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Enhancing the Sustainability of Gulf Intracoastal Waterway Dredge Material Placement Areas

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Cooperative Research Program

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COLLEGE STATION, TEXAS

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16. Abstract

Placement areas for dredged material (DMPA) from the Gulf Intracoastal Waterway (GIWW) are a responsibility of the state of Texas. Given population and industrial growth along the coastline and the continual need for dredging, it is important to use the sites efficiently and ensure their integrity. This research provided the analytical framework and methodology that will enable the Texas Department of Transportation to develop a strategic program for the restoration and protection of the DMPAs of the GIWW along the Texas Coast. The work plan combined general physical, environmental, and economic data to provide strategic direction and develop information on techniques and potential measures to enhance the long-term performance of placement areas and dredging activities. A tool using Analytic Hierarchy Process was created to evaluate various feasible solutions based on consideration of multiple criteria such as lifecycle costs, safety, and environmental sustainability.

The research focused on East Matagorda Bay, the highest priority segment of the GIWW. Protecting this reach of the GIWW against long-fetch bay-induced wind/wave energies will significantly increase navigation safety and efficiencies and reduce navigation channel shoaling, resulting in reduction of maintenance dredging cycles.

The research produced an extended list of improvement features, considerations, and evaluation options that could be prioritized as shoreline changes are observed or storm-induced waves and shoaling or current/wave-regimes negatively impact navigation safety.

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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EXECUTIVE SUMMARY

INTRODUCTION AND BACKGROUND

This research provides the analytical framework and methodology that will enable the Texas Department of Transportation (TxDOT) to develop a strategic program for the restoration and protection of the dredge material placement areas (DMPAs) of the Gulf Intracoastal Waterway (GIWW) along the Texas Coast. The work plan was designed to combine general physical, environmental, and economic data to provide strategic direction and develop information on techniques and potential measures to enhance the long-term performance of placement areas and dredging activities. A tool using Analytic Hierarchy Process (AHP) was created to evaluate various feasible solutions based on consideration of multiple criteria such as lifecycle costs, safety, and environmental sustainability.

SELECTION OF CRITICAL AREA FOR DETAILED EVALUATION

Several stakeholders were interviewed to acquire insight into their organization's viewpoints on creating and maintaining sustainable DMPAs. These stakeholders included state resource agencies, federal agencies, non-governmental organizations (NGOs), and barge operators. Several critical issues and priorities were discussed that led to the selection of East Matagorda Bay (EMB) as the focus of the detailed evaluation. Specific issues and concerns included:

- EMB includes the areas of greatest concern for barge operators and is the U.S. Army Corps of Engineers' (USACE)'s second highest concern due to the lack of space for new DMPAs mainly on the bay side.
- Several agencies commented on activities needed in this region.
- The diversification of ecological habitats can promote the development of adaptive restoration options, which include:
    - Increasing the areas for seagrasses.
    - Reducing strong cross currents.
    - Reducing siltation on the GIWW.
    - Incrementing the number of mooring facilities.
    - Creating new bird islands.
    - Identifying the DMPAs in need of restoration.
    - Possibility of creating whooping crane habitats.
    - Developing new oyster reefs to control energies affecting bay shorelines and GIWW infrastructure.

EAST MATAGORDA BAY: CURRENT CONDITIONS, DREDGING ACTIVITIES, AND POTENTIAL ECONOMIC IMPACTS

DMPAs 101 and 105 are located within the vicinity of the selected area in EMB where there are land gaps or breaches along the south side of the GIWW. DMPAS 101, 102-A, 102-B, 102-C, 103, 104, and 105 are located north of the GIWW. Some of these DMPAs are currently designed to have shoreline protection measures in place. Only one property in that segment of the GIWW is owned by a federal agency; the Big Boggy National Wildlife Refuge managed by U.S. Fish and Wildlife Service (USFWS) is located north of DMPAs 104-A and 104-B. No other property in the area is owned by a state agency or by NGOs. Table 1 summarizes dimensions and conditions of DMPAs in the eastern portion of EMB. Figure 1 shows the above referenced DMPAs.

Table 1. DMPAs Dimensions and Conditions in East Matagorda Bay.

DMPA No.	Acreage	Status	Level of Impact by Bay Shoreline Retreat	Remaining Life in Years*
DMPA 101	45	Active, partially confined in water	Low	Data unavailable
DMPA 101-A	181	Active	None	Data unavailable
DMPA 102-A	252.9	Data unavailable	Severe	Data unavailable
DMPA 102-B	314.94	Data unavailable	Severe	Data unavailable
DMPA 102-C	135.08	Active	Low	Data unavailable
DMPA 102-R	224.50	Data unavailable	None	Data unavailable
DMPA 103	93.15	Data unavailable	Severe	Data unavailable
DMPA 104	469.69	Data unavailable	None	Data unavailable
DMPA 104-A	67.07	Data unavailable	None (Protected)	Data unavailable
DMPA 104-B	81.54	Data unavailable	None (Protected)	Data unavailable
DMPA 105	451.26	Data unavailable	Moderate	Data unavailable
DMPA 105-A	No data	Data unavailable	No data	Data unavailable

Source: USACE Navigation Data Center Database and Kruse et al. (1) and notes from the authors

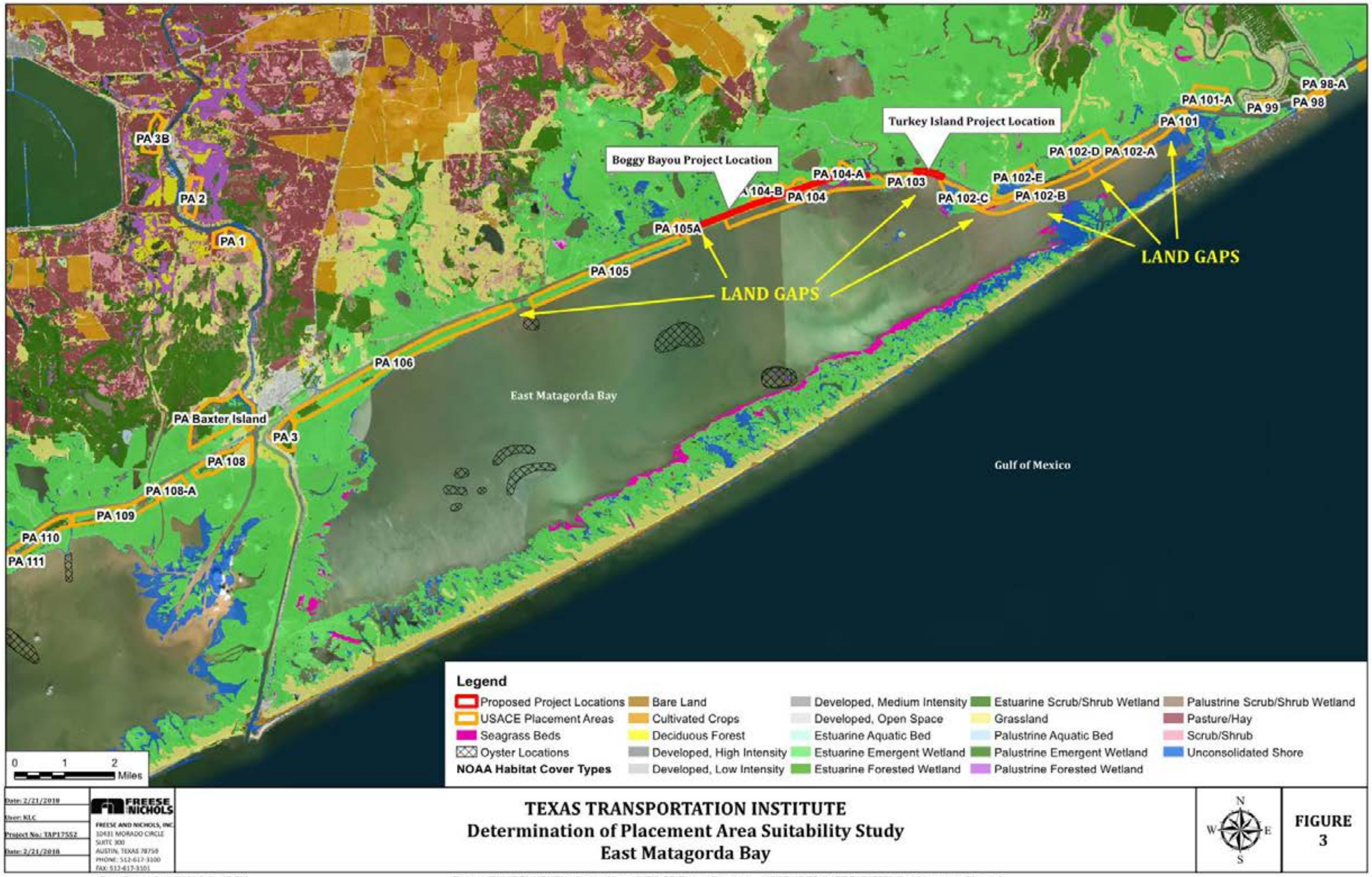

Figure 1. Location of DMPAs in EMB and Habitat Types Identified by National Oceanic and Atmospheric Administration (NOAA).

Note: The figure includes critical environmental issues that are influencing the GIWW.
Source: NOAA Coastal Change Analysis Program (C-CAP) 2010 Land Cover Atlas

Bay shoreline retreat rates have varied from 3 to 4 ft per year (*2*). Several areas were identified on the bayside as critical areas in need of restoration where land gaps or breaches exist. One of these areas is a large land gap of about 4 miles between DMPA 101 and 102-C. Some thin segments of land barrier and the DMPAs remain in place, but most of the area is now open water. A second land gap exists between DMPAs 102-C and 103 with a length of 0.3 miles. A third land gap exists between DMPA 103 and 105 with a length of about 3.8 miles. Only the DMPAs north of the GIWW are protected from bay energies and shoreline impacts from waves generated by vessels. The levees on the DMPAs south of the GIWW are in poor condition, except for DMPA 102-C, which is an active site.

Researchers reviewed USACE dredging data for the GIWW channel from station 702+000 near DMPA 101 to station 776+000 east of DMPA 105. The USACE database shows only two major dredging events that were specifically for this reach; they occurred in 1992 and 1998. In 1992, the USACE reported 1,829,740 cubic yards of material dredged between Big Boggy National Wildlife Refuge (DMPA 104-B) and the mouth of the Colorado River. In 1998, the USACE reported 3,500,000 cubic yards of material dredged in the same section of the GIWW (this actually took place in Fiscal Year 1999). No data are available for recent years. Prices per cubic yard of dredged sediment varied from $1.11 to $3.92.

Chapter 2 explains that there have been several dredging contracts issued by the USACE Galveston District that include portions of Matagorda Bay, although the geographic scope was much broader. If one can assume that dredging takes place every 6 years, the average annual amount of material dredged per the information in the preceding paragraph would be approximately 890,000 cubic yards. However, the data contained in the district's annual activity extract indicate an average annual amount of approximately 1.9 million cubic yards. Given that the dredging records include reaches outside the scope of this study, the actual number would most likely be toward the lower end.

The data suggest that the development of potential solutions for the reduction of navigation hazards by closing the land gaps may be less expensive in EMB than in other bays. The shallow environments will require less sediment to maintain barriers.

Researchers analyzed the economic effect on the barge industry of NOT maintaining the GIWW at its authorized dimensions. A high-level analysis concluded that if 1 ft of water depth in the GIWW is lost, barge operators will incur costs of $12.6 million annually due to the need to light load barges. This is an increase of 15.5 percent in the cost of doing business.

The annual cost of dredging, as derived from contracts that included Matagorda Bay in their scope of work, has been about $5.2 million annually. The actual figure is certainly lower because many of the dredging contracts since 1998 have included Matagorda Bay as one of several areas to be dredged. Even with this somewhat inflated cost number, the benefit-cost ratio is 2.4.

ALTERNATIVE NATURAL SOLUTIONS

Researchers identified potential natural solutions that might address or mitigate the problems identified in EMB. Researchers reviewed studies performed by the USACE, the Texas General Land Office (GLO), and university researchers that address similar problems on the Texas coast and on the coast of other Gulf of Mexico states. Based on this review and the stakeholder interviews, researchers summarized potential natural solutions with a description of how each of the solutions might best be applied to the GIWW in EMB, including the pros and cons in terms of both engineering feasibility and cost.

The solutions with the greatest probability of success and acceptance by state agencies fall into the category of "soft shoreline" or "living shoreline" (LS) solutions. A LS project has a footprint that consists of mostly native material (*3*), which can incorporate vegetation or other living and natural soft elements, either as a stand alone or in combination with some type of harder shoreline structure (e.g., oyster reefs or rock sills) for added stability. The goal of LS projects is to maintain the continuity of the natural land-water interface and reduce erosion while providing habitat value and enhancing coastal resiliency (*4*).

The stakeholders interviewed for this study recommended that LS projects be constructed to protect shorelines from strong currents and high energy and to increase ecosystem diversity. According to the stakeholder interviews conducted for this study, USACE has historically been the only agency to consider such concepts for the primary purpose of improving navigation safety.

According to the criteria developed by NOAA and USACE, LS concepts should include:

- Stabilization of shorelines to reduce rates of shoreline erosion from increased bay energies and storm damage.
- Diversification of habitats for fish and other aquatic species.
- Enhancement of coastal resiliency through maintaining the land-water interface.
- Hybrid solutions that consist of a combination of natural materials (e.g., oyster shell) and nature-based materials (e.g., rocks where they do not naturally occur) that work together to provide shoreline stabilization (*4*).

The introduction of LS concepts started in Texas in the early 2000s. LS concepts have mainly been applied in the Galveston Bay area as a multiagency coordinated effort. These LS projects have transitioned from applications of semisoft structures to hard structures (sometimes submerged).

Examples of LS projects in Texas estuaries include:

- Shamrock Island in Corpus Christi Bay (see page 43).
- West Galveston Bay Mooring Buoy Area (see page 45).
- McFaddin National Wildlife Refuge in Jefferson County (see page 50).
- Mad Island in Matagorda Bay (see page 52).

Several important lessons were learned in reviewing these projects:

- The main reason for shoreline retreat is the lack of sediment being returned to the shorelines. Sediment is moving along the shorelines through bay littoral processes or by suspension processes, but sediments are not being accreted in the shoreline system.

- The first mentioned LS projects developed in Texas (Shamrock Island and West Galveston Bay mooring buoy area) using soft solutions failed. The geotextile tubes failed when exposed to direct wave attack, making them useful only for short-term erosion control (*5*).
- The McFaddin LS shoreline protection project proved that suspended sediment even in low energy environments can be harvested and returned to the natural system.
- The West Galveston Bay mooring buoy area project has served as a shoreline protection and habitat restoration LS alternative.
- The Mad Island GIWW shoreline protection project has been successful in mitigating wave energies from vessels but has had limited results on the return of sediment to the natural system.
- Stakeholders are now considering hard structures in addition to soft solutions for shoreline protection and habitat diversity. The combination of hard and soft concepts has successfully provided direct and indirect benefits to ecological services—in some cases beneficial use of dredge material (BUDM) opportunities—and improved navigation efficiencies.
- None of the previously mentioned LS projects on the GIWW had the main goal of improving or maintaining navigation safety. However, according to USACE staff, the three projects described in this report have improved navigation efficiencies by reducing shoaling and delaying dredging cycles due to the local GIWW shoreline stabilization on the local segment of the navigation channel.
- Staff from USACE Operations Division reaffirmed that the Galveston District has abandoned the use of geotextile tubes as a shoreline protection solution due to past failures. Reef balls appear to be an alternative that can support other soft LS solutions.

The specific solutions to be selected as soft or hard LS structures for shoreline protection of DMPAs may depend more on how those solutions interact with sediment supply, either naturally or artificially (BUDM alternatives).

FEASIBLE SOLUTIONS FOR SELECTED AREA

EMB is a shallow bay that is unique to the Texas coast. During the last century, EMB was separated from West Matagorda Bay (WMB) by the creation of the Colorado River Delta Channel. When EMB and WMB became independent bay bodies, EMB reduced the available environmental flows but increased the amount of sediment supply originating from the inland fluvial sources and from the Gulf of Mexico inlets through Mitchell's Cut, creating one of the few closed-system coastal sediment sinks in Texas.

Table 1 summarizes dimensions and conditions of DMPAs in the eastern portion of EMB.

Recommendations for DMPA improvements to enhance navigation safety and efficiencies in EMB include the following:

- There are three navigation channel turns requiring critical protection against bay-induced wind/wave energies and sediment transport to provide for enhanced navigation safety and efficiencies. Recommended DMPA improvements at these turns include:

- **DMPA 101 West:** Extend DMPA 101 approximately 900 ft westward toward DMPA 102-A to protect the turn.
- **DMPA 102-C East:** Extend DMPA 102-C approximately 2600 ft eastward toward DMPA 102-B to protect the turn.
- **DMPA 102-C West:** Extended DMPA 102-C approximately 2500 ft westward toward DMPA 103 to protect the turn.

