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Special Series

Beneficial use of dredged sediment as a sustainable practice for restoring coastal marsh habitat

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EDITOR'S NOTE:

The current issue addressing UN Sustainable Development Goals highlights “Environmental Management Practices Inspired by SDGs,” aiming to call attention to practices, ideas, and thought leaders contributing to sustainability in all facets of the global economy. The 2020s are a transformative decade for human interaction with the environment, largely inspired by the United Nations' 17 Sustainable Development Goals. Scientific research and environmental management practices lead the way to sustainability, and several SDGs aim to reduce our environmental footprint and preserve, protect, and restore ecological health.

Abstract

Coastal Louisiana (USA) continues to sustain immense land and habitat losses due to subsidence, sea-level rise, and storm events. Approximately 65 million m^3 (85 million cubic yards) of sediment is dredged annually from Gulf Coast federal navigation channels to maintain safe waterway passage. The beneficial use of these sediments continues to increase, and now this sediment is recognized as a critical resource in large-scale (estimated multibillion dollar) ecosystem restoration efforts to mitigate land and habitat losses along the US Gulf Coast. However, the documentation of restoration benefits where dredged sediments are the primary resource is lacking, which limits the potential for future applications. Therefore, this study documents the progress to restore marsh habitat and the resultant benefits in West Bay, Louisiana, and investigates how the restoration practices align with principles of the US Army Corps of Engineers (USACE) Engineering with Nature® (EWN®) and UN Sustainable Development Goals (UNSDGs). West Bay, a 4964-ha subdelta adjacent to the Mississippi River, typifies risks of coastal land loss that also threatens the integrity of the adjacent federal navigation channel. To help restore coastal marsh habitat on a large spatial and temporal scale, the USACE constructed an uncontrolled diversionary channel from the Mississippi River and with subsequent direct and strategic placement of dredged sediment. Restoration performance was assessed through remotely sensed methods using data spanning approximately 70 years. To date, placement of dredged sediment in the bay has facilitated the creation of over 800 ha of new land in the formerly open waters of West Bay. The West Bay restoration project aligns with the principles of the EWN initiative, which supports more sustainable practices to deliver economic, environmental, and social benefits through collaborative processes and meaningfully integrates 10 of the UN SDGs designed to achieve a better and more sustainable future. *Integr Environ Assess Manag* 2021;00:1–12. Published 2021. This article is a U.S. Government work and is in the public domain in the USA.

KEYWORDS: Engineering With Nature®, Mississippi River, Nature-based solution, Uncontrolled diversion, United Nations Sustainable Development Goals

INTRODUCTION

Coastal Louisiana (USA) experiences immense land losses that threaten critical national infrastructure worth billions of dollars (e.g., commercial fisheries, navigation and port infrastructure, and energy supply; Coastal Protection and Restoration Authority [CPRA], 2017; Couvillion et al., 2011). Yet, to mitigate related impacts and restore coastal ecosystems at this scale, innovative, sustainable, and resilient approaches are clearly required to achieve success (Kress et al., 2016; Kurth et al., 2020). Creative utilization of dredged sediments, a valuable natural resource excavated from federal navigation channels (e.g., the Mississippi River),

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will play a critical role in achieving long-term coastal restoration goals (CPRA, 2017; Khalil & Freeman, 2015). Therefore, there is a need to document and understand the practice of using dredged sediments as part of an innovative nature-based solution (NbS) in coastal Louisiana marsh restoration projects and how these practices align with US Army Corps of Engineers (USACE) environmental operating principles and international sustainability goals.

Engineering With Nature® (EWN®) is a USACE-led initiative that supports sustainable practices, projects, and outcomes through the use of NbS defined as the intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits through collaboration (Bridges et al., 2018; King et al., 2020). The EWN initiative broadens the potential value and co-benefits achieved through the USACE flood risk management, navigation, water operations, and ecosystem restoration missions through the incorporation of natural processes (e.g., uncontrolled sediment diversions and strategic sediment placement). This initiative aligns closely with the dredging and navigation industry's sustainability initiatives for development of waterborne infrastructure (e.g., Working with Nature [PIANC, 2018]; Dredging for Sustainable Infrastructure Central Dredging Association/International Association of Dredging Contractors [CEDA/IADC, 2018]) and also aligns with the Sustainable Development Goals (SDGs) established by the United Nations (UN, 2019), and is consistent with the criteria set forth in the Global Standards for Nature-based Solutions (IUCN, 2020). The sustainable practice achieved by the beneficial use of dredged sediments responds to several of the 17 UN SDGs (Laboyrie et al., 2018); therefore, documenting how beneficial use projects achieve broader sustainability initiatives provides valuable information to inform future restoration efforts.

The West Bay, Louisiana restoration project is a long-term restoration project that uses the innovative and sustainable practices of sediment beneficial use via both strategic (Gailani et al., 2019) and direct placement of sediment dredged from the adjacent federal navigation channel combined with the natural hydrodynamic forces through the diversion to shape the restored habitat (Bridges et al., 2018; McQueen et al., 2020). Conventional practice is to dispose of the sediment in a deepwater area of the Mississippi River at Head of Passes or utilize dredged material to nourish wetlands and restore subsided river banklines along the navigation channel. The latter placement option is considered a benefit to the navigation mission and yet does not address the broader long-term threat of subsidence and marsh loss in adjacent bays. The innovation was the combination of an uncontrolled sediment diversion with the direct and strategic placement of dredged sediment (including dynamic sediment features) that promotes the trapping of sediment from the diversion's stream and settlement of sediment in a larger expanse of West Bay than could be reached with dredged material discharges alone. As such, this project offers an opportunity to identify and document the alignment between the EWN initiative with UN SDGs.

West Bay restoration began in 2003 under the authority of the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA; Title III; Public Law 101-646) to mitigate extensive coastal land loss (70% land loss [ca. 3240 ha or 8000 ac]) and resultant risks to the federal navigational bankline. Project goals focused on restoration of land through the introduction of riverine sediment from an uncontrolled diversionary channel from the Mississippi River (560–1415 cm or 20 000–50 000 cfs discharge) and the placement of dredged sediments (Louisiana Department of Natural Resources, Coastal Restoration Division [LDNR-CRD], 2003). To date, the restoration actions have successfully restored a portion of the land and habitat once present in the bay (McQueen et al., 2020).

