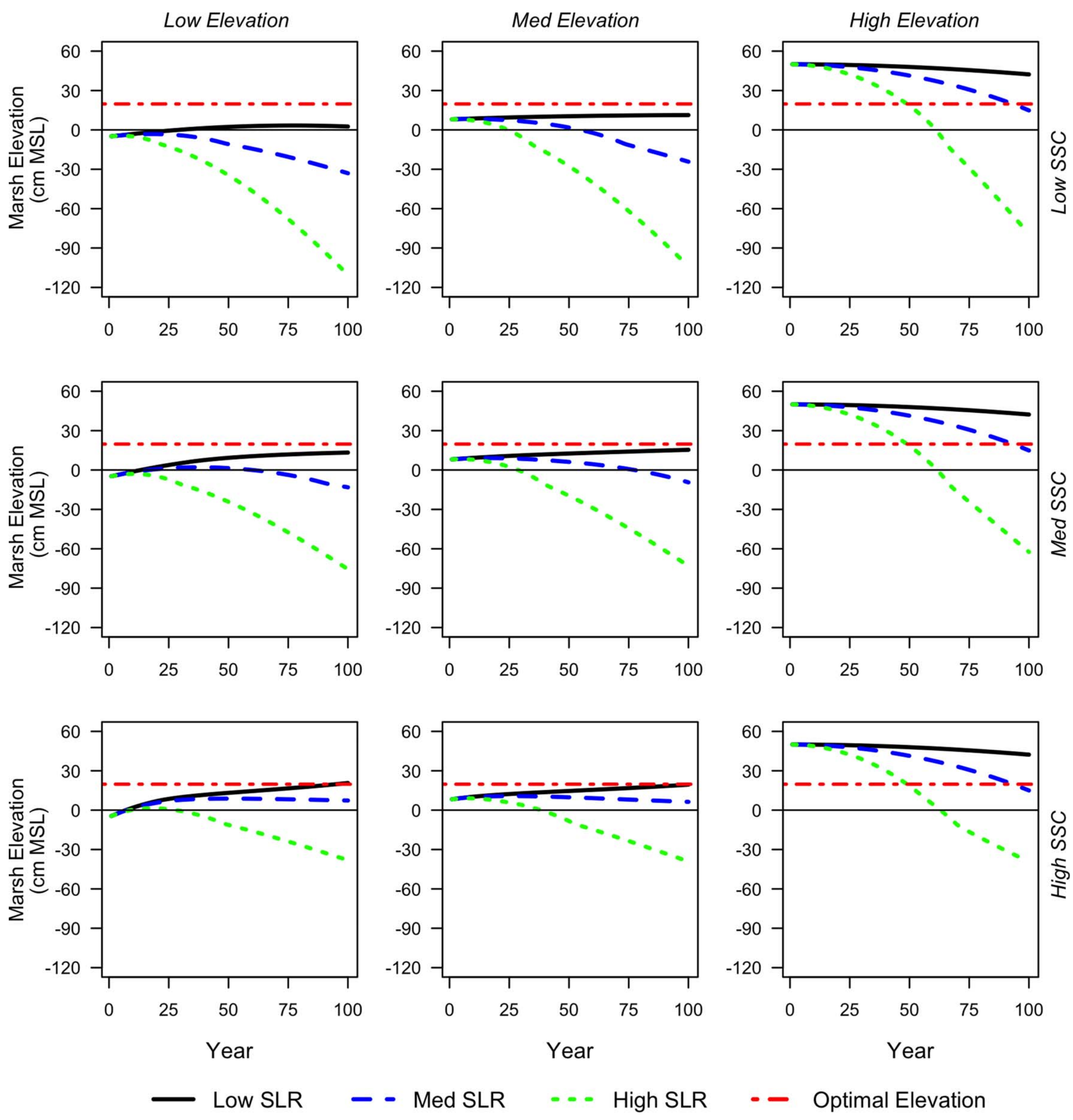

Fig. 8. Modeled marsh elevations with no BUDM. Each row represents a different SSC, and each column represents a different initial marsh elevation. Line pattern and dashed lines represent the different SLR projections used in the simulation. Optimal elevation refers to the surface elevation where primary production is at its maximum. Scenarios are defined in Table 1.