- Several DMPAs may not be a priority for improvements in the next few years but may affect GIWW navigation and operations if nothing is done. They include:
  - **DMPA 103:** This DMPA should be restored and/or expanded for the long-term sustainability of the GIWW since it provides protection against bay wind/wave energies at the navigation channel turn.
  - **DMPA 105:** This DMPA has sufficient existing footprint to remain functional for a few more years of shoreline retreat but will require shoreline protection to the DMPA's GIWW-facing side.
  - **DMPAs 102-A and 102-B:** These DMPAs have extended designated footprints and will require substantial investments and sediment volumes to improve their condition. DMPAs 102-A and 102-B are essentially physically non-existent, which cause major problems to DMPAs 102-D and 102-E located on the north side of the GIWW. The protection features constructed to protect the GIWW-facing shorelines of DMPAs 102-D and 102-E are being impacted by long-fetch bay wind/wave erosional energies, which cross the GIWW uninterrupted. Additionally, the GIWW's barge-induced waves and wakes impact the GIWW-facing shoreline protection features of DMPAs 102-D and 102-E. By physically improving DMPAs 102-A and 102-B, long-fetch wind/wave energies will be reduced before reaching the GIWW, which will reduce navigation safety impacts within the GIWW and erosional impacts to DMPAs 102-D and 102-E GIWW-facing shorelines.
- Solutions for managing shoreline retreat at the evaluated DMPAs and the GIWW shorelines are expected to be on the harder (gray) side of the NOAA classification, but are not expected to include bulkheads, seawalls, and geotextile tubes. These structures do not retain or trap sediment in coastal environments. Application of these methods may accelerate shoreline retreat on the adjacent shorelines since these devices transfer the energy to the next area and are not considered feasible for the evaluated locations. Table 2 shows the general characteristics of each solution.

Table 2. General Characteristics of the Green and Gray Shoreline Protection Infrastructure.

Green Alternatives	Descriptions
Vegetable only	Roots hold soil in place to reduce areas and breaks small waves.
Edging	Structure to hold the toe of existing or vegetated slope in place. Protects against shoreline erosion.
Sills	Parallel to existing or vegetated shoreline, reduces wave energy and prevents erosion. A gapped approach would allow habitat connectivity, greater tidal exchange, and better waterfront access.
Sediment replenishment	Large volume of sand added from outside source to an eroding beach. Widens the beach and moves the shoreline seaward.
Sediment replacement and vegetation	Helps anchor sand and provide a buffer to protect inland area from waves, flooding, and erosion.
Gray Alternatives	**Descriptions**
Breakwater	Offshore structure intended to break waves, reducing the force of wave action and encouraging sediment accretion. Can be floating or fixed to the ocean floor, attached to shore or not, and continuous or segmented. A gapped approach would allow habitat connectivity, greater tidal exchange, and better waterfront access.
Groin	Perpendicular, projecting from shoreline. Intercept water flow and sand moving parallel to the shoreline to prevent beach erosion and break waves. Retain sand placed on beach.
Revetment	Lays over the slope of a shoreline. Protects slope from erosion and waves.
Bulkhead	Parallel to the shoreline, vertical retaining wall. Intended to hold soil in place and allow for a stable shoreline. **(Not Recommended)**
Seawall	Parallel to shoreline, vertical or sloped wall. Soil on one side of wall is the same elevation as water on the other. Absorbs and limits impacts of from land. **(Not Recommended)**

Source: (3,4)

- During the analysis conducted for the historical solutions dedicated to mitigating or reducing shoreline erosion along the GIWW, it was identified that one specific project on the shorelines of the GIWW in Jefferson County has successfully performed as a wave attenuation, sediment retention, and shoreline stabilization feature after its construction. The uniqueness of this project is that it allowed for the retention and the capture of sediment behind the breakwater. The methodology applied to this project can serve as the basis for the future development and implementation of shoreline protection structures for DMPAs.
- In addressing the GIWW sedimentation problem in West Galveston Bay, USACE developed several design recommendations that are pertinent to the evaluation of options for EMB:

    - A rip rap revetment was found to be the lowest cost acceptable alternative for structures adjacent to channels.
    - Oyster castles are the lowest-cost alternative for bay-side structures and structures adjacent to channels.
    - USACE recommends the implementation of sacrificial berms in addition to hard structures for bay-facing berms or shorelines of the bay barrier islands to serve as training dikes and allow for the continued placement of dredge materials.
- Rock breakwaters are recommended for GIWW-facing shore protection features along the GIWW because wave heights are typically 5 ft or less.
- Rock revetments are recommended for bay-facing shorelines as a long-term shoreline stabilization alternative.
- USACE has used articulated mat revetments on the GIWW for the protection of DMPAs in EMB and West Galveston Bay. These articulated revetments have had significant failures due to continued scouring.
- Reef balls are ideally suited for a wide-range of aquatic habitats even when used in engineering applications. Concrete made with special concrete additives for reef balls, including pH like seawater, assures compatibility with marine environments and enhances its attractiveness to colonizing organisms.

PROPOSED SHORELINE PROTECTION SOLUTIONS IN EAST MATAGORDA BAY

The highest priority area in EMB includes the navigation channel turns adjacent to DMPA 102-C. This area was identified as a priority for navigation safety. Protecting this reach of the GIWW against long-fetch bay-induced wind/wave energies will significantly increase navigation safety and efficiencies and reduce navigation channel shoaling, resulting in reduction of maintenance dredging cycles. The DMPA berm or shorelines along the GIWW will require a rock breakwater. For the bay-facing berms or shorelines, combination solutions consisting of green and/or gray features may effectively provide multifaceted protection. However, these solutions should be determined case-by-case.

There is an extended list of improvement features, considerations, and evaluation options that could be prioritized as shoreline changes are observed or storm-induced waves and shoaling or current/wave-regimes negatively impact navigation safety (see Table 3).

Table 3. Proposed Improvement Features for Evaluated Reach/DMPAs.

DMPA	GIWW-Facing		Bay-Facing	
	Issue	Feature	Issue	Feature
101	GIWW-Facing Shoreline Erosion	a) Breakwater Shoreline Protection (allowing for overtopping and sediment exchange)	Continue Monitoring Shoreline Changes	N/A
West of 101	No Elevated Land between GIWW and Bay causing Shoaling in GIWW	a) Extend DMPA 101 westward for tie-in into Existing Bay Barrier Habitat	No Elevated Land between GIWW and Bay causing Shoaling in GIWW	a) Extend DMPA 101 westward for tie in into Existing Bay Barrier Habitat
		b) Evaluate the Option of Segmented Breakwaters parallel to GIWW to trap Sediment introduced through Mitchell's Cut		b) Evaluate the Option of Segmented Breakwaters parallel to GIWW to trap Sediment introduced through Mitchell's Cut
102-A	No Elevated Land between GIWW and Bay causing Shoaling in GIWW	a) Build up DMPA with Dredge Material	No Elevated Land between GIWW and Bay causing Shoaling in GIWW	a) Build up DMPA with Dredge Material
		b) Evaluate adding Rock Revetment/Breakwater on GIWW side post Dredging		b) Evaluate adding Sacrificial Berm and/or Segmented Reef Balls on Bay Side
102-B	No Elevated Land between GIWW and Bay causing Shoaling in GIWW	a) Build up DMPA with Dredge Material	No Elevated Land between GIWW and Bay causing Shoaling in GIWW	a) Build up DMPA with Dredge Material
		b) Evaluate adding Rock Revetment/Breakwater on GIWW side post Dredging		b) Evaluate adding Sacrificial Berm and/or Segmented Reef Balls on Bay Side
East of 102-C	Predominantly Water - Interconnecting Bay and GIWW	a) Extending DMPA past GIWW Curve via Dredge Material Placement.	Predominantly Water - Interconnecting Bay and GIWW	a) Build up DMPA with Dredge Material
		b) Evaluate adding Rock Revetment/Breakwater on GIWW side post Dredging		b) Evaluate adding Sacrificial Berm and/or Segmented Reef Balls on Bay Side
102-C	Continue Monitoring of Erosion	N/A	Continue Monitoring of Erosion	N/A
Between 102-C & 103	Predominantly Water - Interconnecting Bay and GIWW	a) Extending DMPAs and connect DMPA 102-C and 103 via Dredge Material Placement.	Predominantly Water - Interconnecting Bay and GIWW	a) Build up DMPA with Dredge Material
		b) Evaluate adding Rock Revetment/Breakwater on GIWW side post Dredging		b) Evaluate adding Sacrificial Berm and/or Segmented Reef Balls on Bay Side
103	GIWW-Facing Shoreline Erosion	a) Breakwater Shoreline Protection (allowing for overtopping and sediment exchange)	Bay-side Erosion	a) Evaluate Segmented Reef Balls or Breakwaters on Bay Side
105	Predominantly Water - Interconnecting Bay and GIWW	a) Extending DMPA past GIWW curve via dredge material placement.	Area is predominantly water only - interconnected with Bay and GIWW	a) Build up DMPA with dredge material
				b) Reef balls on bay side (segmented)

For immediate solutions, enough sediment is available in DMPAs 102-C, 102-D, and 102-E if shoreline and energy protection solutions are needed to restore or expand DMPAs to protect the EMB GIWW turns.

PROGRAMMATIC APPROACH TO THE SUSTAINABILITY OF THE DMPAS

Programmatic approaches to contribute to the sustainability of DMPAs along the GIWW can be classified under three primary needs: 1) finance, 2) sediment, and 3) policy.

Financial resources are necessary to develop and implement project features. Leveraging of funding sources with other contributed financial resources is an ideal approach to cost share project development and implementation across various federal, state, and/or local programs. Contributed financial resources could be provided in the form of cash, real property, and/or technical work-in-kind services contributions.

In many instances, ensuring the viability and sustainability of DMPA function and features requires initial placement of large volumes of sediments, followed by future placement of sediments to account for short- and long-term erosion and/or elevation losses. GIWW maintenance dredged material would be the primary sources for sediments; however, DMPAs requiring larger volumes of sediment beyond the quantities generated by routine maintenance dredging may require identifying and designating in-bay areas as sources for sediment harvesting.

Implementation of DMPA and navigation safety improvements are tied to federal and state policies that govern the extent that federal and state agencies may be involved in the modification of DMPA and navigation channel features.

APPLICATION OF FINDINGS TO OTHER AREAS

As part of this project, researchers developed a tool to enable analysts to apply the findings of this research to a broader set of potentially critical areas along the GIWW. Researchers used the AHP method to develop a tool to facilitate the use of the information collected in this study in formulating the decision-making problem (i.e., objectives, strategies, structural alternatives, and criteria). The tool is spreadsheet-based to provide flexibility to add and modify the criteria and alternatives for other areas.

Appendix B includes a user guide with example input and outputs.

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

The solutions recommended in this report are translatable to other Texas bay systems experiencing degradation and corresponding GIWW navigation safety issues:

- The protection and restoration of existing DMPAS is important to protect maritime traffic against wind and wave environmental forces.
- Reaches at and near GIWW bends or turns should be designated as DMPA protection and restoration priority areas.

- Longer reaches of the GIWW within bay systems should be protected by enhanced or created DMPAs or the enhancement of natural land barriers.
- Improvements or restoration of existing DMPAs are dependent upon the existing conditions of the DMPA, such as the DMPA's environmental location.
- Low crested breakwaters that allow for wave overtopping and sediment exchange should be considered as the primary option for site-specific evaluation, to promote continuous marsh nourishment and enhancement.
- Alternative protection features applicable to the DMPAs with bay-facing shorelines can consist of sacrificial berms in low energy areas, and revetments consisting of rock or reef balls, segmented breakwater systems, or continuous breakwaters in moderate to high energy areas.
- Potential shoreline protection solutions should incorporate the harvesting of suspended sediments induced by vessel wakes and transported within the bay toward the DMPAs.

CHAPTER 1: SELECTION OF CRITICAL LOCATIONS TO BE EVALUATED

INTRODUCTION

This task gathered insights from key stakeholders to identify at least four critical locations of concern along the GIWW and select one for further evaluation.

The Texas A&M Transportation Institute/Freese & Nichols, Inc. team interviewed several GIWW stakeholders to acquire an understanding of their priorities and concerns. The stakeholders interviewed include:

- State resource agencies.
  - Texas GLO Coastal Resources Program.
  - Texas GLO Oil Spill Division.
  - Texas Parks and Wildlife Coastal Fisheries (TPWD).
- Federal agencies.
  - NOAA, National Marine Fisheries Service (NMFS).
  - USACE.
  - USFWS Texas Coastal Program.
- NGOs.
  - Ducks Unlimited (DU).
  - Galveston Bay Foundation (GBF).
  - Texas Audubon Society.
  - The Nature Conservancy (TNC).
- Barge operators (two).

Two of the stakeholders declined to suggest critical locations or focused on only one segment of the GIWW; however, most of the stakeholders discussed priorities over the entire GIWW.

Themes/concerns that emerged from the interviews include:

- **Navigation safety** is a key element of good GIWW stewardship. Increased safety reduces the potential for accidents and oil spills and reduces the need to employ less than optimal operational practices, such as pushing into shorelines.
- The **need for material** to repair/strengthen DMPAs may compete with the need for material for beneficial use (BU) projects in some areas.
- **Diversification and creation of habitats** such as fisheries, marshes, seagrasses, and bird rookery islands should be included in any solutions to the reestablishment, replacement, or repairs to the DMPAs. Previous BUDM projects focused on one specific type of habitat, which resulted in limited success from the ecosystem restoration point of view. TPWD believes that there is a wide range of dredge material that can be used for bird island restoration combined with submerged habitats from some GIWW DMPAs without compromising their integrity.
- TPWD **does not promote the use of bulkheads or walls** on the bay shorelines of the DMPAs as a solution to their degradation. TPWD's experience indicates that across the Texas coast, bulkheads always induce erosion on the adjacent properties. The best

example is the GIWW shorelines of Port O’Connor, where bulkheads induced erosion on the adjacent and opposed shorelines of the channel. Other areas affected by erosion induced by bulkheads or walls include East and West Galveston Bays and EMB.

- **Preservation of access points for recreational purposes** should be considered in dredging material placement area solutions on the GIWW.
- **Preservation and restoration of seagrasses and protection of fish habitats** in the bays should be considered in any proposed DMPA activities. Any action that reduces strong energies affecting the seagrasses will benefit the natural environment.
- Most of the sites of concern mentioned by one of the barge operators are near cuts through the land barrier islands. Appendix A provides maps of the areas they mentioned.

Several specific locations were mentioned and discussed by the stakeholders. Details are provided in the following section.

LOCATIONS EVALUATED

Six specific segments of the GIWW were mentioned by the stakeholders. Three of these featured prominently in their remarks; they are the first three discussed below.

East Matagorda Bay

EMB is the number one concern for barge operators. It is USACE’s second highest concern. Specifically, the Caney Creek area on the east end of the bay is heavily affected by the cut through the barrier islands. The current is especially strong when the tide goes out. Heavy and frequent siltation is also an issue through the land gaps (See Figure 2). One of the barge operators indicated that the reach between mile markers 420 and 421 is where they have the most groundings in the GIWW. Two-way traffic is not possible. This same operator also mentioned an area at the west end of EMB. Where the barges leave the land cut, there is constant heavy siltation and they frequently drag bottom in this area.

The second barge operator mentioned a problem area for westbound traffic at mile marker 425 in the Bay where there is a right turn. Mile marker 435.5 presents the operator’s biggest concern for grounding. There is an old dock in this vicinity, and there is a cut here where the current is very strong. Due to the sediment flow, the channel is very narrow here.

Figure 2. Land Gaps between EMB and the GIWW.

An important concern of GBF is that the barging and navigation interests have requested space for mooring areas mainly during the windy months of the winter and spring. Mooring areas can be disruptive for bird islands; however, the protection of the islands may be combined with bay conditions for seagrasses and oysters.

EMB is the only area DU commented on. They recognized that the bay is shallow next to the GIWW and fetches are strong. In their opinion, the area north of Dressing Point Island (mile marker 427) is a critical area where sediment is needed to restore the DMPAs, but DU is not sure whether the best method is a breakwater with dredge material or another approach.

For EMB, NMFS is interested in protecting and preserving Brown Cedar Cut (mile marker 423/424) due to the abundance of seagrasses. Although Brown Cedar Cut is located on the barrier island side, sediment can be brought from the GIWW to restore some of those seagrasses.

NMFS believes an oyster survey should be conducted before proceeding with the development and construction of specific protections to the navigation channel along the GIWW (including islands).

USFWS staff believes there is limited evidence that energies coming from the Gulf are affecting navigation safety; however, they recognize that strong energies are affecting the area. Barge operators disagree. They believe the strong energies are coming directly from the Gulf. As an alternative solution, USFWS staff recommended that TxDOT should consider the concept of confined habitat areas as a way to reduce these energies in the channel. These confined habitat areas may be functioning as small DMPAs that can be dedicated to a diverse set of wildlife while reducing shoaling in the channel. The concept of confined habitat areas would be a good approach for this region without targeting any specific habitat. Close to Mitchell's Cut (mile marker 420/421), more habitat for whooping cranes can be developed on these small structures creating confined marshes free of predators on DMPA 102-A (east of this location).

West Galveston Bay

West Galveston Bay is USACE's number one area of interest. The West Galveston Bay shorelines have a significant group of federal and state stakeholders involved in the protection of natural resources, including the protection of the shorelines of the USFWS refuges in the area. West Galveston Bay also includes one of the last areas where seagrasses are attached to the former barriers protecting the GIWW and the DMPAs on the bay side. Seagrasses disappear when bay shorelines of DMPAs disappear.

One of the barge operators specifically mentioned West Galveston Bay as a concern but gave other areas a higher priority.