West Bay has been the subject of several studies investigating various aspects of the diversion and the placement of 28 million m^3 of sediment placed in the bay beginning in 2002 (McQueen et al., 2020). The recognized marsh restoration benefits of creating uncontrolled diversions were realized in the Louisiana coastal region in the 1980s and the 1990s based on successes from smaller-scale diversion projects (<4000 cfs flow) in the lower Mississippi River (e.g., South Pass, Pass-a-Loutre, Loomis Pass; LDNR-CRD, 2003; Plitsch, 2017; Trepagnier, 1994). These successes, along with the seminal Land Loss and Marsh Creation (LLMC) study in 1984, conceptualized the benefits of larger-scale diversions and provided a basis for the West Bay diversion (USACE, 2001).

Since 2003, when the diversion was completed, several monitoring studies have reported the hydrodynamic and morphological evolution of the diversion and subaerial growth within the bay (Allison et al., 2017; Barras et al., 2009; Kolker et al., 2011, 2012; Plitsch, 2017; Yuill et al., 2016). In 2013, Allison et al. (2017) estimated that during low flow discharges, the basin retained 4%–60% and 40%–100% of silt and sand, respectively. Estimates of the sand fraction (0.064–0.25 mm) in the suspended sediment load in the lower Mississippi River and diversion channel typically ranged from 5% to 40% (during 2004–2014) and were proportional to the flow velocity (Yuill et al., 2016). Although diversion channel morphology changes during the time period translated to highly variable sand loads (250%–750% differences), during low (8800 m^3/s) and high river flow velocities (21 000 m^3/s), the sand flux was estimated to be ca. 0.1 and 100 kg/s, respectively (Yuill et al., 2016). During an observation period between 2004 and 2014, sand loading to the basin was estimated to be the highest in 2009, corresponding to the development of a scour hole in the diversion contributing to higher flow discharges into the bay (Yuill et al., 2016). Allison and Meselhe (2010) suggested that transport of sand particles through the diversion would likely be limited to brief high-energy discharge intervals that could flush stored sediments from the river's bedload.

The results of these studies indicated that during the first five years after the diversion was built, the rate of land emergence in the basin was minimal; this triggered the

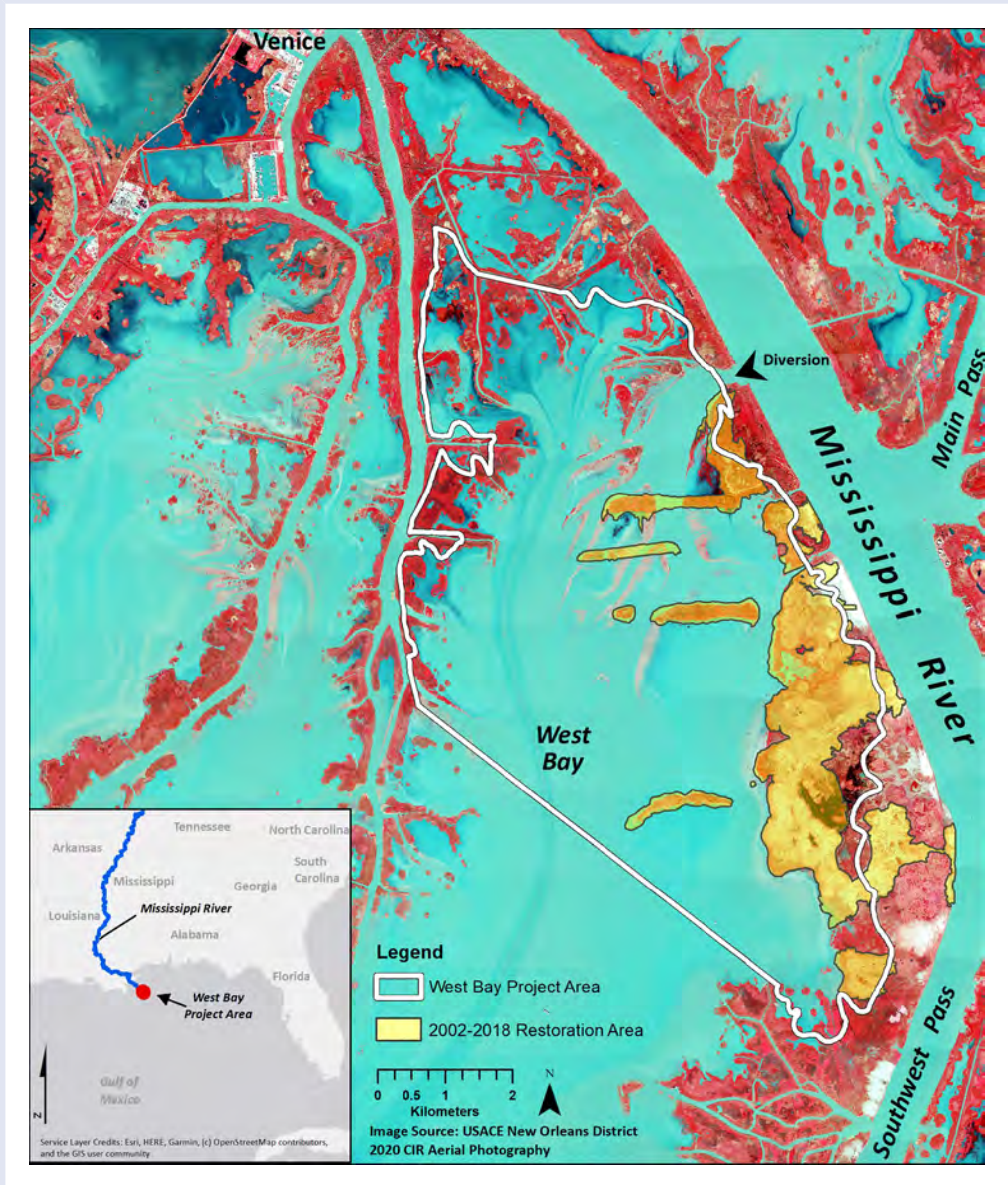


FIGURE 1 West Bay, Louisiana project location, and restoration areas completed between 2002 and 2018