13 other scenarios. Marsh collapse occurred by model year 71 in all scenarios with a high SLR rate. The scenario of low SLR, high SSC, and high initial marsh elevation resulted in the highest above-ground biomass concentration at the end of the model timespan, although most low SLR scenarios resulted in an above-ground biomass concentration near the maximum allowed in the model. The final below-ground biomass was lowest in the scenarios of medium SLR, low SSC, and low initial marsh elevation (104 kg/m^2) and highest in the scenario of high SLR, high SSC, and high initial marsh elevation (220 kg/m^2; Fig. S3).

Marsh Response to TLP

The two placement scenarios, each adding a total of 150 cm of DM to the marsh over 100 years, were simulated under the model conditions that led to the largest elevation deficit (high SLR, low SSC, and low initial elevation: Fig. 8 upper left panel; Table 1). Although the total thickness of DM added was the same in both TLP scenarios, the biomass and the elevation differed throughout the model timespan due to lift size and frequency (Figs. 9–11). At each TLP event, elevation increased due to the height of placement (10 or 20 cm), and above-ground biomass reduced in a simulated burial and die-off event (Fig. 9). Above-ground biomass was more sensitive to elevation changes at elevations below optimal compared with above optimal. As the marsh surface fell further below the optimal elevation, above-ground biomass decreased faster (Fig. 9). The smaller, more frequent lifts allowed the marsh to maintain an elevation closer to or above that which is optimal for vegetation, boosting productivity. This higher vegetative productivity resulted in a higher above- and below-ground biomass (Figs. 9 and 10), which contributed to vertical accretion (Fig. 11). The final marsh elevation was slightly higher in the scenario with smaller, more frequent lifts than that with the larger, less frequent lifts. Either placement strategy allowed the marsh to maintain near-optimal elevation for vegetative productivity and the no placement scenario

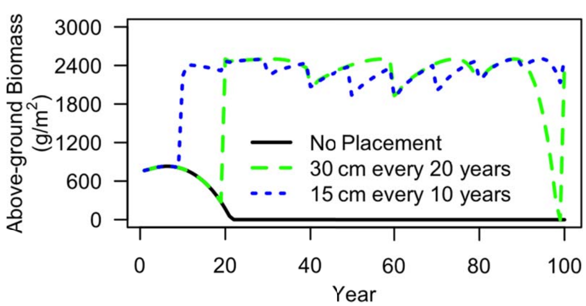

Fig. 9. Above-ground biomass concentration during the modeled TLP and no action scenarios.

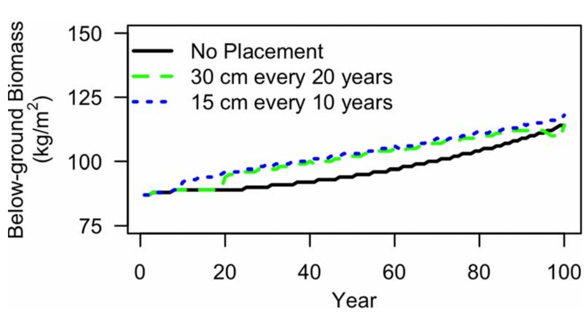

Fig. 10. Below-ground biomass concentration during the modeled TLP and no action scenarios. Note the vertical scale does not begin at zero.

demonstrated a total marsh collapse (zero above-ground biomass) at model year 22 (Fig. 11). Given the height of sediment placement via the BUDM and area of wetland application, a volume of material required could be calculated, which for this case study translated into a reduction in DMMAs fill volume. For this calculation, two assumptions were made: (1) the bulk density of the pre and postsediment were identical; and (2) sediment volume lost during dredging and placement was estimated as 5%. The first assumption allowed the sediment volume sourced from the DMMA to equal the sediment volume placed on the wetland after 1 year. The second assumption stated that the total sediment loss through the remobilization, transport, and placement operations was estimated as 5%. The consolidation of material after placement is accounted for intrinsically in the MEM. Given these assumptions, 150 cm of material placed on the Blakeley Island marsh, Mobile Alabama (5.5 km^2), would equate to 7.8 million m^3 of material removed from the DMMA.