West Galveston Bay is an area where sediment for placement area repairs may compete with the need for BU projects. Also, there is contamination on the north side of West Galveston Bay in a superfund project, north of DMPA 63 (mile marker 368 to 370), which needs to maintain a barrier separating the GIWW from the bay. Figure 3 illustrates the areas of greatest concern in this region.

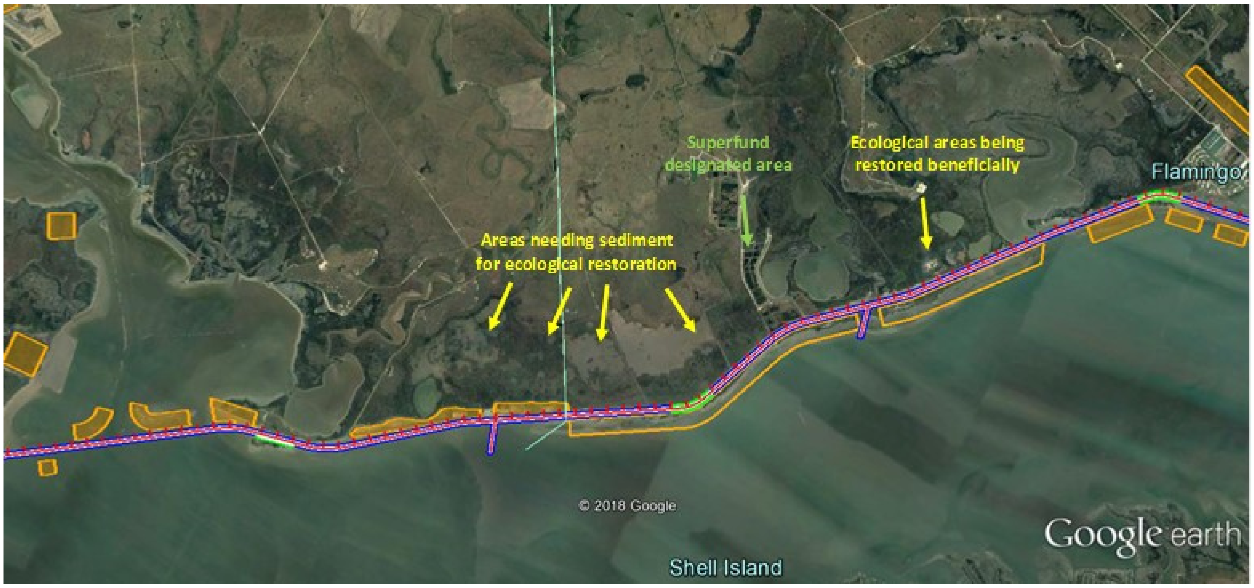

Figure 3. Potential and Current BUDM in West Galveston Bay.

Seagrass habitat and marshes on the bay sides of the DMPAS are a big issue in several sections of this region. Resource agencies indicated that disposal of dredge material on the DMPAs should include a platform for seagrasses. NMFS has a preference to rebuild the original islands and create habitat conditions on the bay side with a template for habitats and seagrasses.

GBF remarked that recent dredged material from the GIWW went to Pierce Marsh for successful marsh restoration. USFWS put emphasis on the structure built by the USACE to protect the mooring buoy area (close to the intersection between GIWW and Chocolate Bay Navigation Channel). A set of soft structures (mainly created with geo-textile tubes) was built to protect the GIWW from bay energy, which resulted in a very diverse set of environmental conditions for different aquatic and bird habitats. The soft structures have allowed some species of seagrasses and oysters, salt grasses, and elevated areas with grass and bushes (including mangroves) to adapt to the new habitat conditions. USFWS has suggested that this is an example of a confined habitat area that may be a simple alternative to protect the GIWW where natural habitat will flourish if sediments are retained and soft structure can provide protection to navigation.

Stakeholders also suggested that more DMPAs are needed at the intersection of Chocolate Bay and the GIWW since the gaps between DMPAs are large. One barge operator highlighted the reach of West Galveston Bay just east of Chocolate Bayou. Its captains call this the washout area because the shoreline is receding rapidly. Currently, it is not a problem as long as it is well marked, but it may become a problem if the land continues to disappear.

East Galveston Bay

The pending closure of Rollover Pass will reduce the amount of dredging needed, which in turn will reduce the amount of sediment for reestablishment of DMPAs.

USFWS recommends that protection for navigation on the GIWW needs to maintain water connectivity between the GIWW and East Galveston Bay. Closing the connection between the bay and the GIWW may generate fish kills or water quality problems on the GIWW.

Some small islands are also located on the south side of the GIWW next to Rollover Pass. It would be helpful to restore these islands to reduce the impact of the vessels waves on the marshes close to Rollover Pass. GLO intends to close Rollover Pass, and if these islands are not protected, the waves generated by barges will go directly to the restored areas. The islands can reduce these impacts.

A second open gap between the bay and the GIWW is located between Stingaree Cove and Yates Cove, close to Port Bolivar. The land barrier is disappearing and needs to be protected and restored. The GIWW shorelines may have to be armored at this site to reduce the rate of erosion of the entire land area.

The entire GIWW section from Sievers Cove to Port Bolivar needs a wider and more extensive mooring buoy or parking area for barge operators.

Cedar Lake

At mile marker 409/410, there is a cut that creates a very troublesome current and a lot of sand flushes in. At times, the channel is only 70 to 80 ft wide in this area.

Matagorda Bay

One barge operator mentioned that the GIWW immediately east of the Matagorda Ship channel is constantly shoaling and forcing them to light load. It requires very frequent dredging.

San Antonio Bay

Barge operators mentioned that the constant shallowness of this bay is a concern. Mile marker 504 at the west end of the bay is a trouble spot. There is a dam there (this may be a cofferdam) that is not getting the job done. An inspection of an aerial photo of the area indicates that there is a placement area or some type of marsh/island project just east of mile marker 504. Again, heavy siltation is a problem.

AREA SELECTED: EAST MATAGORDA BAY

Researchers concluded that the area of concern that is most common and important to the various interests involved is EMB:

- EMB includes the areas of greatest concern for barge operators and is USACE's second highest concern due to the lack of space for new DMPAs mainly on the bay side.
- Several agencies commented on activities needed in this region.
- The diversification of ecological habitats can promote the development of adaptive restoration options, which include:
  - Increase the areas for seagrasses.
  - Reduction of strong cross currents.
  - Reduction on siltation on the GIWW.
  - Increment in the number of mooring facilities.
  - Creation of new bird islands.
  - Identification of the DMPAs in need of restoration.
  - Possibilities to create whooping crane habitat.
  - Develop new oyster reefs to control energies affecting bay shorelines and GIWW infrastructure.

CHAPTER 2: CURRENT CONDITIONS, DREDGING ACTIVITIES, AND POTENTIAL ECONOMIC IMPACTS

INTRODUCTION

The overarching priority for this research project is to improve navigation safety, provide protection to the GIWW, and improve navigation efficiencies by restoring and constructing DMPAs to act as barriers against energies affecting the bay shorelines and navigation infrastructure. Researchers analyzed the physical conditions within the study area and provided an interpretation of different data sources, including the USACE Navigation Data Center Database. The assessment of the conditions of the DMPAs has been critical for recommendations of sustainable solutions to navigation safety.

The following sections summarize the findings for EMB.

PHYSICAL CONDITIONS

DMPAs 101 and 105 are located within the vicinity of the selected area in EMB where there are land gaps or breaches along the south side of the GIWW. DMPAs 101, 102-A, 102-B, 102-C, 103, 104, and 105 are located south of the GIWW. Some of these DMPAs are currently designed to have shoreline protection measures in place. Only one property in that segment of the GIWW is owned by a federal agency; the Big Boggy National Wildlife Refuge managed by USFWS is located north of DMPAs 104-A and 104-B. No other property in the area is owned by a state agency or by NGOs. Figure 4 shows the above referenced DMPAs.

The DMPAs have been constructed on former private property that was leased for the development of dredging facilities. Easements developed with private citizens for these properties along this segment of the GIWW date back to before 1940.

Rates of shoreline retreat along this segment of the GIWW were not available, but rates of bay shoreline retreat were available for EMB. Bay shoreline retreat rates have varied from 3 to 4 ft per year (*2*).

Several areas were identified on the bayside as critical areas in need of restoration where land gaps or breaches exist. One of these areas is a large land gap of about 4 miles between DMPA 101 and 102-C. Some thin segments of land remain on the former land barrier and DMPAs, but most of the area is now open water. A second land gap exists between DMPAs 102-C and 103 with a length of 0.3 miles. A third land gap exists between DMPA 103 and 105 with a length of about 3.8 miles. Only the DMPAs north of the GIWW are protected from bay energies and shoreline impacts from waves generated by vessels. The levees on the DMPAs south of the GIWW are in poor condition, except for DMPA 102-C, which is an active site.

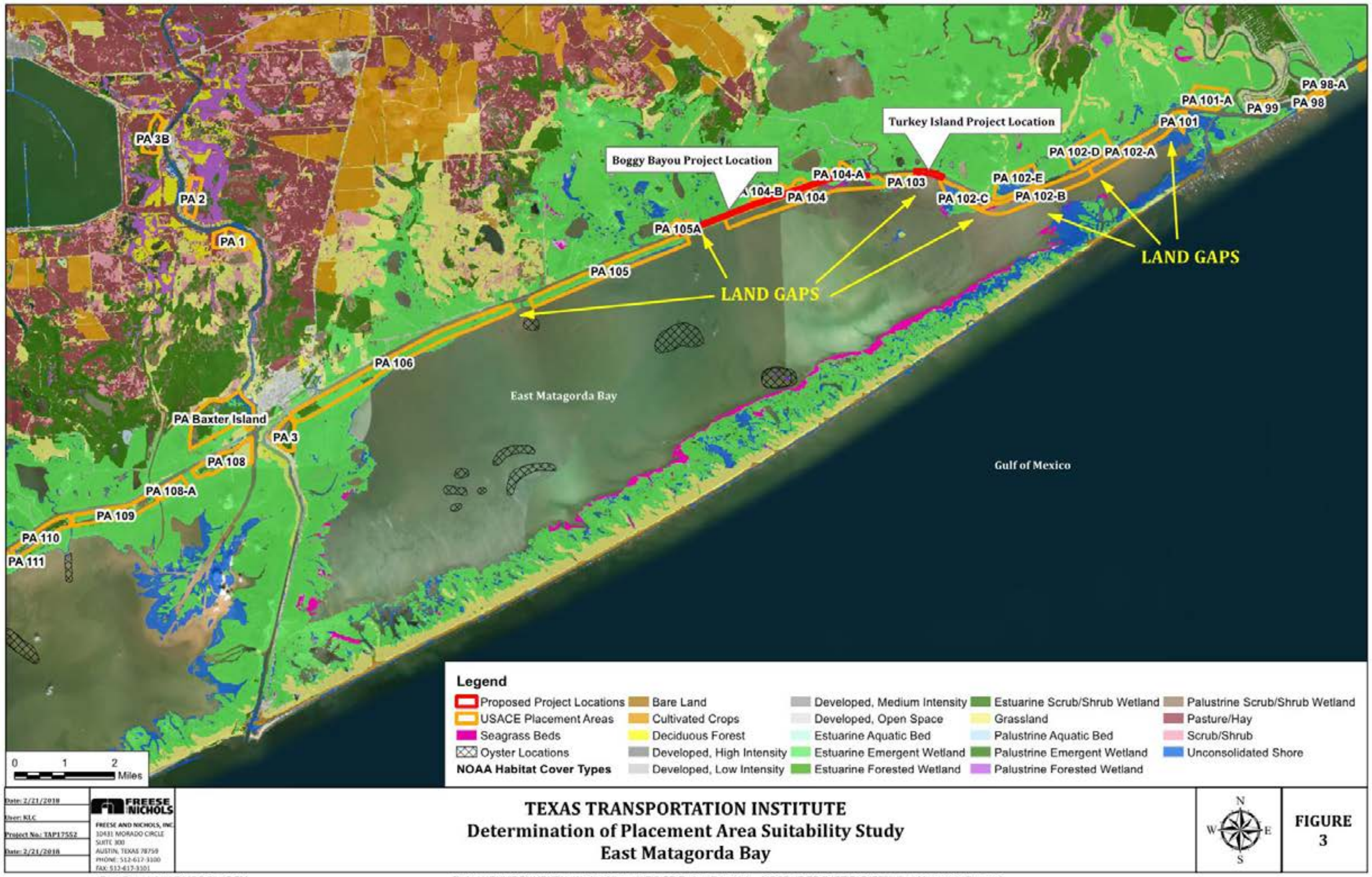

Figure 4. Location of DMPAs in EMB and Habitat Types Identified by NOAA.
Note: The figure includes critical environmental issues that are influencing the GIWW.
Source: NOAA C-CAP 2010 Land Cover Atlas

Active DMPAs are currently designed to have protection systems, such as levees, in place to sustain energies from the bay. Table 4 presents the general characteristics of the DMPAs. Not all the sites in Matagorda County DMPAs that are classified as severe in Table 4 have adequate shoreline protection measures in place to mitigate against shoreline retreat. Geotechnical data are currently not available for any of these DMPAs within the USACE Navigation Data Center Database.

Table 4. DMPAs Dimensions and Conditions in East Galveston Bay.

DMPA No.	Acreage	Status	Level of Impact by Bay Shoreline Retreat	Remaining Life in Years*
DMPA 101	45	Active	Low	Data unavailable
DMPA 101-A	181	Active	None	Data unavailable
DMPA 102-A	252.9	Data unavailable	Severe	Data unavailable
DMPA 102-B	314.94	Data unavailable	Severe	Data unavailable
DMPA 102-C	135.08	Active	Low	Data unavailable
DMPA 102-R	224.50	Data unavailable	None	Data unavailable
DMPA 103	93.15	Data unavailable	Severe	Data unavailable
DMPA 104	469.69	Data unavailable	None	Data unavailable
DMPA 104-A	67.07	Data unavailable	None (Protected)	Data unavailable
DMPA 104-B	81.54	Data unavailable	None (Protected)	Data unavailable
DMPA 105	451.26	Data unavailable	Moderate	Data unavailable
DMPA 105-A	No data	Data unavailable	No data	Data unavailable

Source: USACE Navigation Data Center Database and Kruse et al. (1)

DREDGING DATA

Researchers reviewed USACE dredging data for the GIWW channel from station 702+000 near DMPA 101 to station 776+000 east of DMPA 105. The USACE database shows only two major dredging events that were specifically for this reach; they occurred in 1992 and 1998 for these areas. In 1992, USACE reported 1,829,740 cubic yards of material dredged between Big Boggy National Wildlife Refuge (DMPA 104B) and the mouth of the Colorado River. In 1998, the USACE reported 3,500,000 cubic yards of material dredged in the same section of the GIWW. (This actually took place in Fiscal Year 1999.) No data are available for recent years. Prices per cubic yard of sediment dredged varied from $1.11 to $3.92.

As will be explained later in this chapter, there have been several dredging contracts issued by the USACE Galveston District that included portions of Matagorda Bay, although the geographic scope was much broader. Therefore, the actual amount needed to maintain the Matagorda Bay reach of the GIWW is somewhere between the numbers reported in the previous paragraph and the numbers report in the analysis of reduced draft. If one can assume that dredging takes place every 6 years, the average annual amount of material dredged per the information in the preceding paragraph would be approximately 890,000 cubic yards. However, the data contained in the district's annual activity extract indicate an average annual amount of approximately 1.9 million cubic yards. Given that the dredging records include reaches outside the scope of this study, the actual number would most likely be toward the lower end.

No BUDM opportunities have been reported in recent years in the area. Information on which DMPA the dredged material was deposited is unavailable. Historical records and recent aerial photos show that some material was placed on the DMPAs north of the GIWW; however, no data were found to determine specific volumes.

HABITAT TYPES

In general, the DMPAs in EMB are surrounded by estuarine and open water, shallow bay ecosystems (see Figure 4). Oyster reefs dominate the submerged waters on the bay side, but data needed to quantify the extension of this bay bottom habitat are unavailable. As bay shorelines continue to retreat, the habitats also retreat or migrate. Determining solutions that not only protect navigation but also protect the natural environment will provide holistic approaches to these interconnected processes.

The bathymetric data shown in Figure 5 indicate that the water depths of the submerged lands in the land gaps (DMPAs) are less than 3 ft deep. On the east side of EMB between DMPAs 101 and 103 the submerged lands are up to 2 ft deep. Between DMPAs 103 and 105, depths go to 3 ft. The data suggest that the development of potential solutions for the reduction of navigation hazards by closing the land gaps may be less expensive than in other bays. The shallow environments will require less sediment to maintain barriers.