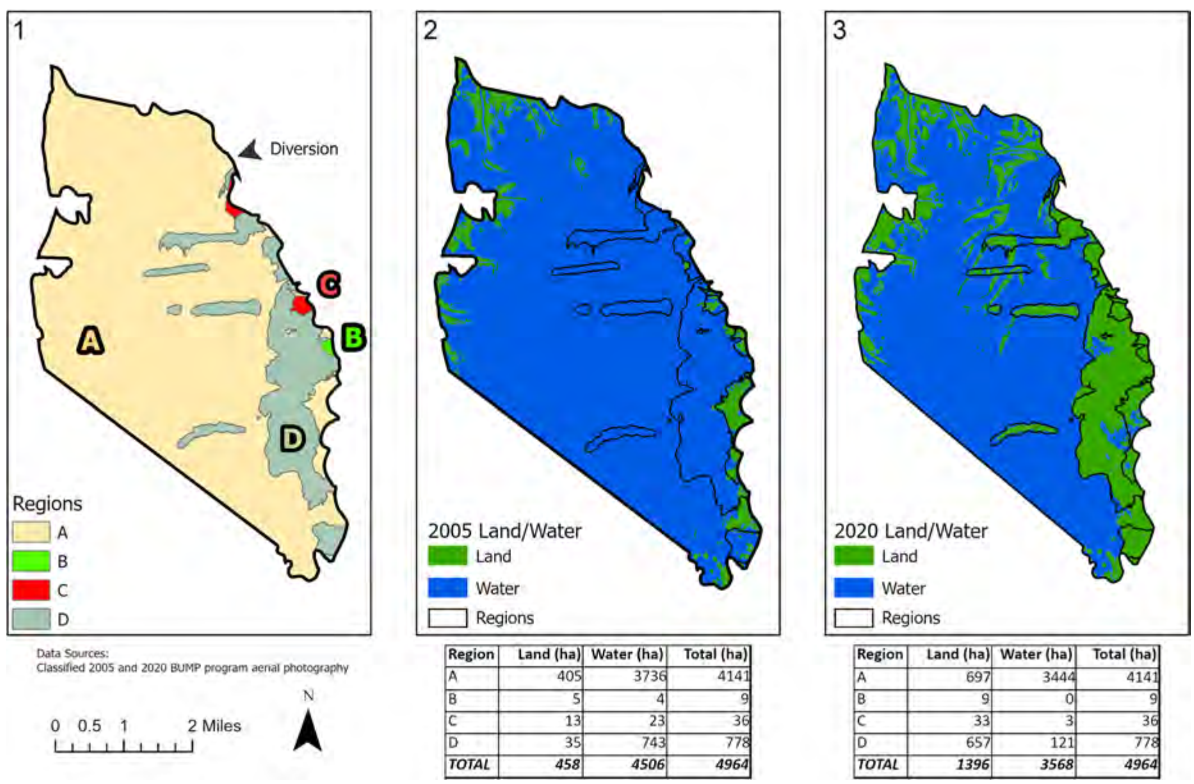
project to adaptively manage the flow by constructing a series of dynamic berms to increase the sediment trapping efficiency in the basin (McQueen et al., 2020). By 2013, hydrodynamic and sediment transport modeling data indicated that the diversion shifted from erosional processes to depositional processes, favoring the deposition of sediments (Yuill et al., 2016). Additionally, observations from field particle tracer studies combined with computational fluid dynamics modeling indicated that sediment trapping efficiency was enhanced by the dynamic sediment features and that future sediment diversions may benefit from this strategy (Allison et al., 2017).

West Bay is one of the few mesoscale restoration projects (ca. 4964 ha or 12 266 ac) on the Mississippi River to use an uncontrolled diversion (LA 29°10′50.50″N; 89°18′16.20″E; i.e., a diversion of water from the main river channel that is not managed through use of control gates, pumps, or other methods) coupled with large-scale dredged sediment placements (>28 million m^3 of dredged sediment to date; Figure 1). Implementation of NbS at this scale would not have been possible without the unique collaboration between the stakeholders. Stakeholder engagement involved numerous federal, state, and regional partners (e.g., US Fish and Wildlife Service; Louisiana Department of Natural Resources; CPRA; USACE), each with different objectives, expectations, and values. The federal navigation channel through the Birds-foot delta region of the Mississippi River is of substantial importance to United States and world commerce. The channel is kept fully functioning by routine dredging maintenance to provide safe vessel passage and prevent the enormous economic impacts associated with transportation disturbance, including all the joined upriver shallow draft waterways north of Baton Rouge. Therefore, the objective of this paper is to present information to demonstrate how the execution of a long-term dredging project provided value and co-benefits consistent with EWN and UN SDGs for sustainably achieving USACE navigation and ecosystem restoration missions.

METHODS

Mapping land and water areas and broad-based land cover over temporal scales enables the documentation of land change trends within the West Bay project area. Remotely sensed methods and data were used to assess the performance of ecosystem restoration activities in the project area through the analysis of historical and current aerial photography spanning approximately 70 years. To quantify land areas before 2007, land and water areas were determined from 1945 black and white aerial photography (0.35 m [1.15 ft] pixel resolution; USACE, 2020) and four color-infrared (CIR) aerial photographs for the following years at 1 m pixel resolution: 1983 (USDA 2020), 1998 (CWPPRA, 1998), 2004 (US Geological Survey [USGS], 2004), and 2005, all taken during November through January (USGS et al., 2006). For the most recent ecosystem restoration measures implemented post-2007, CIR aerials from nine different time periods were used to assess land and water areas. The post-2007 aerials were collected during the winter months (November to January) as part of the USACE Beneficial Use of Dredged Material Monitoring Program (BUMP; USACE, 2016) at a pixel resolution of 0.6 m for the years 2008, 2009, 2011, 2012, 2015, 2016, 2018, 2019, and 2020. Broad-based land cover classifications were generated for BUMP years 2008, 2015, and 2020.