Discussion

Observed Marsh Properties

Sediment accretion rates at Blakeley Island, Mobile, Alabama, slightly outpaced recent rates of relative SLRs that were measured by NOAA but were lower than the USACE medium and high 100-year SLR projections, which indicated the vulnerability to submergence and requisite of restoration. Stress caused by increased inundation might reduce plant productivity and lead to a decrease in vertical accretion (DeLaune et al. 1987) and TLP might help to maintain elevation (reducing inundation) and boost vegetative productivity (Ford et al. 1999; VanZomeren et al. 2018). The Blakeley Island, Mobile, Alabama, soil cores exhibited low SOM; in salt marshes, SOM might be the dominant component of accretion (Hill and Anisfeld 2015) and concentrations might rise with increased vegetative productivity, which prevents submergence.

Model Response to Inputs

The model results were summarized to show how changes in the rate of SLR, SSC, and initial marsh elevation might affect future marsh elevation and biomass production. High SLR rates might cause unstable wetland conditions through inundation, because

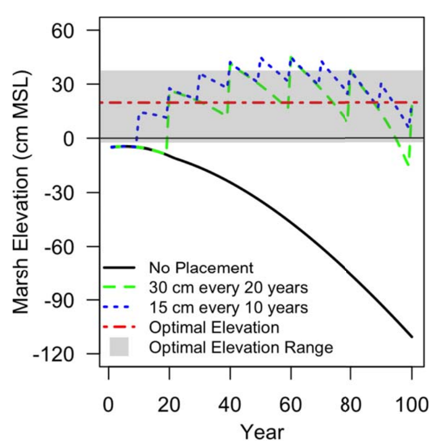

Fig. 11. Marsh elevation during the modeled TLP and no action scenarios. Optimal elevation refers to the elevation at which primary production is maximized and optimal elevation range is defined as the elevations where primary production is ≥75% of the primary productivity at the optimal elevation.

rising seas outpace vertical accretion. Sedimentation from high SSC might promote vertical accretion through the trapping of mineral material and organic material gains from increases in vegetative productivity. Marshes that start at high elevations might persist above MSLs for longer, but often have a similar fate to those marshes at lower starting elevations. The concentrations of above-ground biomass were strongly influenced by elevation and inundation time. Vegetative productivity might fall as inundation time increases, establishing a positive feedback loop where the lack of in situ biological production hinders vertical accretion, further reducing vegetative productivity rates. Several factors influence below-ground biomass; high vegetative productivity allows more biomass accumulation, and increased inundation time could reduce organic matter decay.

The initial accretion rate in the model most closely resembled the observed conditions in high SSC and low SLR scenarios. The observed accretion rate represents recent past (decadal) conditions and these specific model scenario parameters were generally based on past conditions: the low SLR was based on the historic rate and the high SSC value was an estimate of the current concentration. Accretion is dependent on the capture and settling potential of suspended sediment, biomass production, and water level. Because the initial accretion rate was lower at higher rates of SLR but similar SSCs, the model inferred that higher rates of SLR might inhibit biomass production and accumulation through inundation. A high rate of SLR reduced the relative marsh elevation.

Model Limitations

The model results were subject to limitations that were imposed by the study design and inherent to the MEM version 8.6. The case study was evaluated via model inputs that represented the range of possible and projected conditions rather than observed conditions over the marsh area. This strategy was chosen for practicality, because modeling at a fine scale of marsh conditions drastically increased computational load and effort. Estimating future conditions over a range of current and projected conditions allowed for variation and uncertainty; the predicated trade-off was that the results might be less precise but more accurate. The model format and case study approach were developed to be accessible for coastal managers.