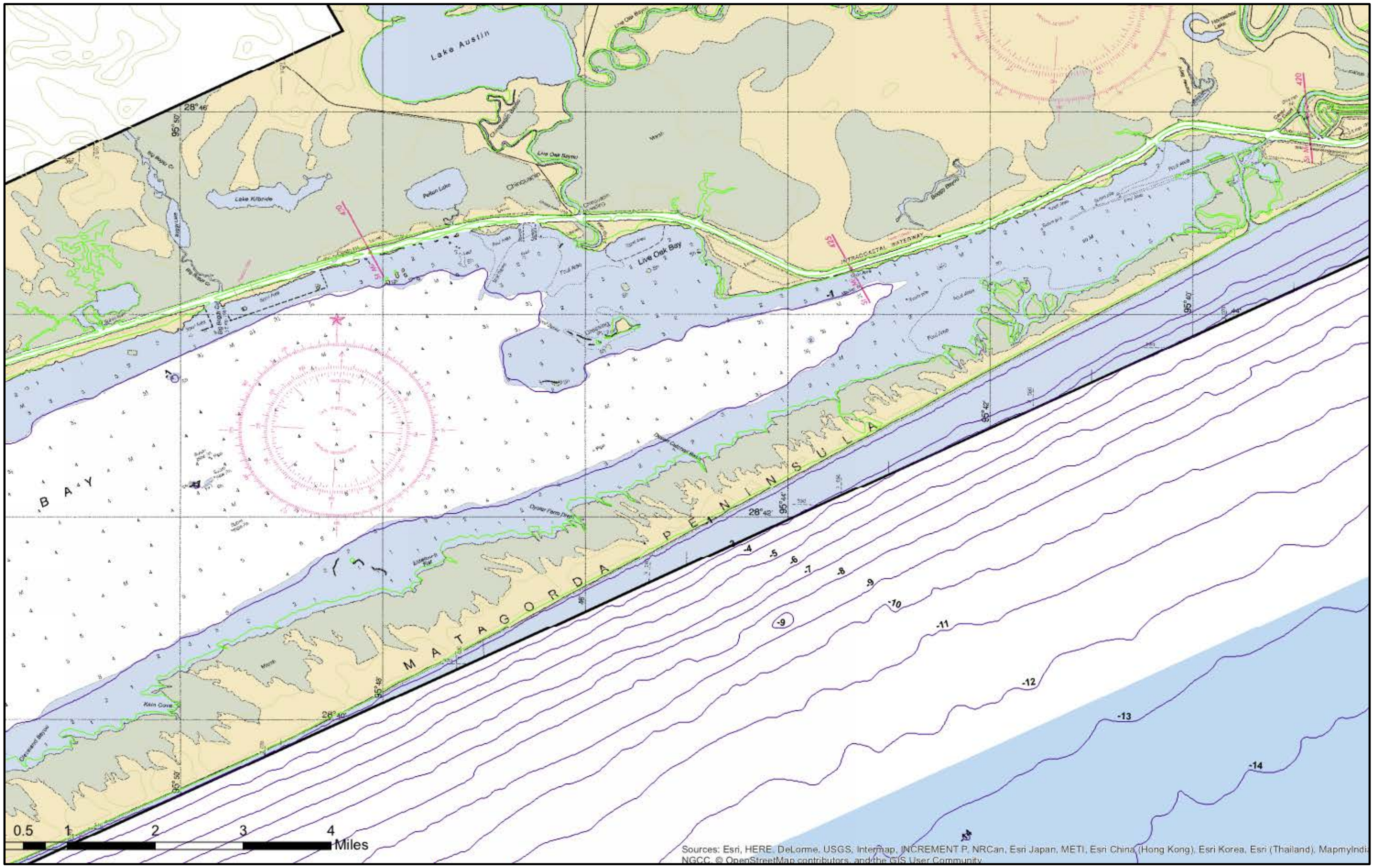

Figure 5. Bathymetric Chart of EMB.

Source: NOAA Nautical Chart Catalog and Chart Viewer. Visited on 2-22-2018. The blue boundary in the bay contour is the mark of -3 ft.

EFFECT OF REDUCED DRAFT

Researchers analyzed the economic effect on the barge industry of NOT maintaining the GIWW at its authorized dimensions. Because individual barge trip records are not available to the public, researchers asked USACE Galveston District personnel to provide some general statistics on barge traffic that passes through Matagorda Bay. Other data elements were extracted from public records as explained below.

Assumptions and Base Data

The main assumption for this analysis on shoaling is that the GIWW will be allowed to shoal to the point that current average drafts will be reduced by 1 ft.

The costs being estimated here are from the operator's perspective. It is assumed that costs will be incurred by operators on a per tow basis; that is, the cost to perform a tow is independent of how much tonnage is actually moved. The actual rate charged to the shipper will vary based on time sensitivity, market demand, and other contractual issues.

All barge and fleet characteristics are based on summary trip data provided by the USACE Galveston District. These data were compiled by USACE from the confidential trip data for calendar year 2016, the most recent year available. All historical costs (operating and dredging) are indexed and stated in 2016 dollars to provide consistency in comparisons.

Since reduced water depth only affects loaded barges, the analysis is limited to barges drafting more than 8 ft. For tows requiring more than 8 ft of draft, these data indicate an average of 2.6 barges per tow. There is a wide variety of barge configurations. The predominant draft is 1.7 ft for empty barges; therefore, 1.7 ft is used as the standard for empty barges in this analysis.

Cost figures for operating towboats and barges were taken from the USACE's Economic Guidance Memorandum (EGM) 05-06,[1] which provides Shallow Draft Vessels Operating Costs for 2003. This is the most recent information that is publicly available. An adjustment was made to fuel cost for this analysis due to the dramatic increases in fuel costs since 2003 and the now-prevalent use of ultra-low sulfur diesel (ULSD). At the time the EGM was prepared, the standard fuel was No. 2 high sulfur diesel fuel. Due to new emissions and sulfur content regulations, the fuel used in this analysis was No. 2 ULSD. According to the Energy Information Administration, the average price per gallon of ULSD in 2016 was $2.304.[2] The Inland Waterway Fuel Tax of $0.29 per gallon was added on to get the total cost per gallon of $2.594. This is 222 percent of (or 2.22 times) the cost per gallon used in the EGM.

[1] Accessible at http://planning.usace.army.mil/toolbox/library/EGMs/egm05-06.pdf as of February 7, 2014.
[2] The peak since 2003 was $3.97 in 2012. Since fuel costs are such a large component of overall costs, such an increase in fuel costs would have a dramatic effect on costs incurred by light loading.

The other operating costs that the USACE reported were inflated using the Inland Waterways Towing Transportation Producer Price Index[3] to reflect 2016 dollars. This caused a 45.6 percent increase to the costs provided in the memorandum (or 1.456 times the stated costs).

The towboat horsepower used for this analysis is the 1800–2000 HP category. For liquid barges, the 297.5-ft × 54-ft barge without coils was used. For dry cargo barges, the 195-ft × 35-ft covered hopper barge was used.

Using USACE data, the average trip length for tows drafting more than 8 ft was 372 miles. This results in an average trip duration of 372 miles ÷ 5 mph = 74.4 hours or 3.1 days.

The following calculations form the basis of the evaluation of the economic effect:

Towboat cost per trip in 2016 dollars:

Non-fuel daily cost: ($5,057.63 − $2,215.40) × 1.456 = $4,138.29
Daily fuel cost:[4] $2,215.40 × 2.22 = $4,918.19
Cost per day: $4,138.29 + $4,918.19 = $9,056.48
Cost per trip = $9,056.48 × 3.1 = $28,075.09

Tanker barge cost per trip in 2016 dollars:
EGM daily cost: $597.34
Adjust daily cost: $597.34 × 1.456 = $869.73
Trip cost: $869.73 × 3.1 = $2,696.16

The dry barge cost per trip in 2016 dollars:
EGM daily cost: $107.98
Adjust daily cost: $107.98 × 1.456 = $157.22
Trip cost: $157.22 × 3.1 = $487.38

Weighted average barge cost per trip in 2016 dollars:
Approximately 86.8 percent of the barges carrying this tonnage were liquid cargo barges. Weighting by type of barge yields an average barge cost of:
(0.868 × 2,696.16) + (0.132 × 487.38) = $2,404.60

Trip cost: $28,075.09 + ($2,404.60 × 2.6 barges/tow) = $34,327 in 2016 dollars

Light Loading Analysis

The number of barges drafting greater than 8 ft was 6,489.
The number of tows with barges drafting more than 8 ft was 2,367.
The cost of these trips = 2,367 × $34,327 or $81,252,009.
Tons actually transported on these barges came to 15,137,886.

[3] This index can be found on the Bureau of Labor Statistics website, www.bls.gov.
[4] $2,215.40 is the cost of fuel shown in EGM 05-06.

Current weighted average draft is 9.53.
Weighted average tons per barge is 2,333.
Average tons/ft = 2,333/(9.53 – 1.7) = 297.96.
Required cargo reduction per barge with loss of 1 ft draft is 297.96.

Adjusted tons transported (amount that could be moved in the same number of trips with maximum draft of 8.53 ft): 6,489 × (2,333 – 298) = 13,205,115.

This leaves 15,137,886 − 13,205,115 = 1,932,771 tons stranded. To move this cargo will require additional trips. The additional trips required with an average draft of 8.53 ft = 1,932,771 ÷ (2.6 barges/tow × 2,035 tons/barge[5]) = 366.

The cost of additional trips is 366 × $34,327 = $12,563,682.

This is an increase of 15.5 percent in the cost of doing business—($81,252,009 + $12,563,682) / $81,252,009). This additional cost must be borne by someone. Since companies are in business to make a profit, that someone is ultimately the consumer.

(Note: The additional cost does not include port fees or barge cleaning and shifting fees for the additional barges that must be used when light loading. This is strictly the transportation cost differential.)

Cost of Dredging

Table 5 shows the costs incurred by the Galveston District for dredging for the 20-year period FY 1998–FY 2017. The data were taken from the *Fiscal Year Annual Report of the Secretary of the Army on Civil Works Activities Extract: US Army Corps of Engineers, Galveston District* for fiscal years 1998–2012. The statistics for FY 2013–2017 were derived from dredging records provided in response to a Freedom of Information Act request. The costs are for contracts that included at least part of Matagorda Bay and east to and including Caney Creek. Many of these contracts included sections outside the target area, but it is not possible to break those amounts out from the information published in the *Extract*, so these figures are definitely on the high end. Table 5 also provides the details of the dredging activity.

[5] This is 2,333 – 298, as shown in the previous paragraph.

Table 5. Annual Operations and Maintenance Cost Incurred by USACE.

FY	Original Cost	Price Adjusted Cost[6]	Cubic Yards Dredged
1998	480,632	829,965	219,877
1999	7,499,696	12,635,457	4,464,567
2000	6,552,284	10,816,891	3,583,840
2001	50,000	81,109	--
2002	7,970,401	12,542,679	4,381,758
2003	5,488,125	8,440,298	2,592,117
2004	5,337,499	7,942,039	3,457,773
2005	3,453,182	4,905,298	1,904,979
2006	2,983,522	4,042,149	300,000
2007	9,465,265	12,322,658	3,577,573
2008	942,049	1,185,266	5,455,876
2009	0	0	--
2010	14,643,666	17,369,291	3,009,089
2011	3,929,038	4,510,530	2,209,268
2012	0	0	--
2013	0	0	--
2014	5,612,500	5,877,393	1,895,405
2015	0	0	--
2016	0	0	--
2017	0	0	--
Average	3,720,393	5,175,051	1,852,606

Differential between Annual Average Costs Avoided by Dredging and Cost of Dredging

The annual average operating costs that could be avoided by dredging the GIWW is compared to the cost of dredging below:

Costs Avoided	Cost of Dredging
$12,563,682	$5,175,051

Ratio of cost avoided to cost of dredging: 2.4

Even with an aggressive inclusion of dredging costs, it is clearly in society's financial interest to pursue dredging in a timely manner.

[6] Used Civil Works Construction Cost Index System (EM 1110-2-1304) data for Channels and Canals to reflect 2016 dollars.

CHAPTER 3: ALTERNATIVE NATURAL SOLUTIONS

INTRODUCTION

Researchers identified potential natural solutions that might address or mitigate the problems identified in earlier tasks. Researchers reviewed studies performed by the USACE, the GLO, and university researchers that address similar problems on the Texas coast and on the coast of other Gulf of Mexico states. Based on this review and the stakeholder interviews, researchers summarized potential natural solutions with a description of how each of the solutions might best be applied to the GIWW in EMB, including the pros and cons in terms of both engineering feasibility and cost.

The interviews conducted in the early stages of the research project and the information compiled and reported in previous chapters indicated that the solutions with the greatest probability of success and acceptance by state agencies fall into the category of soft shoreline or living shoreline solutions.

According to NOAA, the term *living shorelines* is a broad term that encompasses a range of shoreline stabilization techniques within estuarine coasts, bays, sheltered coastlines, and tributaries. A LS project has a footprint that consists of mostly native material (*3*), which can incorporate vegetation or other living and natural soft elements, either as a stand alone or in combination with some type of harder shoreline structure (e.g., oyster reefs or rock sills) for added stability. The goal of LS projects is to maintain the continuity of the natural land-water interface and reduce erosion while providing habitat value and enhancing coastal resiliency (*4*).

These basic concepts of LS projects are being adapted to local conditions that include multipurpose goals. Concepts such as energy mitigation, sediment harvesting, habitat diversification, and shoreline protection under different estuarine conditions (low or high energy environments) have been recommended by various coastal states as part of LS project goals.

These innovative applications have been adapted to local conditions in states such as Alabama, New Jersey, and Massachusetts (*4*). Results of these efforts illustrate the benefits of adapting general LS concepts to local or regional conditions while maintaining the land-water interface that supports ecosystem services and habitat values (*3*).

In Texas, stakeholders interviewed for this study recommended that LS projects be constructed to protect shorelines from strong currents and high energy and to increase ecosystem diversity. Along the Texas coast, the DMPAs that have historically protected segments of the GIWW are disappearing because of reduced sediment supply and increased current and wave energy resulting from sea level change and storm events. The concept of using LS solutions for navigation safety is new to Texas. The remainder of this chapter evaluates various LS options. These LS options offer a more sustainable alternative for the protection of DMPAs in the future, which has the support of the Texas stakeholders.

Federal and state agencies and other entities interested in LS concepts as an alternative to current shoreline protection and habitat restoration concepts include the following: NOAA, USACE, USFWS, GLO, TPWD, GBF, and TNC among others. Although each of these groups has dedicated time and funding toward evaluating applications of LS concepts, only a few projects have been implemented as LS projects. According to the stakeholder interviews conducted for this study, the USACE has historically been the only agency to consider LS concepts for the primary purpose of improving navigation safety.

CRITERIA FOR LIVING SHORE CONCEPTS

In 2015, NOAA and the USACE compiled a list of criteria for projects to be considered as LS projects, including shoreline protection and stabilization alternatives combined with habitat diversification concepts (Figure 6) (*3*). This was the first step in classifying shoreline erosion and storm protection alternatives. Regional approaches have adapted these concepts for LS projects for specific needs and circumstances.

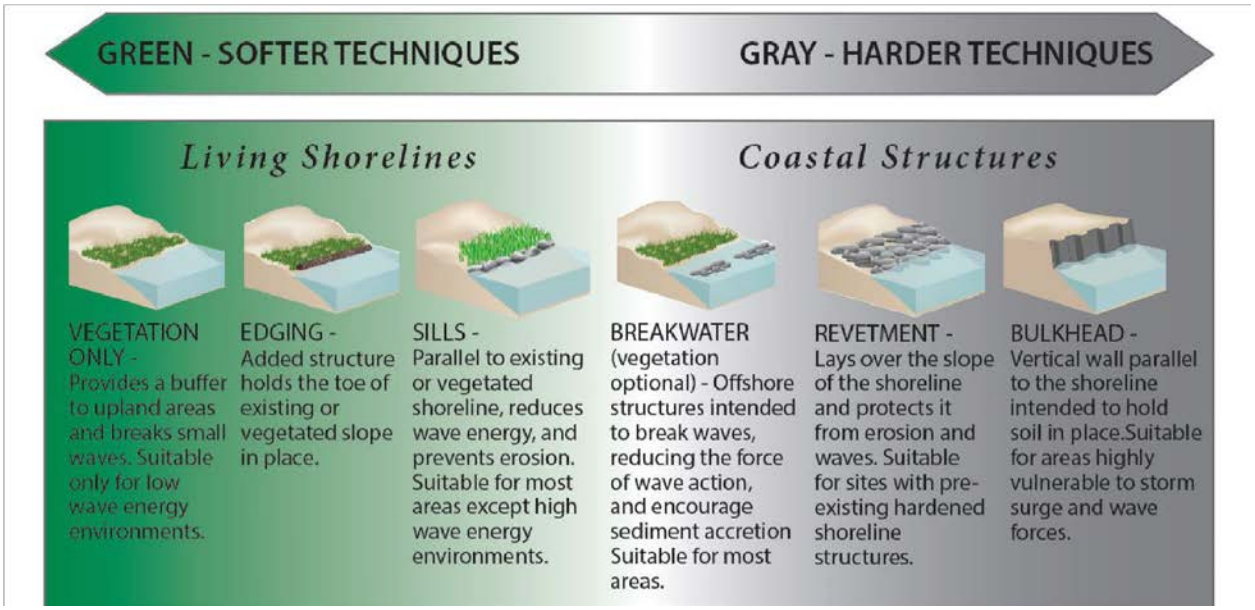

Figure 6. Definition and Classification of LS Techniques.

Source (3)

According to the criteria developed by NOAA and the USACE, LS concepts should include:

- Stabilization of shorelines to reduce rates of shoreline erosion from increased bay energies and storm damage.
- Diversification of habitats for fish and other aquatic species.
- Enhancement of coastal resiliency through maintaining the land-water interface.

To determine the most appropriate shoreline protection technique for a specific project, several site-specific conditions must first be assessed. The following general physical and environmental conditions should be considered with other local factors to identify the most appropriate combination of soft and hard shoreline protection solutions:

- **Fetch:** Fetch is a cross-shore distance along a stretch of open water over which wind blows and generates waves. For any given shoreline, there may be several fetch distances, depending on the predominant wind direction.