An unsupervised classification approach identified and mapped pre-2007 land and water characterizations and post-2007 land/water and broad-based land cover for all CIR aerial photography via ENVI® Classification Workflow. This approach uses the spectral signatures of the pixels in the aerial image and groups each pixel by spectral similarities for the total number of user-defined classes. For these analyses, distinguishable features in the image determined the total initial class number chosen. Next, the Normalized Difference Vegetation Index (NDVI) was used to further refine the classification, with final groupings combined into the following classes for broad-based land cover: water, bare ground, sparse vegetation, moderate vegetation, and aquatic vegetation. In addition, two distinct classes were generated for land and water. The water features such as open water, streams, and aquatic vegetation comprised the water class,



Region	Land (ha)	Water (ha)	Total (ha)
A	405	3736	4141
B	5	4	9
C	13	23	36
D	35	743	778
TOTAL	***458***	***4506***	***4964***

Region	Land (ha)	Water (ha)	Total (ha)
A	697	3444	4141
B	9	0	9
C	33	3	36
D	657	121	778
TOTAL	***1396***	***3568***	***4964***

FIGURE 2 Direct dredge material placement activities and nature-based benefits contributed land and water trends. (1) Map of regions where A = nature-based benefit areas, B = 2002 direct dredge placement area, C = 2003 direct dredge placement areas, and D = 2006–2020 multiple direct dredge placement areas. (2) Map and table displaying the 2005 land and water trends per region. (3) Map and table displaying the 2020 land and water trends per region

while the land class encompassed the remaining areas such as bare ground and marsh. One exception to the classification approach is the manual digitization of land and water area polygons for the 1945 historical black and white aerial photo. The final classifications for each year were converted into vector shapefiles, where West Bay project statistics for land and water ratios and broad-based land cover hectares were generated using the ArcGIS® Calculate Geometry tool.

To evaluate the land changes generated from restoration activity between 2002 and 2020, the West Bay project was subdivided into four regions of interest (Regions A–D) based on direct dredge material placement activities and nature-based benefits derived from the river diversion and dynamic sediment features (Figure 2). Region A (4141 ha) represents the areas within the West Bay project that did not receive direct dredge material placement between 2002 and 2020. Region B, located along the east central project boundary, encompasses a 9-ha area where dredge material was placed in 2002. Two noncontiguous areas of dredge material (36 ha) placed in 2003 comprise Region C, while Region D is located along the project's eastern boundary and includes multiple direct dredge material placements that occurred between 2006 and 2020, including the dynamic sediment features. The dredge placement areas used in the analysis were digitized by the USACE New Orleans District using BUMP aerial photography for each placement year based on visual assessments of subaerial features. To quantify land and water hectares for each region, two vector shapefiles were generated for each classification year (2005 and 2020) using the ArcGIS® Identity tool to intersect the region area and land and water classification polygon shapefiles. Next, summary statistics of land and water hectares were calculated for each region using the ArcGIS® Summarize tool. This analysis only measures visible land and water features at the time the 2005 and 2020 aerial photos were taken and does not account for 3D measures of elevation where dredge material was placed on top of existing land.

RESULTS

Land and water ratios

Remote sensing-derived land and water ratios are a basic, yet important statistical metric for characterizing ecosystem restoration success. Land and water hectares from 14 data points between 1945 and 2020 were examined. As early as the 1940s, the West Bay project area (4964 ha) was mostly comprised of land (90% or 4461 ha), although, by 1983, the land area was dramatically reduced to 674 ha, with approximately 3780 ha of land lost (Figures 3 and 4). Construction of an uncontrolled sediment diversion from the Mississippi River into the West Bay project area in 2003 may have influenced the slight increase in land area from 1998 (580 ha) to 2004 (591 ha). However, a direct impact from Hurricane Katrina in 2005 was the probable cause of sediment erosion and a 3% reduction in land area. By 2008, the land area increased to 665 ha (13%) and remained variable until 2016. From 2016 to 2020, the bay's continual increase in land area in 2016 (1008 ha), 2018 (1341 ha), 2019 (1388 ha), and 2020 (1396 ha) reflects the benefit of multiple restoration efforts such as sediment retention features and marsh creation areas in recent years (Figures 2–4).

Broad-based land cover analysis

Broad-based land cover classifications provide a method for quantifying land change trends and evaluating the ecosystem being restored. Five distinct classes were assessed for three years (2008, 2015, and 2020) over a 12-year period (Figure 5). Across all three years, open water remained the most dominant habitat, with 3835, 3706, and 3460 for 2008, 2015, and 2020, respectively. However, the total water area decreased by 375 ha throughout the analysis period, primarily due to the construction of the dynamic sediment features (McQueen et al., 2020) and open water dredged material placement along the eastern project boundary. From 2008 to 2020, moderate vegetation areas and sparse

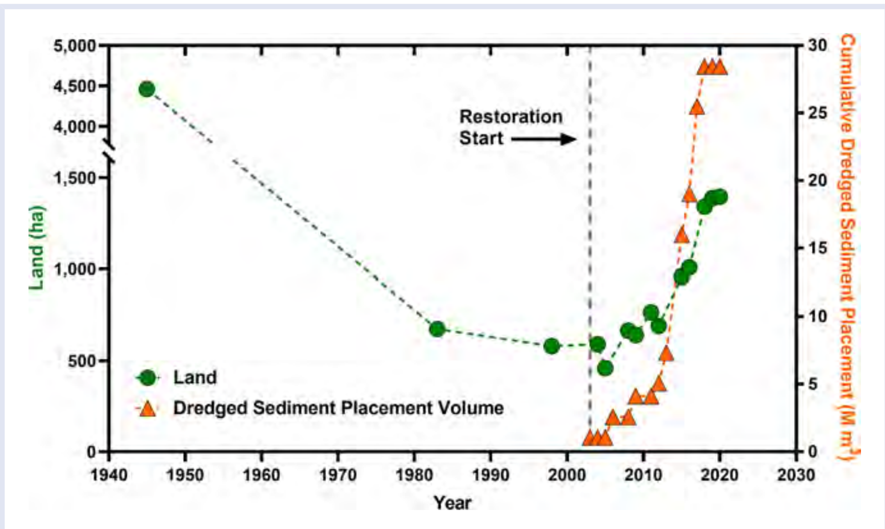


FIGURE 3 Land coverage (ha) changes in West Bay, Louisiana, and cumulative volumes (million m^3) of dredged riverine sediment placed for marsh restoration