The inherent model limitations were identified with conditions outside the tidal range. The version of the MEM with the TLP feature used in this study produced high organic matter content when the marsh elevation reached or exceeded MHW, because there was no mechanism for mineral input under these conditions. With little or no flooding, there was no opportunity for sediment delivery, and combined with low SLR, the SOM concentration increased to high levels. Here, the SOM production alone contributed sufficient vertical accretion to maintain constant relative elevation throughout the model timespan. In contrast, the initial conditions of the low and medium initial marsh elevation scenarios had a lower SOM concentration and could accrete above the rate of SLR in some scenarios through the trapping of mineral and organic suspended material and in situ biological production, which allowed a larger elevation gain than that of the high initial elevation scenarios. Given a longer model runtime, marsh elevation in these scenarios of low SLR and variable initial elevation would be similar, because the organic matter would reach equilibrium in each scenario.

Model validation through the assessments of the observed and modeled SOM and accretion rates suggested that the model performed adequately for general planning purposes. However, model applications should be limited to marsh elevations within mean higher high and mean low water (MLW) levels (which represent the majority of wetlands, particularly those in need of restoration). To fit the modeled SOM profile to the observed profile at Weeks Bay, Alabama, it was necessary to fix the initial elevation of the marsh at MLW, far below the observed elevations (13–19.5 cm; Morris et al., unpublished data, 2016). At an initial elevation of MLW, the initial vertical profile of sediment organic matter in the MEM (20% of dry weight at the surface, declining to 17.5% at depth) most closely resembled actual conditions in this study. The model computed a starting organic matter profile as if the marsh had been in equilibrium with the sea level, given the entire suite of parameter values. In this case, the starting marsh elevation was far from equilibrium and the relative elevation of the simulated marsh approached and eventually approximated the specified optimum elevation (20 cm). The model initial soil accretion rate was similar to but lower than the observed values. Through model tuning and agreement with the observed conditions, the MEM estimated in this application could be considered reasonable to assess the BUDM and DMMAs fill-reduction capacity in the near future (years to decades). With any long-term prediction, estimates further ahead should be viewed with less certainty. Estimates generated by the MEM could inform the development of management strategies with time, as action is taken, adaptive management must be incorporated.

BUDM Considerations

Logistically, the BUDM increases in cost and becomes less feasible with distance to placement (Randall et al. 2000). In shore-based operations, hydraulic pipelines could be used to transport material (Burt 1996). The material in the DMMA could be converted into a slurry, which a small cutter suction dredge could transport via a pipeline to the placement location (Burt 1996). Pipelines for this type of dredge reach approximately 5 km in length, with extensions beyond 5 km powered by booster pumps (USACE 2015). The entirety of the Blakeley Island, Mobile, Alabama, is within reach of standard operations with approximately half (46%) of the marsh within 500 m of a DMMA (Fig. 12).

The BUDM has widespread applicability due to the potential benefits for multiple aspects of coastal management. In this study, marsh resilience to SLRs was the foremost consideration, and infrastructure and resource conservation were secondary, although significant benefits. DMMAs are critical infrastructures for dredging operations and the fill volume should be utilized efficiently. By implementing a reliable fill-reduction method, DMMAs could last longer as a navigation dredging resource. In 2019, the DMMAs at Blakeley Island, Mobile, Alabama, had an estimated capacity that included potential increases to dike walls that totaled 23.4 million m^3 out of the previous total of 26.6 million m^3 (RMG 2010; USACE 2019). A biennial removal of 0.5 million m^3 of material represents the reoccurring maintenance to the DMMAs when other activities are conducted where appropriate (RMG 2010). The DMMA lifespan could be estimated given this minimal management and incorporating the BUDM at the Blakeley Island marsh, Mobile Alabama, (Fig. 13). Assuming similar restoration strategies, limiting the DMMA fill to capacity over 50 years via the BUDM, the restoration of an additional 11.6 km^2 of wetlands, which is approximately 2.1 times the marsh area of Blakeley Island, Mobile, Alabama, would be required.