- **Physical Conditions:** Physical conditions refer to the slope of the foreshore[7] or beach face, a geologic condition, or the bathymetry in the offshore environments.
- **Reach:** A reach is a longshore segment of a shoreline where influences and impacts such as wind direction, wave energy, littoral transport, etc. mutually interact.
- **Resiliency:** Resiliency can be interpreted to mean the ability to avoid, minimize, withstand, and recover from the effects of adversity, whether natural or man-made, under all circumstances of use. This definition also applies to engineering, ecological, and community resilience.
- **Storm Surge:** Storm surge refers to the resulting temporary rise in sea level due to the action of wind stress on the water surface and low atmospheric pressure created during storms, which can cause coastal flooding. Note that surge is different from the day-to-day tidal exchanges. Additionally, storm tide refers to the total water level rise from a storm event.
- **Tidal Range:** Tidal range refers to the vertical difference between high tide and low tide.
- **Wave energy:** Wave energy is related to wave height and describes the force a wave is likely to have on a shoreline. Different environments will have lower or higher wave energy depending on environmental factors such as shore orientation, wind, channel width, and bathymetry. Wakes from passing vessels, or boats, can also generate wave energies that have an impact on nearby shorelines. The three different classifications of wave energy are described below:
  - **Low:** Low wave energy refers to limited fetch in a sheltered, shallow, or small water body (such as an estuarine, riverine, or bay environment). Low wave energy refers to waves that are less than 2 ft in height.
  - **Medium:** Medium wave energy consists of a combination of low and high wave energy elements. For example, an area that is shallow but has a large fetch or partially sheltered area would result in a medium wave energy environment. This classification of energy refers to waves that are 2 to 5 ft in height.
  - **High:** High wave energy refers to areas that experience large fetch and/or deep-water environments, such as the open ocean.

CLASSIFICATION OF LIVING SHORELINE ALTERNATIVES

As mentioned earlier, the term LS can be applied to a wide variety of shoreline protection and stabilization techniques. LS concepts are sometimes referred to as nature-based concepts, green shorelines, or soft shorelines. A subset of the LS concepts may be hybrid solutions that consist of a combination of natural materials (e.g., oyster shell) and nature-based materials (e.g., rocks where they do not naturally occur) that work together to provide shoreline stabilization (*4*).

The interactions between the soft shoreline protection and the hard-coastal structure concepts are important in determining the vulnerability, reliability, risk, and resiliency of the identified solution for specific projects (*4*). Figure 6 shows the range of project techniques that are available for shoreline protection and stabilization projects, including green or nature-based materials only, to green/gray or hybrid materials, to gray or all-built materials.

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[7] The foreshore is the part of a shore between high- and low-water marks, or between the water and cultivated or developed land.

Table 6 through Table 15 provide details on the range of shoreline protection techniques that can be implemented at project sites to provide shoreline stabilization. This information is extracted from NOAA documentation (*3*). The tables are organized along the lines of Figure 6, moving from all-natural to all-artificial solutions.

The costs for each technique used on each LS project vary since several factors come into play at the time of construction. Also, the maintenance cost should be considered as part of the general benefit-cost analysis. Some of the main factors determining the cost at the time of construction include:

- **Availability of Contractors.** Historically, for Texas, the availability of contractors capable to build LS projects is a very important factor. A limited number of contractors can work in the bay waters, and it is reflected in the bid responses.
- **Availability of materials.** The availability of materials may include anything from geo-textile fibers to rock supply. Rock for submerged breakwaters and revetments is in general coming mainly from Missouri. The need to transport materials from other parts of the country is an important factor.
- **Access to the site.** Access to the site is important. Access to shallow sites can increase the cost during construction.
- **Risks for contractors.** The potential risks for contractors include interruptions during construction generated by barge or vessel waves, storms, etc.; the potential exposure to navigation accidents; and the presence of pipelines close to the project sites.

The costs shown in the tables follow the estimated costs published by NOAA (*3*) to be used in preliminary analysis. This does not include the local cost of past LS projects. The tables use the following cost ranges:

Initial Construction Cost of LS Projects:

● = up to $1000 per linear foot
●● = $1001–$2000 per linear foot
●●● = $2001–$5000 per linear foot
●●●● = $5001–$10,000 per linear foot

Operations and Maintenance Cost of LS Projects (yearly for a 50-year project life):

♦ = up to $100 per linear foot
♦♦ = $101–$500 per linear foot
♦♦♦ = over $500 per linear foot

Green Softer Techniques

Table 6. Characteristics of Vegetation Only Techniques.

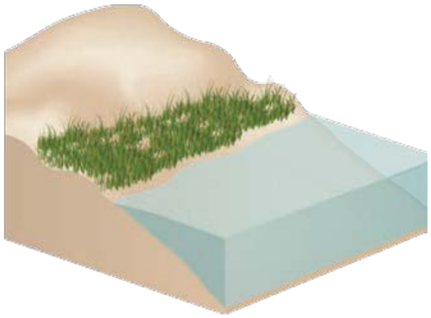
General Description: 	This applies to roots holding soil in place to reduce erosion. It provides buffering for upland areas and breaks small waves. It is suitable for low wave energy environments.
Material Options:	Native Plants.
Benefits:	• Dissipates wave energy • Slows inland water transfer • Increases natural storm water infiltration • Provides habitat and ecosystem services • Minimal impact to natural community and ecosystem processes • Maintains aquatic/terrestrial interface and connectivity • Flood water storage
Disadvantages:	• No storm surge reduction ability • No high-water protection • Appropriate in limited situations • Uncertainty of successful vegetation growth and competition with invasive
Management of navigation vessel waves:	This technique does not handle the day-by-day impacts of waves from navigation vessels well.
Initial Construction Cost:	● = up to $1000 per linear foot
Operations and Maintenance Cost:	♦ = up to $100 per linear foot per year

Table 7. Characteristics of Edging Techniques.

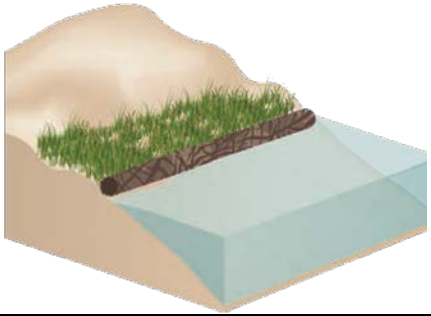
General Description: 	This structure holds the toe of existing or vegetated slope in place. It protects against shoreline erosion. It is suitable for most areas except high wave energy environments.
Material Options:	Vegetation. Base with Material Options (low wave only, temporary) • Snow fencing • Erosion control blankets • Geotextile tubes • Living reef (oyster/mussel) • Rock gabion baskets
Benefits:	• Dissipates wave energy • Slows inland water transfer • Provides habitat and ecosystem services • Increases natural storm water infiltration • Toe protection helps prevent wetland edge loss
Disadvantages:	• No high-water protection • Uncertainty of successful vegetation growth and competition with invasive species
Management of navigation vessel waves:	This technique does not handle the day-to-day impacts from waves caused by navigation vessels well.
Initial Construction Cost:	●● = $1001–$2000 per linear foot
Operations and Maintenance Cost:	♦ = up to $100 per linear foot per year

Table 8. Characteristics of Sill Technique.

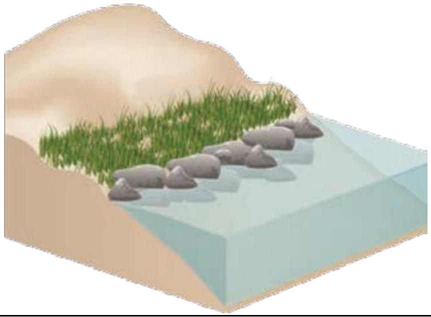
General Description: 	This is constructed parallel to existing or vegetated shoreline to reduce wave energy and prevent erosion. A gapped approach would allow habitat connectivity, greater tidal exchange, and better waterfront access. It is suitable for most areas except high wave energy environments.
Material Options:	Vegetation Base with Material Options: • Stone • Sand breakwaters • Living reef (oyster/mussel) • Rock gabion baskets
Benefits:	• Provides habitat and ecosystem services • Dissipates wave energy • Slows inland water transfer • Provides habitat and ecosystem services • Increases natural storm water infiltration • Toe protection helps prevent wetland edge loss
Disadvantages:	• Require more land area • No high-water protection • Uncertainty of successful vegetation growth and competition with invasive species
Management of navigation vessel waves:	This technique may handle the day-to-day impacts of waves from navigation vessels moderately well, but this technique will eventually fail in the long-term.
Initial Construction Cost:	●● = $1001–$2000 per linear foot
Operations and Maintenance Cost:	♦ = up to $100 per linear foot per year

Table 9. Characteristics of Beach Nourishment-Only Technique.

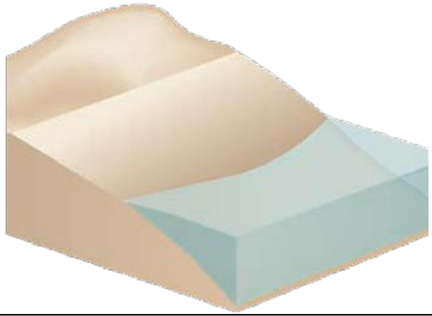
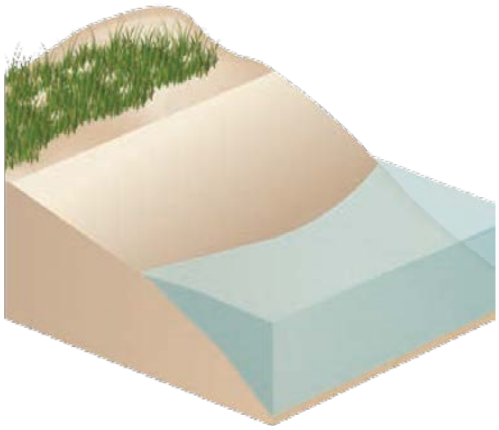
General Description: 	Large volume of sand is added from outside source to an eroding beach. This widens the beach and moves the shoreline seaward. It is suitable for low-lying oceanfront areas with existing sources of sand and sediment.
Material Options:	Sand in large amounts
Benefits:	• Expands usable beach area • Lower environmental impact than hard structures • Flexible strategy • Redesigned with relative ease • Provides habitat and ecosystem services
Disadvantages:	• Requires continual sand resources for re-nourishment • No high-water protection • Appropriate in limited situations • Possible impacts to regional sediment transport
Management of navigation vessel waves:	This technique does not handle the day-to-day impacts from waves caused by navigation vessels well.
Initial Construction Cost:	●●● = $2001–$5000 per linear foot
Operations and Maintenance Cost:	♦♦ = $101–$500 per linear foot per year

Table 10. Characteristics of Beach Nourishment and Vegetation on Dune Technique.

General Description: 	This helps anchor sand and provide a buffer to protect inland area from waves, flooding, and erosion. It is suitable for low-lying oceanfront areas with existing sources of sand and sediment.
Material Options:	Sand with vegetation. Can also strengthen dunes with: • Geotextile tubes • Rocky core
Benefits:	• Expands usable beach area • Lower environmental impact • Flexible strategy • Redesigned with relative ease • Vegetation strengthens dunes and increases their resilience to storm events • Provides habitat and ecosystem services
Disadvantages:	• Requires continual sand resources for re-nourishment
Management of navigation vessel waves:	This technique does not handle the day-to-day impacts from waves caused by navigation vessels well.
Initial Construction Cost:	●●● = $2001–$5000 per linear foot
Operations and Maintenance Cost:	♦♦ = $101–$500 per linear foot per year

Grey Harder Structures

Table 11. Characteristics of Breakwater Structures.

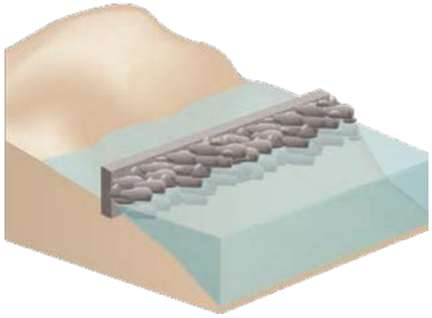
General Description: 	These offshore structures break waves, reducing the force of wave action and encouraging sediment accretion. They can be floating or fixed to the ocean floor, attached to shore or not, and continuous or segmented. A gapped approach would allow habitat connectivity, greater tidal exchange, and better waterfront access. They are suitable for most areas except high wave energy environments, often in conjunction with marinas.
Material Options:	• Grout-filled fabric bags • Wood • Armor stone • Rock • Pre-cast concrete blocks • Living reef (oyster/mussel) if low wave environment
Benefits:	• Reduces wave force and height • Stabilizes wetland • Can function like reef • Economical in shallow areas • Limited storm surge food level reduction
Disadvantages:	• Expensive in deep water • Can reduce water circulation (minimized if floating breakwater is applied) • Can create navigational hazard • Require more land area • Uncertainty of successful vegetation growth and competition with invasive • No high-water protection • Can reduce water circulation • Can create navigation hazard
Management of navigation vessel waves:	This technique should be recommended only after intense analysis of local conditions is conducted, as breakwaters can induce adjacent shoreline erosion.
Initial Construction Cost:	●●●● = $5001–$10,000 per linear foot
Operations and Maintenance Cost:	♦♦♦ = over $500 per linear foot per year

Table 12. Characteristics of Groin Structures.

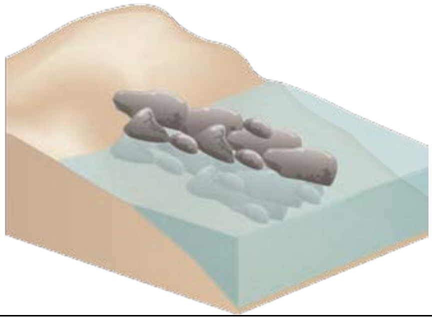
General Description: 	These structures are placed perpendicular to and projecting from shoreline. They intercept water flow and sand moving parallel to the shoreline to prevent beach erosion and break waves. They retain sand placed on beach. They are suitable for coordination with beach nourishment.
Material Options:	• Concrete/stone rubble • Timber • Metal sheet piles
Benefits:	• Protection from wave forces • Methods and materials are adaptable • Can be combined with beach nourishment projects to extend their life
Disadvantages:	• Erosion of adjacent sites • Can be detrimental to shoreline ecosystem (e.g., replaces native substrate with rock and reduces natural habitat availability) • No high-water protection
Management of navigation vessel waves:	Groins may be considered as a solution on wide navigation channels where shorelines are not close to the main channel. However, these structures can induce adjacent shoreline erosion or induce sedimentation into the navigation channel.
Initial Construction Cost:	●●● = $2001–$5000 per linear foot
Operations and Maintenance Cost:	♦♦ = $101–$500 per linear foot per year

Table 13. Characteristics of Revetment Structures.

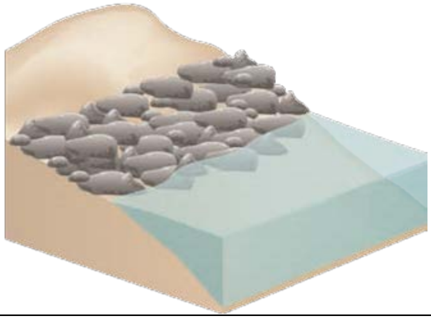
General Description: 	These structures lay over the slope of a shoreline. They protect the slope from erosion and waves. They are suitable for sites with pre-existing hardened shoreline structures.
Material Options:	• Stone rubble • Concrete blocks • Cast concrete slabs • Sand/concrete filled bags • Rock-filled gabion basket
Benefits:	• Mitigates wave action • Little maintenance • Indefinite lifespan • Minimizes adjacent site impact
Disadvantages:	• No major flood protection • Require more land area • Loss of intertidal habitat • Erosion of adjacent unreinforced sites • Require more land area • No high-water protection • Prevents upland from being a sediment source to the system
Management of navigation vessel waves:	Revetments can handle day-to-day waves from vessels well, but the structures may induce adjacent shoreline erosion.
Initial Construction Cost:	●●●● = $5001–$10,000 per linear foot
Operations and Maintenance Cost:	♦♦ = $101–$500 per linear foot per year

Table 14. Characteristics of Bulkhead Structures.

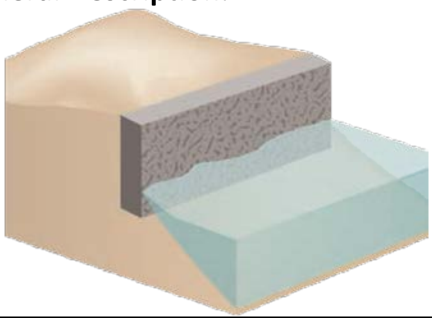
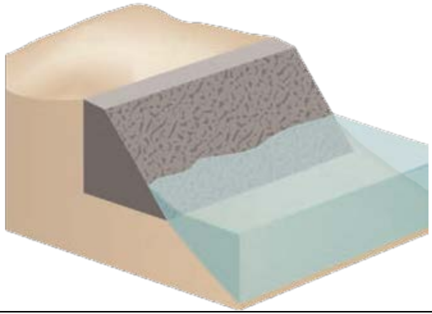
General Description: 	These are vertical retaining walls placed parallel to the shoreline. They hold soil in place and allow for a stable shoreline. They are suitable for high-energy settings and sites with pre-existing hardened shoreline structures. They accommodate working waterfronts (e.g., docking for ships and ferries).
Material Options:	• Steel sheet piles • Timber • Concrete • Composite carbon fibers • Gabions
Benefits:	• Moderates wave action • Manages tide level fluctuations • Long lifespan • Simple repair
Disadvantages:	• No major flood protection • Erosion of seaward seabed • Erosion of adjacent unreinforced sites • Loss of intertidal habitat • May be damaged from overtopping oceanfront storm waves • Prevents upland from being a sediment source to the system • Induces wave refection
Management of navigation vessel waves:	Bulkheads can handle the day-to-day waves from vessels but may induce adjacent shoreline erosion.
Initial Construction Cost:	●●● = \$2001–\$5000 per linear foot
Operations and Maintenance Cost:	♦♦ = \$101–\$500 per linear foot per year

Table 15. Characteristics of Seawall Structures.