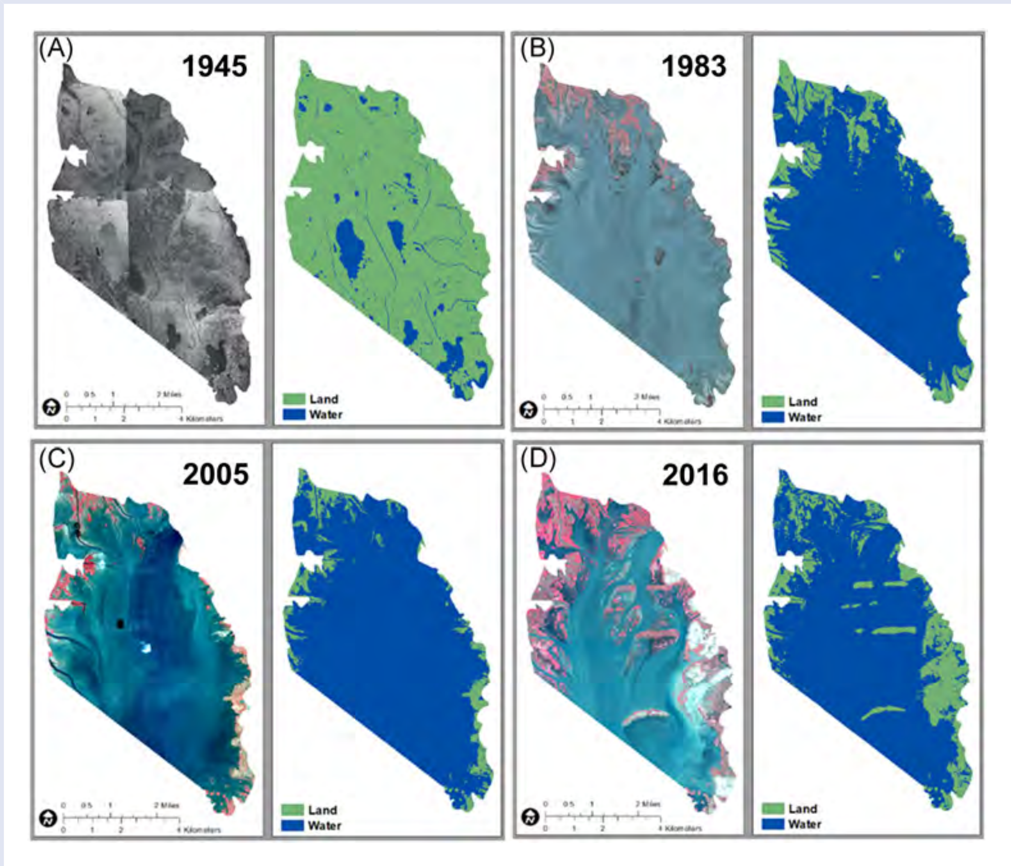


FIGURE 4 Land and water ratios based on land and water classified aerial photography for the West Bay, Louisiana project area from 1945 to 2015. Two panels depict each evaluation year; the left panel displays the aerial photography and the right panel depicts the photo-derived land and water classification. (A) 1945 black and white aerial photography and land and water classification. (B) 1983 CIR aerial photography and land and water classification. (C) 2005 CIR aerial photography and land and water classification. (D) 2016 CIR aerial photography and land water classification. CIR, color-infrared

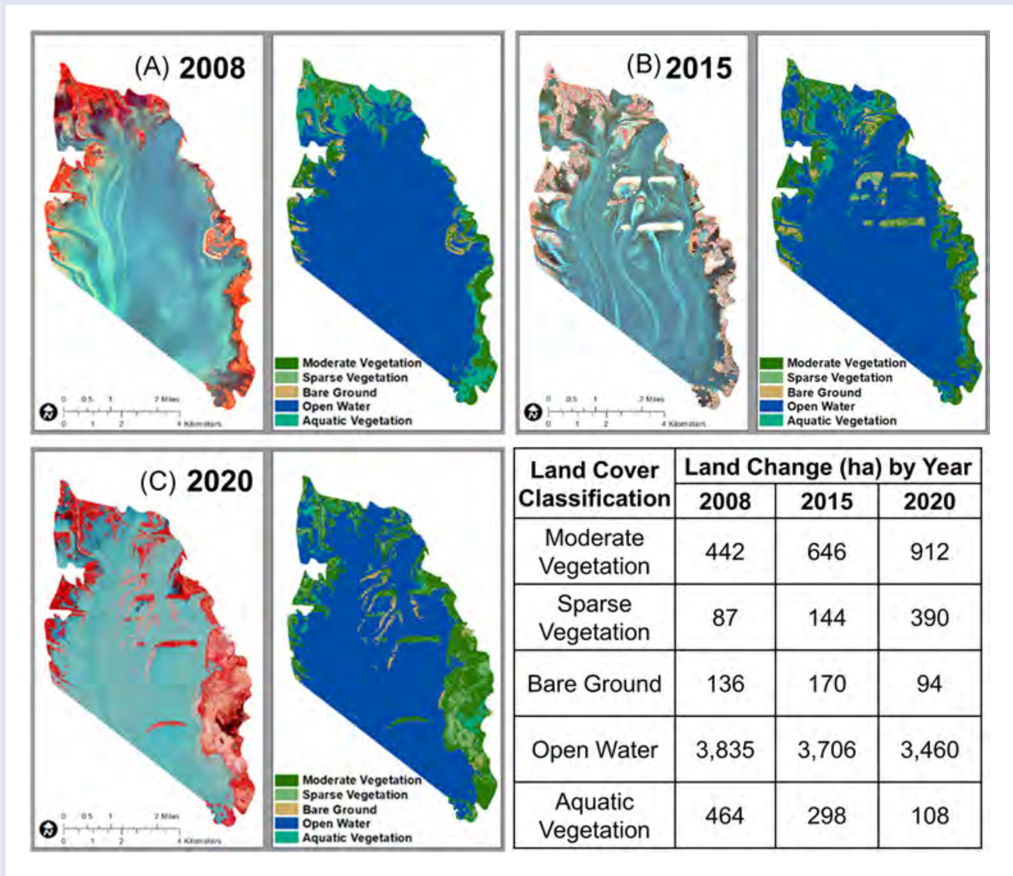
vegetation increased by 303 and 470 ha, respectively, while bare ground displayed a decrease from 136 to 94 ha for the analysis period, indicating colonization of native vegetation. Aquatic vegetation steadily decreased throughout the analysis period, with 464 ha in 2008, 298 ha in 2015, and 108 ha in 2020. Previous research has documented the effects of these natural processes such as river flooding and tidal influence on coastal marsh environments in the Mississippi River Delta (Day et al., 2007; Hiatt et al., 2019; Reed, 2002; Schoolmaster et al., 2018), and it is likely that the changes are attributed to water-level fluctuations.