Sediment resources from average dredging activity could be evaluated against the total potential area of wetland restoration via the BUDM. These opportunities were evaluated at the local, estuary, state, and national scales using a mapping exercise and wetland areas and volumes of DM that could be beneficially used were calculated (Table 2). Each year, approximately 99 million m^3 of DM in the United States is not used beneficially (USACE 2020a). This material, which is currently being disposed of in

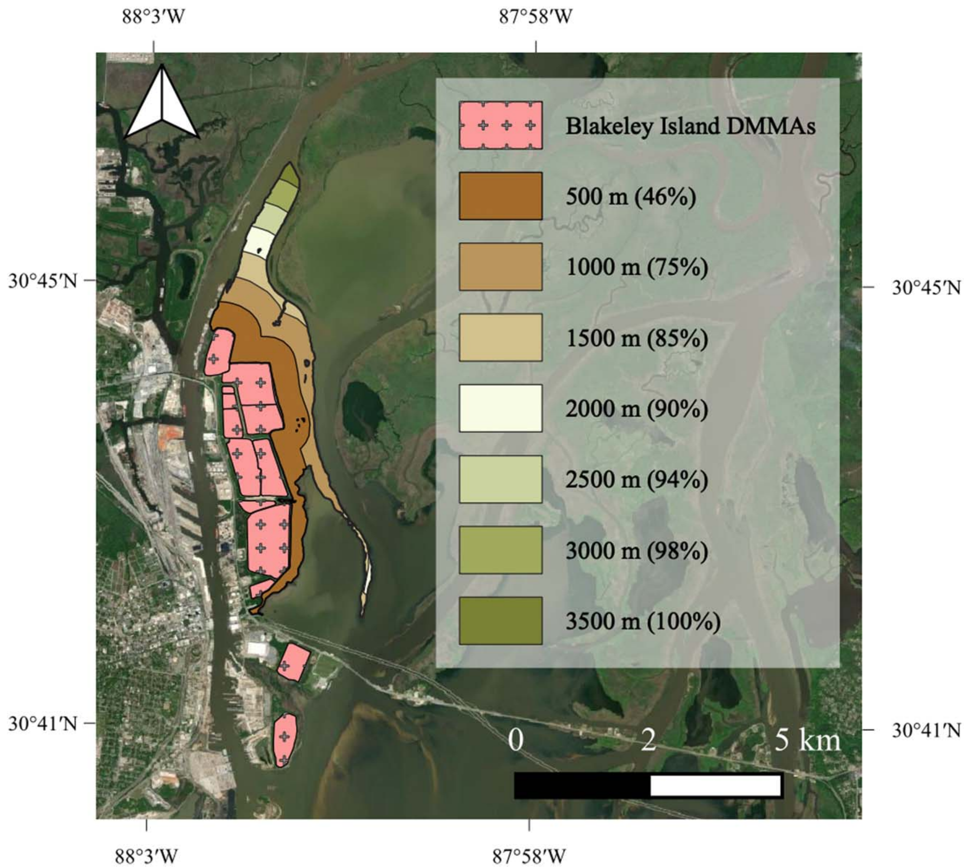

Fig. 12. Map of Blakeley Island, Mobile, Alabama, DMMAs and adjacent marsh that show distance intervals from DMMAs to marsh and corresponding cumulative marsh area. (Sources: Esri, HERE, Garmin, OpenStreetMap, Maxar, Earthstar Geographics, USDA FSA, USGS, Aerogrid, IGN, IGP.)

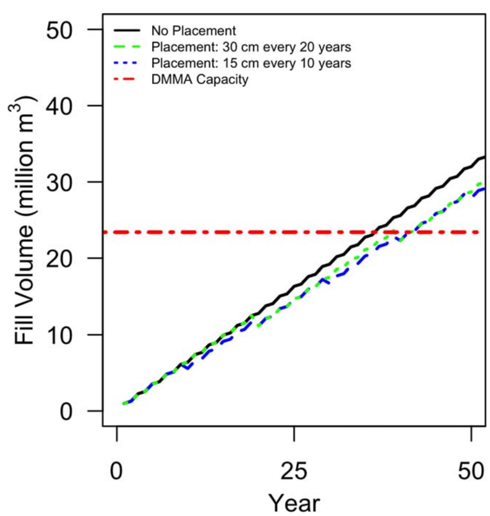

Fig. 13. Blakeley Island, Mobile, Alabama, DMMAs fill volume over time that considered the modeled TLP and no action scenarios.