General Description: 	These structures vertical or sloped walls parallel to the shoreline. The soil on one side of the wall is the same elevation as water on the other. They absorb and limit impacts of large waves and direct flow away from land. They are suitable for areas highly vulnerable to storm surge and wave forces.
Material Options:	• Stone • Rock • Concrete • Steel/vinyl sheets • Steel sheet piles
Benefits:	• Prevents storm surge flooding • Resists strong wave forces • Shoreline stabilization behind structure • Low maintenance costs • Less space intensive horizontally than other techniques (e.g., vegetation only)
Disadvantages:	• Erosion of seaward seabed • Disrupt sediment transport leading to beach erosion • Higher up-front costs • Visually obstructive • Loss of intertidal zone • Prevents upland from being a sediment source to the system • May be damaged from overtopping oceanfront storm waves
Management of navigation vessel waves:	Seawalls mitigate against the impacts of day-to-day energies from waves caused by navigation vessels. However, these structures may induce adjacent shoreline erosion.
Initial Construction Cost:	●●●● = $5001–$10,000 per linear foot
Operations and Maintenance Cost:	♦♦♦ = over $500 per linear foot per year

EXAMPLES OF LIVING SHORELINE PROJECTS IN TEXAS ESTUARIES

Researchers were informed during interviews with several Texas coastal stakeholders and NGOs that the introduction of the LS concepts started in Texas in the early 2000s. LS concepts have mainly been applied in the Galveston Bay area as a multiagency coordinated effort. These LS projects have transitioned from applications of semisoft structures to hard structures (sometimes submerged). This is in part because investments in shoreline protection as public (grants) or private investments require long-term performance and low maintenance. Soft solutions may require higher maintenance costs.

Some of the information presented in this section was provided by different stakeholders and then confirmed by aerial photos or information from the USACE or other agencies. Researchers believe the accuracy of dates, characteristics for the described projects, dimensions, materials, etc., may change in the details but not in the end results or the outcome of the projects.

Shamrock Island in Corpus Christi Bay

Shamrock Island (Figure 7) was developed in the early 2000s as a shoreline protection project by the GLO and the TNC in Corpus Christi Bay. The island acts as key habitat for migratory birds, is an important colonial water bird rookery island, and is free of predators due to its distance from the bay shorelines. Wave energy, vessel wakes, and lack of sediment supply in the area have induced high rates of shoreline retreat on this sandy island.

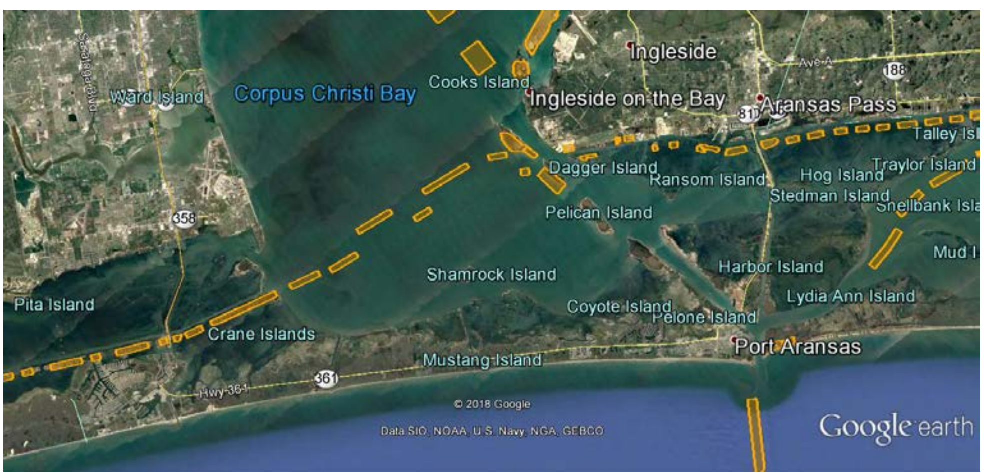


Figure 7. Aerial Image of Location of Shamrock Island.

An aerial image from 2004 (Figure 8) shows that the island shoreline protection used geotextile tubes (also called Geotubes®) as a semisoft solution. These were constructed on the northeast side of the island to reduce wave energy resulting from north winds across the long fetch from the northeastern portion of Corpus Christi Bay. The project was developed circa 2002 and two years later the geotextile tubes were already failing as presented in a close-up in Figure 9.

Figure 8. Shamrock Island in 2004 after Installation of Geotextile Tubes on Northeastern Portion.

Figure 9. Close-Up of Geotextile Tubes in 2004 Failing.

According to TNC staff, Shamrock Island went through three cycles of shoreline protection. The original geotextile tubes used for the first cycle had limited impact on the protection of the island. New devices had to be used to reduce the impacts of waves and currents and sediment loss occurring on the island shorelines. Figure 10 shows one of the last cycles of LS used for the protection of the island, which consists mainly of submerged and above-water segmented rock breakwaters. These new alternatives to shoreline protection are considered grey concepts (hard coastal structures) under LS classification, but stakeholders considered this project as a LS project. In any case, Shamrock Island served as a pioneer project in the testing of soft solutions that ultimately transitioned from semisoft concepts to hard structures. For this reason, this project continues to be considered a successful implementation of LS solutions because no sea walls or high breakwaters were constructed.

Figure 10. Shamrock Island in 2016 Showing New Set of Shoreline Protection Devices, including Submerged and above Water Rock Breakwaters.

Living Shoreline Projects along the GIWW

Three LS projects are located along the GIWW on the upper Texas coast: 1) West Galveston Bay Mooring Buoy Area, 2) McFaddin National Wildlife Refuge (Jefferson County), and 3) Mad Island in Matagorda Bay. These three projects are described below.

West Galveston Bay Mooring Buoy Area

The West Galveston Bay Mooring Buoy project was constructed in the early 2000s and is located on the GIWW (Stations 451+000 to 453+000) on the west side of West Galveston Bay Figure 11 and Figure 12). This project is considered a pioneer project because of the involvement of the USACE Galveston District, the success and diversification of the project, and the BUDM opportunities that were created. The project was initially implemented because the former land barrier that protected the mooring buoy area disappeared due to erosional forces, which created a high-energy environment that affected the safety of barge navigation across Chocolate Bay.

The first phase of the project created a rim of geotextile tubes filled with dredge material. Unfortunately, as with Shamrock Island, the geotextile tubes failed within a few years of installation. Following the failure of the geotextile tubes, reef balls were installed on the top, in front, and behind the tubes. These reef balls were considered soft structures because they can easily be removed, updated, or replaced (Figure 13, Figure 14, and Figure 15). The use of reef balls has served the purpose of moderately maintaining the dredge material within the site, providing protection to the mooring buoy area. The protection has allowed a diversity of habitats, including salt marsh, seagrass beds, and locations for bird nesting to develop.

Figure 11. West Galveston Bay Mooring Buoy Area Shoreline Protection and Habitat Restoration Project.

Figure 12. West Galveston Bay Mooring Buoy Area Shoreline Protection and Habitat Restoration Solution after Construction in January 2004.

Figure 13. Close-Up of Geotextile Tubes after a Few Years of Performance in January 2004.

Figure 14. Close-Up of Geotextile Tubes after 10 Years of Performance in January 2010.

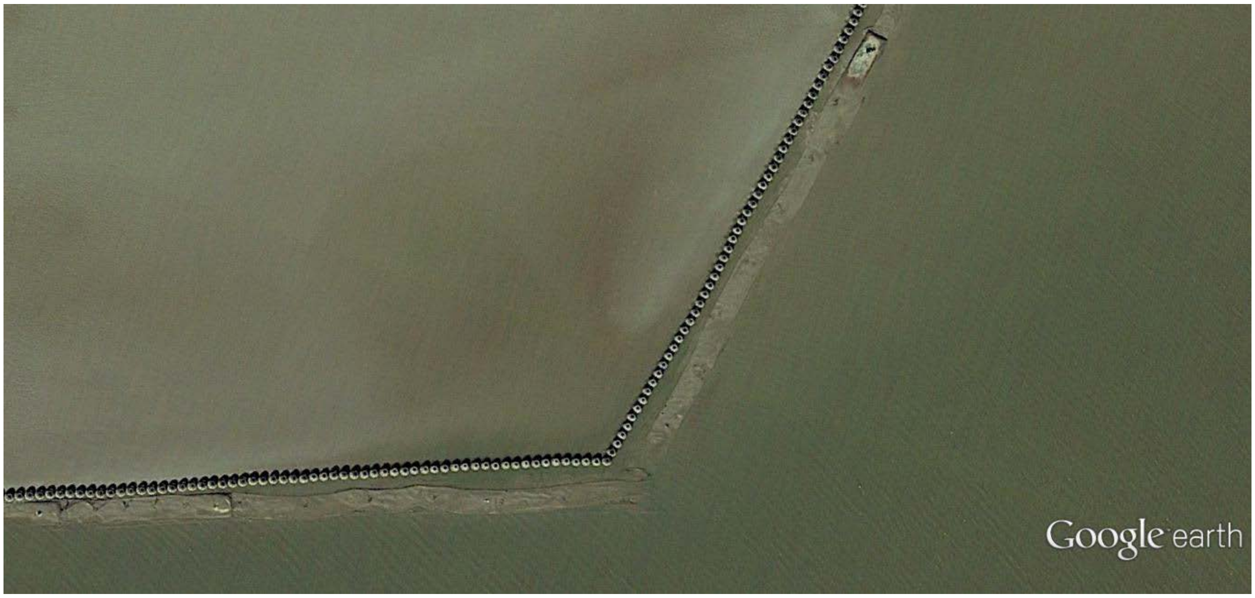


Figure 15. Close-Up of the Geotextile Tubes after 15 Years of Performance in January 2017.

Note: The former geotextile tubes were replaced with reef balls by the GBF and USACE.

The West Galveston Bay Mooring Buoy Area Shoreline Protection and Habitat Restoration Project has been considered a model scenario for the present study, since the project has met the criteria to be considered a soft LS solution. The project continues to receive dredge material as a BUDM alternative and is considered an adaptive management habitat solution where the shoreline protection can be expanded, elevated, or replaced without changing its habitat benefits. In some areas, the project has served as a sediment trap facilitating the accumulation of sediment moving through the north side of the bay. Additionally, the accretion has facilitated the development of seagrasses on the south side of the project.

Townsend et al. (*6*) developed a study funded by the USACE looking for potential solutions to the protection of the DMPAs and GIWW in West Galveston Bay. The study developed a qualitative analysis of wave processes and sediment available in the bay system. The conclusion was that a shoreline protection solution for the bay barrier islands, and DMPAs should include a combination of hard structures and sacrificial berms that reduce shoaling in the channel and ensure the continued availability of placement areas for dredged sediment.

The study proposed several design alternatives intended to protect the former bay barrier islands, the GIWW, and DMPAs. The proposed alternatives included solutions that were adapted from several previously proposed designs by the USACE Galveston District and included recommendations that the alternatives should stabilize inlets to reduce near-shore erosion, incorporate BUDM from nearby navigation channels, be economically feasible, and have the potential to be approved by resource agencies. Specifically, the recommended alternatives included:

- Breakwaters: articulated concrete block, rip rap, reef balls, oyster castles.
- Sacrificial berms.
- Revetments: rip rap, reef balls.

Figure 16 to Figure 18 illustrate the recommended alternatives.

Breakwater

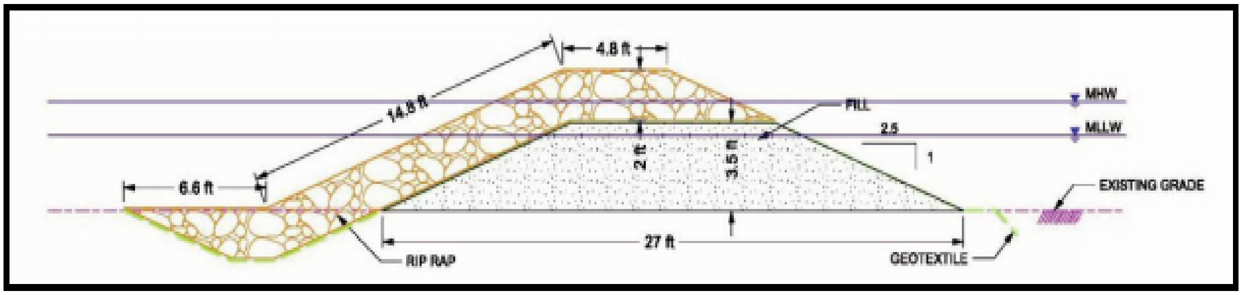


Figure 16. Typical Cross Section for a Rip Rap Revetment Used by USACE.

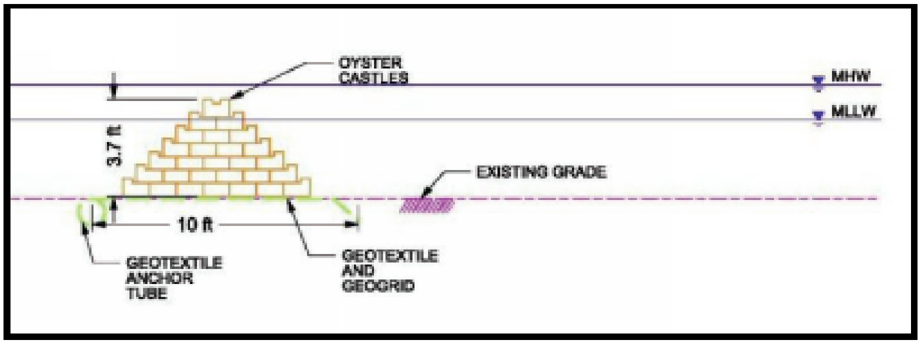


Figure 17. Typical Cross Section for an Oyster Castle Breakwater Used by USACE.

Sacrificial Berm

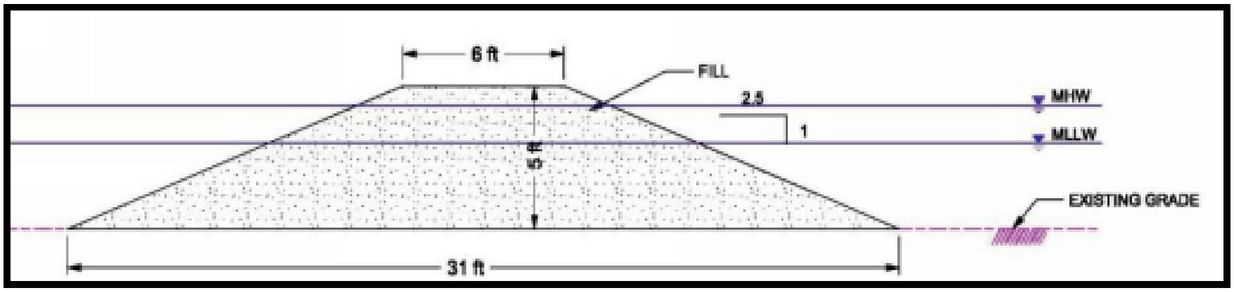


Figure 18. Typical Cross Section for a Sacrificial Berm Used by USACE.

Revetment

Revetments include rip rap and reef balls. These are illustrated in several of the projects described in this report.

McFaddin National Wildlife Refuge—Jefferson County

The McFaddin National Wildlife Refuge and the GLO developed a shoreline protection solution to address the impacts from vessel wakes from barge traffic on the GIWW west of Port Arthur (see Figure 19). The solution consisted of rock breakwaters, with specific heights and open gaps, which would allow sediment to accumulate between the breakwater and shore, supporting marsh growth behind the breakwater. Several segmented rock breakwaters were built following the shape of the GIWW shorelines at the time of design and construction.

Figure 19. McFaddin National Wildlife Refuge Shoreline Protection Solution on GIWW.

The McFaddin National Wildlife Refuge Shoreline Protection project was constructed between 2008 and 2012 and is located on the GIWW between stations 80+000 and 90+000. The project includes about 4 miles of shoreline protection. Figure 20 shows the area prior to construction of the revetments where waves from barges were impacting the shorelines. Figure 21 shows the shorelines as observed in August 2017 (about 5 years after construction of the revetments) where marsh has recovered due to overwash of sediment.