Vegetation and habitat analysis

Areas of newly formed land in West Bay are classified as fresh to intermediate marsh habitat (CPRA, 2020; Plitsch, 2017). Vegetation surveys in 2015 and 2018 indicate that dominant species included *Zizania aquatica* (wildrice), *Vigna luteola* (hairypod cowpea), *Alternanthera philoxeroides* (alligator weed), *Amaranthus australis* (southern amaranth), *Phragmites australis* (common reed), and *Polygonum punctatum* (dotted smartweed). Additionally, an abundance of floating vegetation was present at shallow water locations near the dynamic features created with dredge material, which included duckweed (*Lemna* sp.) and American lotus (*Nelumbo lutea*) (CPRA, 2020). Variation in surface elevation of the newly created land supports multiple habitat types, including shallow (open) water, marsh grasses (moderate vegetation), and sandy berms (bare ground; Figure 5), indicating that diverse habitat structure is available to support a wide variety of flora and fauna.

Analysis of nature-based benefits

This analysis provided a method for quantifying both the direct and nature-based benefits of restoration activities in the West Bay project area. Overall, the analysis showed that each region experienced an increase in land area from 2005 to 2020 by 292, 4, 20, and 622 ha for Regions A, B, C, and D, respectively (Figure 2). The analysis of direct dredge material placement indicated that the greatest conversion of water to land occurred in Region D, the location of 2006–2020 direct dredge material placement. The 2002 placement area (Region B) lost 4 ha of its original 9-ha placement by 2005; however, it continued to rebuild its original land area and maintained its aerial land expression by the year 2020. The additional sediment at Region B may have derived from sediment surplus from placement activities in



Land Cover Classification	Land Change (ha) by Year		
	2008	2015	2020
Moderate Vegetation	442	646	912
Sparse Vegetation	87	144	390
Bare Ground	136	170	94
Open Water	3,835	3,706	3,460
Aquatic Vegetation	464	298	108

FIGURE 5 Broad-based land cover depicting land change trends (ha) in the West Bay, Louisiana project area for (A) 2008, (B) 2015, and (C) 2020. Two panels represent each year; the left panel displays the color-infrared aerial photography and the right panel depicts the photo-derived broad-based land cover classification

Region D. Similarly, the 2003 placement areas (Region C) also lost approximately 23 ha of its original 36-ha deposited material by the year 2005. This 2003–2005 land loss may be related to sediment disbursement due to the 2003 uncontrolled river diversion construction directly north of the placement area (7.6 km upstream of the Head of Passes, Louisiana). However, by 2020, the Region C land area was restored from 13 ha in 2005 to 33 ha in 2020. Measurement of the nature-based benefit of restoration activities in the West Bay project area was performed by examining the land and water area trends in Region A, where no direct dredge placement activities occurred between 2005 and 2020. The 2005 land and water areas were calculated as 405 and 3736 ha, respectively, and used as the baseline for estimating nature-based benefits. By 2020, 292 ha of water area (3444 ha) was converted into land area (from 405 to 697 ha; Figure 2). The increase in land area may be a result of multiple factors including the introduction of sediment laden flows from the Mississippi River through the diversion into West Bay (Sharp et al., 2013). In addition, the trapping of suspended sediment by the dynamic sediment features in Region A likely contributed to enhanced deposition of sediments that passed through the diversion. Cumulatively, direct placement activities have contributed to an increase in 646 ha of land (Regions B, C, and D) from 2005 to 2020 in the West Bay project area, while the land area in the nature-based benefit area increased by 292 ha (Region A). In other words, for roughly every 2 ha of lands created by direct placement, one additional hectare of land was created by implementing NbS, consistent with implementing EWN principles in practice.