upland or ocean placement facilities, could fulfill beneficial placement activities similar to those described in the Blakeley Island, Mobile, Alabama, case study (150 cm over 100 years) at 6,613 km^2 of wetlands, which is greater than the potential area of the coastal continental US states found in this study (6,240 km^2). Wetlands of the appropriate class further than 5 km from a placement site in the coastal states total 18,543 km^2. This case study assessed a single source and placement area for the BUDM; however, opportunities for the BUDM might exist wherever vulnerable ecosystems and dredging are in proximity. These calculations did not take any site-specific characteristics, such as elevation or SLR, or logistical constraints, such as access into consideration. Instead, it provided a baseline to show the potential application of the BUDM. At each scale that was assessed, sufficient DM existed for restoration similar to that presented in the Blakeley Island, Mobile, Alabama, case study over the entire wetland area within 5 km (Table 2).

Although through simplified assumptions, DM could supply wetland restoration efforts at a national scale of wetlands in proximity to placement locations, sites should be assessed individually for need and feasibility. The model placement strategy utilized was developed for the scenario of a wetland with an elevation of below MSL; this represented a more vulnerable condition and elevation among coastal wetlands varies within and between sites. The supply of placement material might be concentrated near large navigation channels, which results in insufficient placement material for restoration elsewhere. In addition, operational constraints might render restoration at sites near the range of distance from placement location, near development, or under private ownership unfit for the BUDM. In general, the BUDM near navigation dredging is not sediment limited. Assuming the characteristics of the Blakeley Island, Mobile, Alabama, site is representative of some US wetlands, the widespread adoption of the BUDM practices could combat much of the expected wetland degradation due to accelerated SLRs over the following century. Approximately three times the suitable wetland area exists outside of the 5 km from a placement operation than within.

Table 2. Wetland areas, DM volume, and potential BUDM volumes at four scales evaluated

Area of interest	Wetland area (km^2)	Wetland area within 5 km (km^2)	Annual DM available (million m^3)	Potential annual BUDM volume (million m^3)	DM usable in BUDM (%)
Blakeley Island, Mobile, Alabama	5.5	5.5	1.0	0.1	8.3
Mobile Bay, Alabama,	69.5	34.2	4.5	0.5	11.4
State of Alabama	177.4	83.7	4.5	1.3	23.1
Coastal continental United States	25,135.6	6,240.2	99.5	93.6	94.0

Future Approach for Implementation

The spatial analysis of potential wetland BUDM restoration sites is a broad classification that is based on land use and placement category most appropriate for this type of action. Using this approach as a screening tool could identify the general capacity and possible sites that could be further examined through some combination of field and modeling approaches as in the case study presented in this study. For instance, the spatial screening method could be applied regionally or subregionally (i.e., state or watershed), and actual operational estimates could be made at smaller scales through the case study approach. Several caveats exist in this process that range from data quality to model limitations and are best addressed by the responsible coastal managers who are best suited to provide rigorous analysis of the varying current and projected conditions.

Conclusions

By applying the BUDM assessment approach described in this study to the extent of a wetland area with BUDM potential, coastal managers could develop local restoration plans to use coastal resources efficiently. In this study, field data-informed modeling was carried out using the MEM to evaluate marsh vulnerability and assess restoration potential at Blakeley Island, Mobile, Alabama. The DM resources at the case study site were sufficient to perform restoration for the next 100 years, and restoration of an additional 2.1 times the marsh area would effectively conserve the DMMA fill volume over the next 50 years. Opportunities to expand the practice of the BUDM exist nationwide, because an estimated 6,420 km^2 or 25% of suitable wetlands exist in proximity to locations of dredged sediment and the total dredging resources are sufficient to conduct restoration on this entire area. Given future improvements in modeling and restoration techniques and technology, wetland restoration via the BUDM could become feasible at more locations and could protect and strengthen ecosystem services that are provided by these wetlands; as this study found, >18,000 km^2 of wetlands meet criteria that indicate their suitability for the BUDM. It is incumbent on the government and industry to incentivize and advance capabilities to increase the extent and frequency of the BUDM and allow more wetland areas to be in reach of restoration.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request: MEM v8.6, model results, spatial analysis results, and field and laboratory observations.

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Supplemental Materials

Table S1 and Figs. S1–S3 are available online in the ASCE Library (www.ascelibrary.org).

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