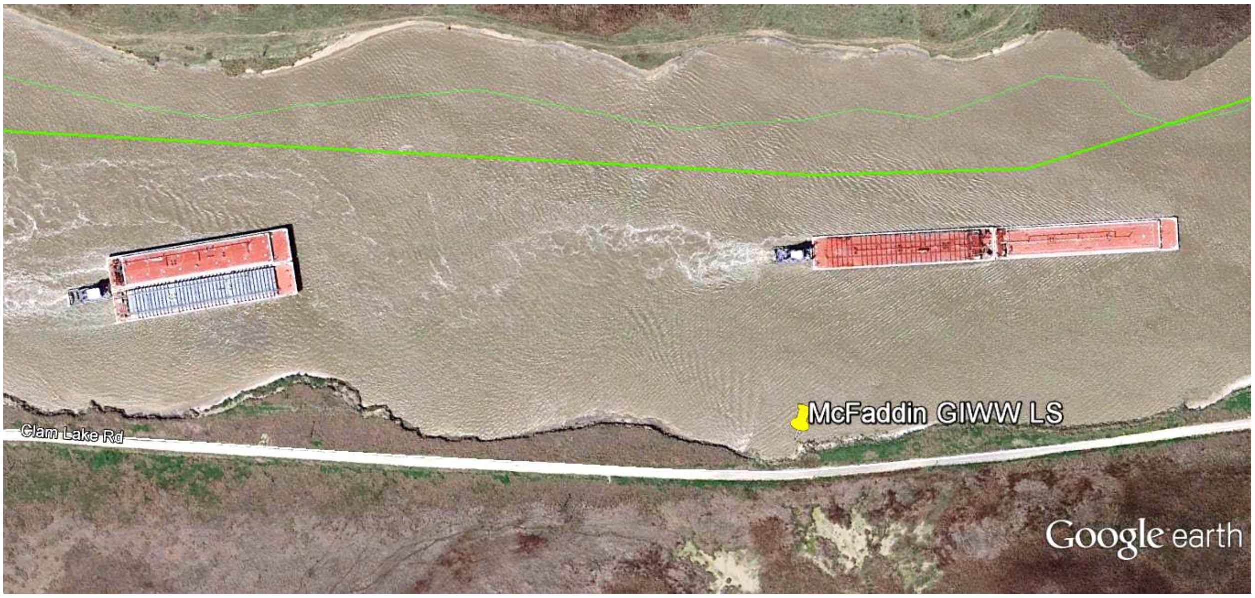


Figure 20. Erosional Forces from Barge Wakes along the Shorelines of GIWW at McFaddin National Wildlife Refuge.

Image captured March 2010.

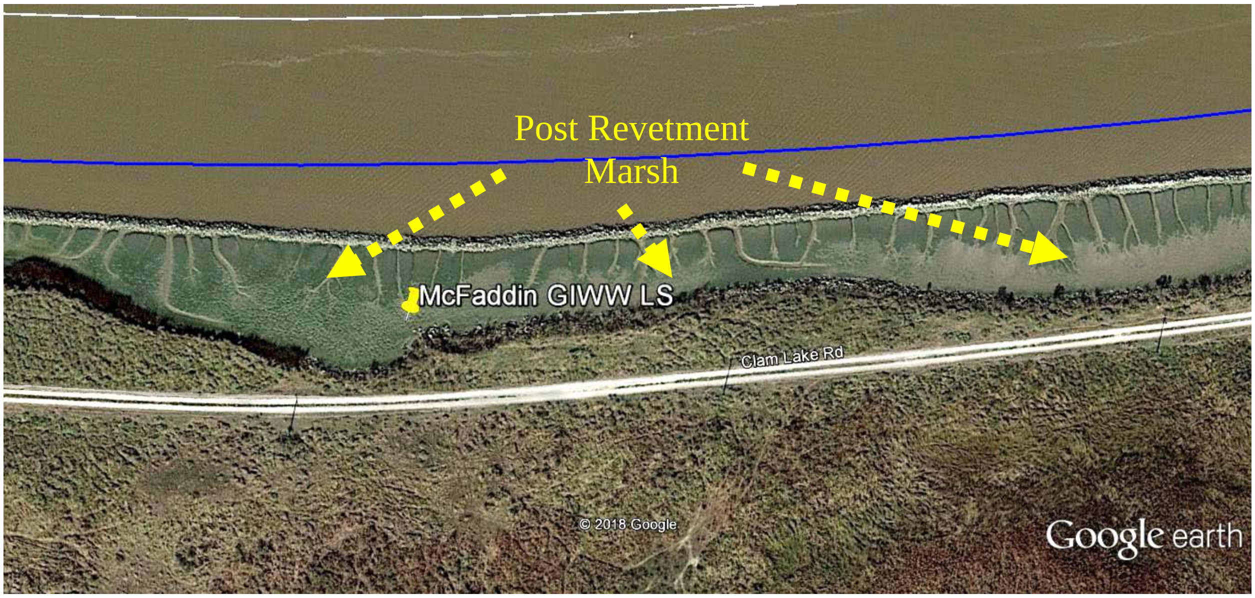


Figure 21. Development of Marsh behind Revetment along Shorelines of GIWW at McFaddin National Wildlife Refuge.

Image captured August 2017.

More than 10 years after construction, the objectives of controlling shoreline retreat and recovering marsh habitat were successfully met. The success of the project can be attributed to the specific engineering design of the breakwaters, which was critical in allowing sediments to wash over the structures and encourage growth of marshes. Because of the specific design elevation of the revetment, the structure can take advantage of the energy and suspended sediment that washes into the marshes. This has created sediment sinks where sedimentation is filling open water and allowing soil elevation to become high enough for marshes to reestablish

(Figure 22). Note the sediment basin and natural marsh accumulation behind the revetment 10 years after construction. Tidal prisms and over wash channels have increased soil elevations to allow for the maintenance of healthy marshes.

Figure 22. Shorelines of GIWW at McFaddin National Wildlife Refuge at Navigation Mark 88+000, August 2018.

This project is an example of a successful shoreline protection solution and was recommended by stakeholders as an example of an LS project. The project is classified under the grey side of the NOAA LS classification for hard structures. The project met the requirements of a LS project by reducing the energies affecting the shorelines along the GIWW and diversifying and reestablishing the original habitats. Additionally, the project created sediment sinks, which are semiconnected to the main navigation channel and receive suspended sediments from high tides and overtopping waves. According to USACE staff, the project has improved navigation efficiencies in the area by reducing shoaling and dredging cycles by retaining sediments behind the breakwaters.

Mad Island—Matagorda Bay

The Mad Island-GIWW Shoreline Protection Project was constructed between 2009 and 2010 and was developed under a partnership between the GLO, TNC, USACE, and the Department of the Interior. The project is located west of the Colorado River Delta in the GIWW on properties managed by TPWD and TNC (Figure 23 and Figure 24) and includes about 2 miles of shoreline protection consisting of rock breakwaters along the GIWW from stations 823+000 to 833+000. Since its implementation, the project has reduced the impacts of waves from vessels along the GIWW shorelines but has not accumulated enough sediment for the reestablishment of natural marsh (Figure 25).

Figure 23. Mad Island Shoreline Protection Project on GIWW (Stations 823+000 to 833+000), November 2014.

Figure 24. Retreating Shorelines and Eroding Marshes along GIWW (Stations 826+000 to 828+000) at Mad Island, January 2009.

Figure 25. Shorelines of GIWW (Stations 826+000 to 828+000) at Mad Island after Installation of Rock Breakwater, January 2014.

A recent visit to the project site revealed that Hurricane Harvey flooded the region and deposited large amounts of sediment and debris in the basins behind the breakwater. Although this was not the purpose of the project, the breakwater was able to successfully retain these sediments and debris resulting from the large floods and the high elevation of the structure that acted as a dam. However, the high elevation has in turn reduced overwashed sedimentation associated with overtopping waves from vessels on a day-to-day basis—waves cannot go over the structure and minimum sedimentation is trapped. Unlike the project at the McFaddin National Wildlife Refuge, this project does not show significant sediment accumulation after six years of project performance and the areas behind the revetment cannot be considered sediment sinks.

LESSONS LEARNED

Several lessons learned can be incorporated into the analysis of the sustainability of DMPAs on the GIWW:

- Ravens et al. (*7*) discussed the main reason for shoreline retreat along the shorelines of Galveston Bay (and other bays), including the shorelines of DMPAs on the GIWW and bay sides, is the lack of sediment supply. The wave action on Galveston Bay (and other bays) is strong, but not significant enough to be the main factor for bay (and GIWW) shoreline retreat. The main reason for shoreline retreat is the lack of sediment being returned to the shorelines. Sediment is moving along the shorelines through bay littoral processes or by suspension processes, but sediments are not being accreted in the shoreline system.
- The first mentioned LS projects developed in Texas (Shamrock Island and West Galveston Bay mooring buoy area) using soft solutions failed. The geotextile tubes failed when exposed to direct wave attack, making them useful only for short-term erosion control (*5*). This is true for the use of these devices in the Gulf shores or the bay and GIWW shorelines.

- The McFaddin LS shoreline protection project proved that suspended sediment even in low energy environments can be harvested and returned to the natural system. A hard structure like the McFaddin GIWW breakwater was able to protect the shorelines without affecting navigation safety while restoring marshes by natural accretion. In the case of the McFaddin project, these concepts performed as a true LS multipurpose project.
- The West Galveston Bay mooring buoy area project has served as a shoreline protection and habitat restoration LS alternative. The project was able to sustain BUDM opportunities while reducing bay energies. The BUDM alternatives have made the project a sustainable LS project due to the availability of sediment. Future repairs or replacements may be necessary, but the concept of coexistence with BUDM alternatives makes this project a good example of a successful LS multipurpose project.
- The Mad Island GIWW shoreline protection project has been successful in mitigating wave energies from vessels but has had limited results on the return of sediment to the natural system. To achieve this objective, adaptations to the original design may be necessary.
- After years of project experience, stakeholders in Texas are now considering hard structures as soft solutions for shoreline protection and habitat diversity. Even though hard coastal structures are classified as grey under the LS classification system, the combination of hard and soft concepts has successfully provided direct and indirect benefits to ecological services—in some cases BUDM opportunities—and indirectly improved navigation efficiencies. Regionally, the LS concept has been adapted to include the combination of green and grey solutions as true Texas LS solutions.
- None of the previously mentioned LS projects on the GIWW had the main goal of improving or maintaining navigation safety. However, according to USACE staff, the three described projects have improved navigation efficiencies by reducing shoaling and delaying dredging cycles due to the local GIWW shoreline stabilization on the local segment of the navigation channel.
- Staff from USACE Operations Division reaffirmed that the Galveston District has abandoned the use of geotextile tubes as a shoreline protection solution due to past failures. Reef balls appear to be an alternative that can support other soft LS solutions due to their flexibility, low maintenance, and adaptability to different geomorphological settings. Other LS solutions have been proposed that have not included the diversification of habitats or the harvesting of sediment as part of the project to fit the definition of LS concepts (*3*, *4*).

The specific solutions to be selected as soft or hard LS structures for shoreline protection of DMPAs may depend more on how those solutions interact with sediment supply, either naturally or artificially (BUDM alternatives). Harvesting or retaining sediment in the bays or along the shorelines of the GIWW for the sustainability of DMPAs will generate substrate suitable for submerged or emergent habitats, which will help to mitigate against shoreline retreat. The retention, harvesting, reinstallation, or accretion of sediment is fundamental for the sustainability of DMPAs along the GIWW, independent of the LS solution selected for shoreline protection.

This concept of sediment harvesting and retention may be integrated in the future into the local adaptations of the Texas LS concepts since they appear to play an important role in the function of these solutions. Incorporating sediment harvesting may support sustainability of the GIWW DMPAs as long-term sustainable solutions.

CHAPTER 4: FEASIBLE SOLUTIONS FOR THE SELECTED AREA

INTRODUCTION

This chapter compiles methodologies that have been proposed or applied in Texas and other states on projects dealing with shoreline retreat and erosion along the GIWW-facing and bay-facing shorelines. The GIWW is separated by land from the bay itself in this area. This chapter includes the description of these approaches and how they can be adapted and used for the local environment of EMB. Stakeholder recommendations for solutions that have proven to be successful in mitigating shoreline erosion at similar sites and environments have been considered for EMB. The alternatives proposed in this section for the shoreline protection of DMPAs includes solutions on bay-facing and GIWW-facing shorelines, where DMPAs are being affected by erosion and are at risk of disappearing.

EAST MATAGORDA BAY PHYSICAL CONDITIONS

EMB is a shallow bay that is unique to the Texas coast. During the last century, EMB was separated from WMB by the creation of the Colorado River Delta Channel (see Figure 26). When EMB and WMB became independent bay bodies, EMB reduced the available environmental flows but increased the amount of sediment supply originating from the inland fluvial sources and from the Gulf of Mexico inlets through Mitchell's Cut, creating one of the few closed-system coastal sediment sinks in Texas.

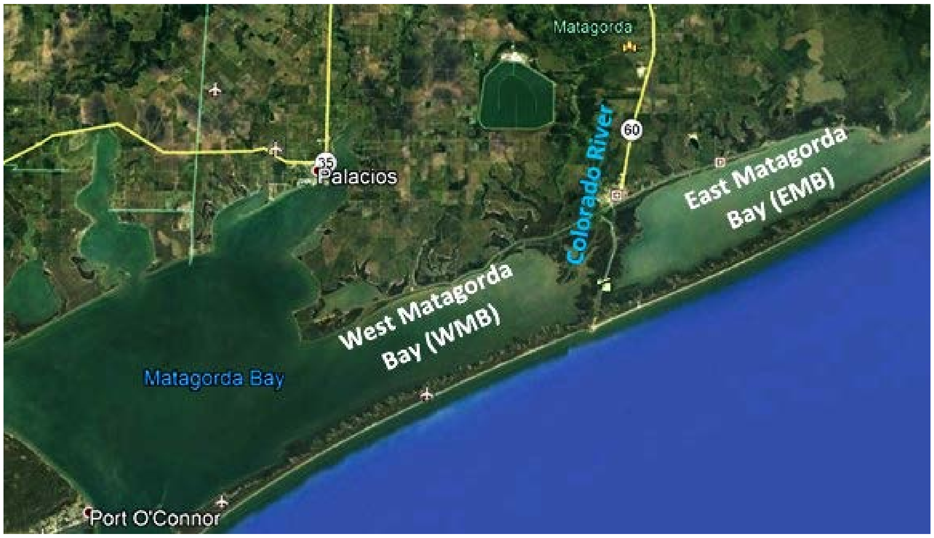


Figure 26. Matagorda Bay Overview.

Source: Google Earth

The construction of the GIWW in the early 1940s also contributed to inducing changes in sediment transport and sedimentation processes within EMB. The GIWW in effect became a sediment trap to naturally transported sediments, which deposited within and shoaled the GIWW's navigation channel.

The main dynamic sources of sediment supply to EMB and to the GIWW are located on the east side of EMB. Significant amounts of suspended sediment originate from the creeks north of the

GIWW, which include Live Oak Bayou, Turkey Island Slough, Boggy Bayou, and Caney Creek (Figure 27). Large amounts of sediment (not quantified) originate from the inlets connecting the bay with the Gulf of Mexico (Brown Cedar Cut and Mitchell's Cut). EMB depths within the eastern side and adjacent to the GIWW range from less than 1 ft to 4 ft Mean Lower Low Water (*8*). As can be observed in aerial photographs (Figure 27), an important source of sediment to the GIWW originates from the Gulf inlets and then from bay circulation processes. Southeastern prevailing winds produce waves and currents that carry sediments into the GIWW from the center of the bay.

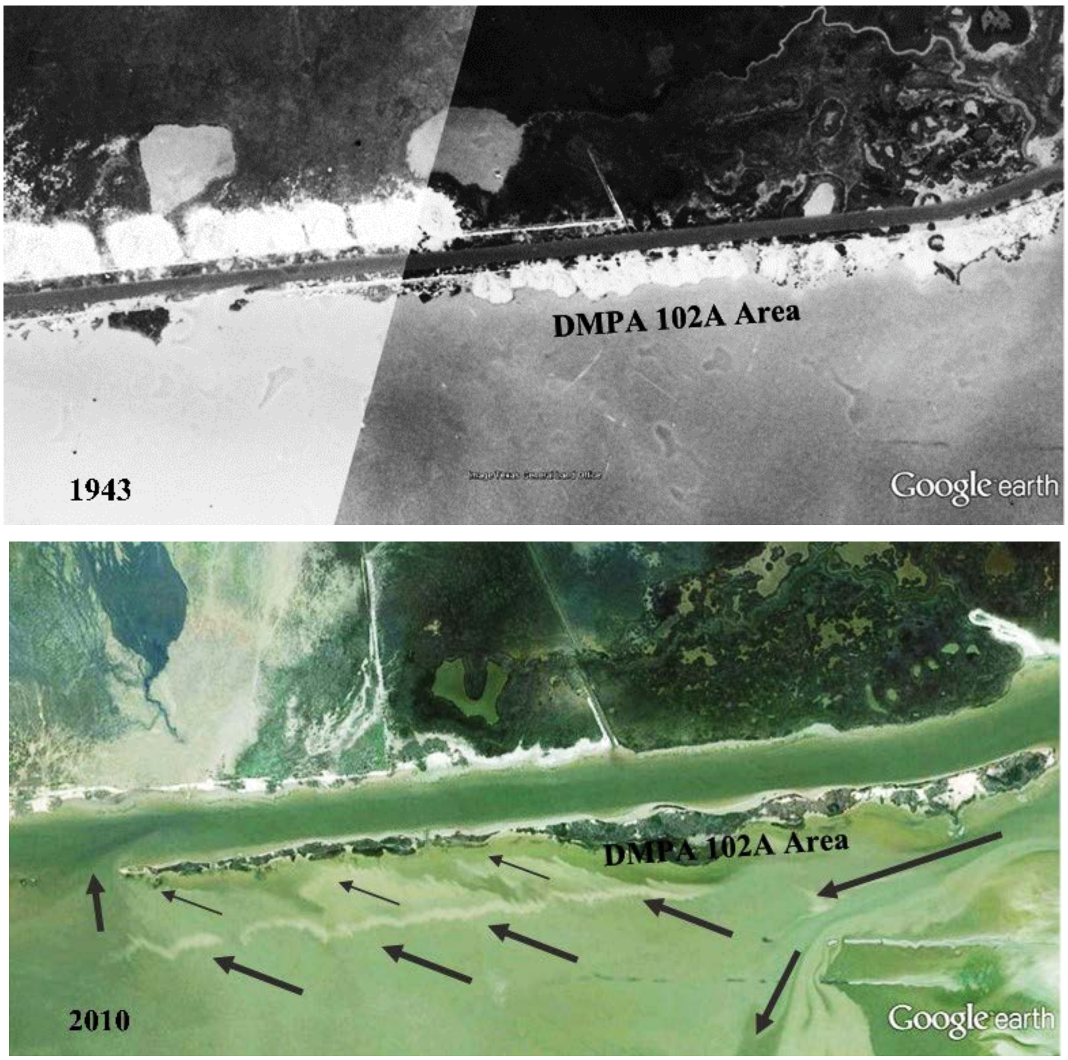


Figure 27. Aerial Photographs from the DMPA Area 102-A in 1943 and 2010.
The arrows show how bay circulation and sediment transport move close and into the GIWW.
Source: Google Earth

Additionally, the disintegration of former DMPAs and existing island barriers of the GIWW can sometimes be a locally significant source of sediments to the GIWW. As these habitats disappear, sediments are mobilized and carried by fetch driven waves and currents and deposited within and shoal the GIWW. The same energies that carry sediments also induce navigation challenges, safety issues to barge operators, and more frequent dredging, which sometimes reduces navigation efficiencies.