DISCUSSION

The beneficial use of dredge sediment in West Bay is providing multiple benefits resulting in a "triple-win" outcome: economic (decreased dredging placement costs and reduced future maintenance of the adjacent federal navigation channel and livestock grazing on areas restored from open water to wetlands with elevations above the ordinary tide and plant communities influenced by rainwater and storm tides; Bush, 2021), environmental (submergent and emergent marsh habitat restoration), and social (recreation and storm protection). Thus, the West Bay project aligns with the principles of the USACE EWN initiative supporting more sustainable practices for delivering the USACE navigation, flood risk, and restoration missions. The EWN principles also align with UN SDGs developed for achieving a better and more sustainable future. The implementation of

TABLE 1 West Bay project actions aligning with UN SDGs

SDG description	Description of project actions contributing to SDG
"Build resilient infrastructure, promote sustainable industrialization and foster innovation."	Dredge sediment placement in West Bay improved the stability and resilience of the banklines of the Mississippi River channel.
"Making cities inclusive, safe, resilient, and sustainable."	Construction of dynamic sediment features with dredged sediment improved marsh restoration and storm resiliency and reduced flood risk of local communities.
"Take urgent action to combat climate change and its impacts."	West Bay is sensitive to coastal erosion accelerated by sea-level rise and climate change. Beneficial use of dredged sediment has slowed the rate and extent of coastal erosion.
"Conserve and sustainably use the oceans, seas and marine resources."	Placement of dredged sediment in West Bay has resulted in an abundance of shallow water intermediate marsh edge features contributing to valuable habitat and refuge for fish and other coastal species in Louisiana.
"Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss."	Dredged sediment placement has restored marsh habitat and successfully improved the quantity and quality of vegetated new land in West Bay and increased biodiversity.
"Promote inclusive and sustainable economic growth, employment and decent work for all."	Efficient use of dredge sediment placement has improved overall efficiencies of dredging and provided uninterrupted safe inland navigation of the Mississippi River Ship Channel region, which is a major engine for the US economy.
"End hunger, achieve food security and improved nutrition and promote sustainable agriculture."	The improved efficiencies in dredging provided uninterrupted navigation to the Mississippi River Ship Channel, which is vital to the US trade of food globally.
"Ensure access to water and sanitation for all."	Dredged sediment placement has restored marsh habitat that protects water-related ecosystems that provide improved water quality and slows saltwater intrusion to coastal drinking water aquifers.
"Ensure sustainable consumption and production patterns."	West Bay implemented large spatial- and temporal-scale beneficial use practices of dredge sediments, increasing organizational sustainability.
"Revitalize the global partnership for sustainable development."	Beneficial use of dredged sediment in West Bay demonstrated a diverse collaboration with federal, state, local stakeholder, and partner organizations to achieve sustainable solutions.

Abbreviation: UN SDG, United Nations Sustainable Development Goals.

the project is aligned with the following SDGs and the identified underlying targets (Table 1; Figure 6).

UN SDG 9—Industry, Innovation, and Infrastructure

The project contributed substantively to the goal of increasing regional inland navigation infrastructure by applying innovative techniques to achieve project objectives (Target 9.1). The multiple dredged sediment placement events in West Bay greatly expanded and restored the marsh habitat to reinforce the west descending bankline of the Mississippi River channel, improving the navigation infrastructure bordering the bay that was threatened by coastal land loss (Figures 3–5). The placement of the uncontrolled diversion location into the west descending bankline is a novel means of utilizing navigation infrastructure for purposes of using natural processes to maximize the benefits associated with restoring land in West Bay. The outcome enabled river commerce to continue uninterrupted.

UN SDG 11—Sustainable Cities and Communities

The project contributed substantively to the goal of applying NbS to provide support to the navigation bankline infrastructure. The five dynamic sediment features, constructed of dredged sediment in 2009, 2013, and 2015, were designed to beneficially lengthen the flow path, accelerate sediment accumulation, and reduce the velocity of the water flowing through the uncontrolled diversion (McQueen et al., 2020). These dynamic features were constructed consistent with the earlier findings of Kolker et al. (2012), who reported that the maximum sediment deposition occurred downstream (south) of the West Bay project boundary. This increased the amount of sediment captured in the bay as opposed to suspended sediments being released further out into the open waters of the Gulf of Mexico. These nature-based sediment features are subsequently being shaped by natural processes and are evolving into natural landform features (Figures 2, 4, and 5). The resultant land restored helps improve the

FIGURE 6 Graphical illustration showing the strength of association between the West Bay project benefits and United Nations Sustainable Development Goals (UN SDGs). Smaller icons in the inner circle represent little to no association; medium-sized icons in the outer circle (SDGs 2, 6, 8, 12, and 17) represent moderate association, and large icons on the outer circle (SDGs 9, 11, 13, 14, and 15) represent substantial association of project benefits with the SDGs

resiliency of local communities vulnerable to impacts from storms (Target 11.5).

UN SDG 13—Climate Action

West Bay, located on the Louisiana Gulf Coast, is sensitive to shoreline erosion, subsidence, sea-level rise, and habitat loss (Couvillion et al., 2011). Since 2002, beneficial use placement activities in West Bay have successfully ameliorated the rate and extent of land loss and built approximately 805 ha (1989 acres since 2004) of land in previous open water areas to restore marsh habitat. The project is contributing meaningfully to the restoration of marsh along the Louisiana coast, reversing land loss in the bay exacerbated by climate change and increasing the resiliency of the federal navigation channel banklines (Target 13.1). The water-to-land conversion is increasing the land and associated marsh vegetation available to serve as a carbon sink (Foran et al., 2018).

UN SDG 14—Life Below Water

The dynamic sediment features, designed to be shaped over time by natural processes, combined with the strategic placement of dredged sediment immediately downstream of the diversion, are examples of how nature's energy was used to create and restore marsh habitat in the bay (McQueen et al., 2020). Based on the land features in the 2005 land and water analysis, the habitat edge present in the West Bay project area was approximately 340 linear km. This analysis year also included three area placements deposited in 2002–2003 that totaled approximately 73 ha. With additional placement events from 2006 to 2018, the habitat edge from the land areas in the 2020 analysis increased by 75 to 415 linear km. The growth of the marsh habitat over time in West Bay has resulted in an abundance of shallow water edge features, known to serve as valuable habitat and refuge for fish and other coastal species in Louisiana (Boesch & Turner, 1984; Peterson & Turner, 1994). The project is consistent with Target 14.2 in that it is sustainably managing and restoring a marine coastal ecosystem to not only reverse significant adverse impacts but also strengthen resilience in the area, thereby contributing to a healthy and productive Gulf of Mexico. Contributing to the overall sustainability of the project is the fact that USACE dredged material management practices in the New Orleans District have decreased reliance on offshore disposal from 4.6 to 2.7 million m^3/year and increased reliance on beneficial use from 1.5 to 6.1 million m^3/year on average over the last 20 years (comparing the 2000–2009 and 2010–2019 decadal averages).

UN SDG 15—Life on Land

The habitat created in the bay by the beneficial use placement activities has been classified as fresh-intermediate marsh (Plitsch, 2017). In a 2015 survey, Plitsch, (2017) used the Floristic Quality Index (FQI) to interpret the quality of these newly created vegetative areas, rated from 0 to 100 (higher scores indicating better habitat quality). The FQI reflects both percent cover and a coefficient accounting for species tolerance to disturbance and fidelity to habitat. The results indicated an FQI of 34 for West Bay, which compares favorably to FQI scores of less than 20 for the Mississippi River Delta in general, indicating that the newly developed land was providing better than regional average habitat quality. Additionally, observational data obtained from 2019 aerial surveys and visual ground observations indicated an abundance of migratory birds utilizing the area (USACE, 2020). Collectively, these data suggest that land building in the bay is favorable for increasing the biodiversity of coastal marshes and forests (Target 15.2).

Project execution also aligns with several additional SDGs, as described below (Table 1; Figure 6).

UN SDG 8—Decent Work and Economic Growth

The Mississippi River is the primary inland navigation system in the United States and is critical to global waterborne commerce. The Mississippi River Ship Channel region accessed by the Southwest pass (the stretch of the Mississippi River from the Gulf of Mexico through the Port of Baton Rouge) is a particularly valuable region, with four ports ranking in the top 13th of annual tonnage for US ports accounting for one-fifth of all waterborne commerce in the United States (USACE, 2018). The Port of South Louisiana is among these ports and ranks the first in total tonnage among US ports, with ~273 million tons in 2018 (USACE, 2018). The total economic contribution of the Mississippi Waterway System provides approximately 256 000 jobs and $27.2 billion dollars in Gross Domestic Product (based on 2016 economic data), with waterborne transport credited with saving up to $9 billion annually as compared to other modes of transport (US Department of Agriculture [USDA], 2019). Sustainable dredging practices demonstrated in this project provided uninterrupted safe inland navigation and thus maintained the economic engine provided by the Mississippi River Ship Channel. Decoupling economic growth from environmental degradation aligns with Target 8.4.

UN SDG 2—Zero Hunger

In addition to the substantial economic value of the Mississippi River Ship Channel, it is also a critical transport route of food and farm products. The Mississippi River Ship Channel region accounts for 57% and 59% of US corn and soybean exports in volume, respectively (corn valued at $4.8 billion and soybeans valued at $12.4 billon USD; USDA, 2019). In 2018, 90 million tons of food and farm products were transported through the Mississippi River Southwest Pass navigation channels, accounting for approximately 33% of total cargo tonnage (273 million total tons in 2018; WCSC 2020). Clearly, the importance of maintaining safe and navigable waterways in Southwest Pass Channel is vital to the US trade of food globally. The novel strategies used to beneficially use sediments dredged from the Mississippi River are providing an economically viable outcome that enables river commerce to continue uninterrupted for global transportation of food and farm products while providing higher ground suitable for livestock grazing that also increases resiliency to climate change impacts (Target 2.4; see also UN SDG 6).

UN SDG 6—Clean Water and Sanitation

The project is taking meaningful steps to protect and restore water-related ecosystems, including coastal marsh and forest habitats (Target 6.6; Figure 5). The use of engineered structures such as diversions is considered one means of ameliorating saltwater intrusion in coastal marshes (White & Kaplan, 2017). In a model simulation study using the SEAWAT model, Xiao et al. (2019) reported that infiltrated rainwater could provide a downgradient freshwater discharge for diluting and flushing saltwater, counteracting the extent of saltwater intrusion, although this process may take several years. These results suggest that the restoration of the coastal forest and marsh in West Bay through the uncontrolled diversion combined with the restoration of upland habitats may slow the spread of saltwater intrusion. This should be confirmed by further research.

UN SDG 12—Responsible Consumption and Production

This SDG is about "doing more and better with less." The USACE is implementing the sustainable management and efficient use of a natural resource (sediment; Target 12.2) by implementing sediment beneficial use practices in West Bay at a large spatial and temporal scale. Using dredged sediment as a natural resource and sustainable practice is a key means by which the USACE is becoming a more sustainable organization. Such practices help reduce the economic costs (i.e., decreased placement costs and reduced future maintenance of the adjacent federal navigation channel) associated with the USACE's $1.5 billion dollars+ annual dredging program. Documentation and communication of these practices facilitate their implementation elsewhere.

UN SDG 17—Partnerships

The USACE, through the relationships developed with the State of Louisiana and other stakeholder and partner organizations, is sharing knowledge, expertise, technology, and financial resources to achieve and document the sustainable NbS being implemented in the bay. Construction of the diversion in 2003 would not have been possible without the unique collaboration forged between the state of Louisiana and USACE through the CWPPRA program, demonstrating that partnerships and cooperation are essential elements for achieving large-scale project success (Target 17.17). This relationship developed during the project offered the opportunity to "build back better" by improving both coastal and community resiliency and restoring the coastal marsh habitat of the area.

The meaningful connections to multiple SDGs illustrate that the USACE, through its Environmental Operating Principle of fostering sustainability as a way of life, is implementing innovative NbS in West Bay. Recent pressures to waterborne infrastructure in terms of economic impacts (e.g., COVID-19) and extreme weather events (e.g., tropical cyclones Marco, Laura, Beta, Delta, and Zeta in 2020) making landfall on the US Gulf Coast highlight the needs for developing sustainable dredging strategies. Such examples provide a more complete understanding of project successes such that these techniques can be integrated into other dredging projects in coastal Louisiana and elsewhere.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

DISCLAIMER

The views and opinions expressed in this paper are those of the individual authors and not those of the US Army Corps of Engineers, US Army Engineer Research and Development Center, or other sponsor organizations. The peer review for this article was managed by the Editorial Board without the involvement of Burton C. Suedel.

DATA AVAILABILITY STATEMENT

Data are available upon request from corresponding author Burton C. Suedel (burton.suedel@usace.army.mil).

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