CONDITIONS OF EVALUATED DMPAS IN EAST MATAGORDA BAY

The conditions of the DMPAs described in the GIWW Master Plan (Master Plan) (*1*) identifies issues of concern at the DMPAs located within EMB. However, the Master Plan only describes the conditions of DMPAs located to the south of the GIWW. Figure 28 overviews the physical features located adjacent to the GIWW and DMPAs in EMB. Table 16 summarizes dimensions and conditions of DMPAs in the eastern portion of EMB.

Figure 28. Distribution of DMPAs and Physical Features in EMB.

DMPA numbers are in white. Source: Google Earth

Table 16. DMPAs Dimensions and Conditions in EMB, Matagorda County.

DMPA No.	Acreage	Status	Level of Impact by Bay Shoreline Retreat	Remaining Life in Years*
DMPA 101	45	Active, partially confined in water	Low	Data unavailable
DMPA 102-A	252.9	Data unavailable	Severe	Data unavailable
DMPA 102-B	314.94	Data unavailable	Severe	Data unavailable
DMPA 102-C	135.08	Active	Low	Data unavailable
DMPA 103	93.15	Data unavailable	Severe	Data unavailable
DMPA 105	451.26	Data unavailable	Moderate	Data unavailable

Source: USACE Navigation Data Center Database and Kruse et al. (1) and notes from the authors.

DMPA 101

DMPA 101, shown in Figure 28, is located at the front of the Mitchell’s Cut Flood Delta. As observed in Figure 29, almost half of the site corresponds to natural marsh habitat, making this DMPA one of the most habitat dominated DMPAs south of the GIWW. This DMPA did not exist immediately after the construction of the GIWW. In 1995, extensive land areas appear to have developed from dredged material placement and the adaptation of natural habitats on the bay side of the GIWW. Erosion on the bay shorelines is minimal since the shorelines are part of the flood delta with abundant natural sediment supply. On the contrary, the shoreline retreat to the GIWW side has been severe. Since 1943, the shorelines of the GIWW have retreated approximately 300 ft on the south side of the channel, as observed in historical imagery in Google Earth. Solutions to preserve DMPA 101 need to focus on protecting the GIWW-facing shoreline from erosion caused by barge generated currents and waves. Extending DMPA 101 to the west would be beneficial for navigation since it would protect the GIWW at the navigation channel bend and hence improve navigation safety and efficiency.

Figure 29. Location of DMPA 101 on North Side of Mitchell’s Cut Flood Delta.
Arrows show how the flow delta is bringing sediment to the bay and the GIWW.
Source: Google Earth and USACE DMPA Database

DMPAs 102-A and 102-B

According to historic aerial imagery (Figure 29), DMPAs 102-A and 102-B have never existed above the water surface. Apparently, the areas were secured for future use, but if used, they would be used as submerged DMPAs. It is recommended that these DMPAs should be filled above the water surface to reduce the shoaling with the GIWW and to further protect navigation transits from wave energy. Figure 30 shows the location and position of DMPAs 102-A and

102-B with respect to EMB and the GIWW. The two images display the vulnerability of the Gulf of Mexico–facing barrier island to breaching during large storm events, which may mobilize significant amounts of sediment into the GIWW. The other permanent sediment source is Mitchell's Cut.

It is anticipated that dredging frequencies at the GIWW will be reduced if DMPA 102-A is extended to the east toward DMPA 101. The gap between DMPA 101 and DMPA 102-A is where the active flood delta at the Mitchell's Cut Inlet provides a significant amount of sediments transported to the bay, with a portion of these sediments transported to the GIWW causing increased shoaling rates if not blocked by a constructed habitat/DMPA.

(a)

(b)

Figure 30. Historical Image of DMPAs 102-A and 102-B in 1943 and 2017.

Notice that in 1943 these DMPAs were not yet built. There was also an overwash-inlet created on the barrier islands after a large storm with a large flood delta connecting DMPA 102-A. The inlet is closed but the area continues to be a shallow environment.
Source: Google Earth and USACE DMPA Database

DMPA 102-C

DMPA 102-C is critical for pilots navigating the GIWW. This DMPA is located between two navigation channel turns of the GIWW. As expressed by the pilots and noted early in this report, navigation channel turns and bay wind/wave energies are problematic for navigation safety. DMPA 102-C has been active and has received dredge material on a regular basis. Therefore, it currently provides for critical habitat and serves as a buffer to bay wind/wave energies impacting the GIWW. Extending this DMPAs to the south and east toward DMPA 102-B will be beneficial for navigation, since it would protect the GIWW navigation channel turn located at the current gap between DMPAs 102-C and 102-B. Figure 31 shows these areas. DMPA 102-C has a shoreline revetment on the GIWW-facing side that has performed relatively well in protecting it from barge-generated waves. The GIWW-facing shoreline has retreated at least 55 ft since 1942. However, recently, it appears that the revetment has helped to mitigate against shoreline retreat.

(a)

(b)

Figure 31. Location of DMPAs 102-B, 102-C, and 103 with Respect to the Turns of the GIWW, and Conditions of the Gaps on Either Side of DMPA 102-C.

Source: Google Earth and USACE DMPA Database

DMPA 103

Shoreline retreat to the bay-facing and on the GIWW-facing sides is a normal occurrence to DMPA 103, which appears to currently provide approximately 40 percent of the DMPA's designated footprint as habitat and bay wind/wave energy buffer for the GIWW. A thin land connection (composed of dredge material) previously existed between DMPAs 102-C and 103, which has almost completely disappeared as shown in Figure 31b. The bay-facing side of this DMPA has retreated at least 150 ft since 1943 based on Google Earth. The GIWW-facing shoreline has retreated at least 200 ft. The area has shown no accumulation of dredge material since its creation. Sediments originating from the creeks north of DMPA 103 are transported to the GIWW and have contributed to its shoaling. Connecting DMPA 103 with DMPA 102-C (as was the case in 1943) (Figure 32) would be beneficial to improve navigation safety by protecting against bay wind/wave energies and by reducing bay transported sediments and deposition within the GIWW.

Figure 32. Thin Layer of Dredge Material Connecting DMPAs 102-C and 103, Circa 1943.
Source: Google Earth and USACE DMPA Database

DMPA 104

Only a small portion at the eastern edge of DMPA 104's designated footprint and a thin layer of dredge material next to the GIWW was built in 1943 close to Turkey Island (Figure 33). Dredged material was disposed along the shorelines, but no infrastructure or shoreline protection features were created to retain and preserve the placed dredged material. Since 1943, the area has been exposed to GIWW barge traffic-induced wave energies and bay wind/wave energies. Therefore, the small area of placed dredged material has nearly disappeared. DMPA 104 has not received dredged material for an extended period of time. Wind/wave energies from the bay easily reach the GIWW, creating navigation safety and efficiency issues where the GIWW is exposed to the bay's sediment transport and currents. Re-activating and building-up DMPA 104 will provide the desired protection to the GIWW and reduce bay-induced energies and shoaling. DMPAs 104A, 104B, and 105A located north of the GIWW have articulated mats as shoreline protection solutions. These DMPAs have shorelines that are relatively stable due to these protections.

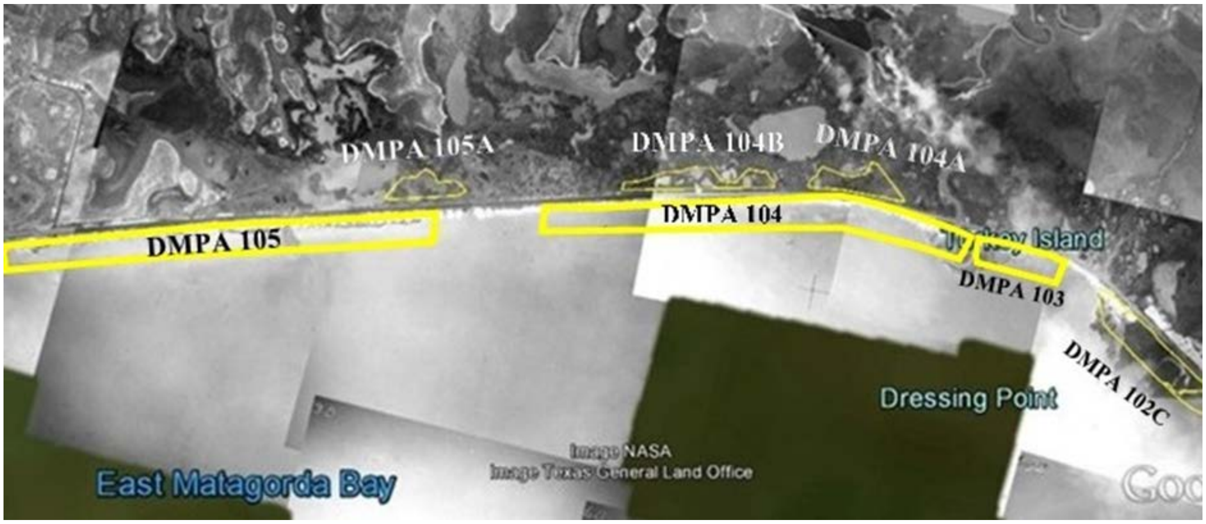


Figure 33. Aerial Photograph of DMPAs 104, 104A, 104B, 105, and 105A from 1943.
Source: Google Earth and USACE DMPA Database

DMPA 105

DMPA 105 is one of the longest DMPAs within EMB (Figure 33). Historic Google Earth imagery shows that the DMPA was built between 1957 and 1965 by accumulation of dredged material but without any protection. DMPA 105's shoreline retreat on the bay-facing and the GIWW-facing sides of the DMPA have been significant. Specifically, GIWW-facing shoreline retreat has been between 200 and 230 ft. The gap between DMPA 105 and DMPA 104 leaves the GIWW navigation channel unprotected and exposed to bay wind/wave energies, storm surges, and sediment transport and deposition.

RECOMMENDED DMPA IMPROVEMENTS TO ENHANCE NAVIGATION SAFETY AND EFFICIENCIES

Primary Priorities to Enhance Navigation Safety by Improving the DMPAs in East Matagorda Bay

Based on the description of the physical conditions of the GIWW navigation channel turns and DMPAs along the GIWW, it appears there are three navigation channel turns requiring critical protection against bay-induced wind/wave energies and sediment transport to provide for enhanced navigation safety and efficiencies. Recommended DMPA improvements at these turns include:

- **DMPA 101 West:** Extend DMPA 101 approximately 900 ft westward toward DMPA 102-A to protect the turn.
- **DMPA 102-C East:** Extend DMPA 102-C approximately 2600 ft eastward toward DMPA 102-B to protect the turn.
- **DMPA 102-C West:** Extend DMPA 102-C approximately 2500 ft westward toward DMPA 103 to protect the turn.

The proposed improvements to these DMPA sections will enhance navigation safety and efficiencies within the GIWW.

Secondary Priorities to Enhance Navigation Safety by Improving the DMPAs in East Matagorda Bay

DMPAs that may not be a priority for improvements in the next few years but may affect GIWW navigation and operations if nothing is done include:

- **DMPA 103:** This DMPA should be restored and/or expanded for the long-term sustainability of the GIWW since it provides protection against bay wind/wave energies at the navigation channel turn.
- **DMPA 105:** This DMPA has a sufficient existing footprint to remain functional for a few more years of shoreline retreat but will require shoreline protection to the DMPA's GIWW-facing side.
- **DMPAs 102-A and 102-B:** These DMPAs have extended designated footprints and will require substantial investments and sediment volumes to improve their condition. DMPAs 102-A and 102-B are essentially physically non-existent, which cause major problems to DMPAs 102-D and 102-E located on the north side of the GIWW. The protection features constructed to protect the GIWW-facing shorelines of DMPAs 102-D and 102-E are being impacted by long-fetch bay wind/wave erosional energies, which cross the GIWW uninterrupted. Additionally, the GIWW's barge-induced waves and wakes impact the GIWW-facing shoreline protection features of DMPAs 102-D and 102-E. By physically improving DMPAs 102-A and 102-B, long-fetch wind/wave energies will be reduced before reaching the GIWW, which will reduce navigation safety impacts within the GIWW and erosional impacts to DMPAs 102-D and 102-E GIWW-facing shorelines.

EXISTING METHODS TO PROTECT THE DMPAS

This study includes the applicability review of feasible shoreline protection solutions as recommended by NOAA (*3*, *4*). NOAA classifies the shoreline protection infrastructure solutions from green to grey, as shown in Figure 34.

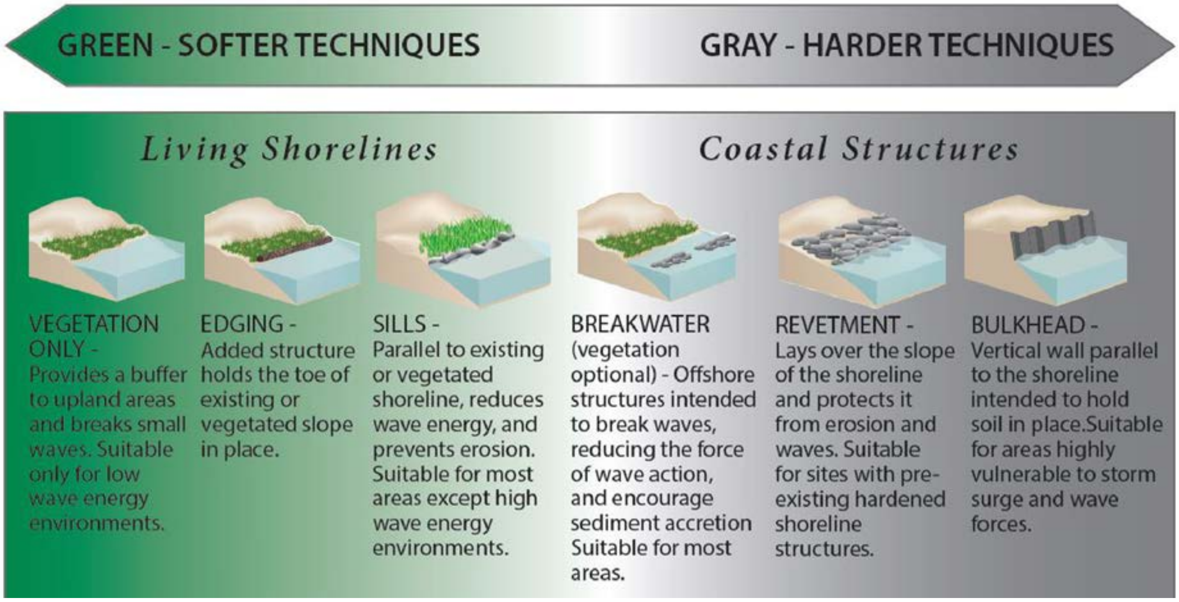


Figure 34. NOAA Shoreline Stabilization Solutions.

Based on the discussions with stakeholders and staff from the TxDOT Maritime Division, solutions for managing shoreline retreat at the evaluated DMPAs and the GIWW shorelines are expected to be on the gray side of the NOAA classification, but are not expected to include bulkheads, seawalls, and geotextile tubes. These structures do not retain or trap sediment in coastal environments. Application of these methods may accelerate shoreline retreat on the adjacent shorelines since these devices transfer the energy to the next area and are not considered feasible for the evaluated locations. Table 17 shows the general characteristics of each solution.

Table 17. General Characteristics of the Green and Gray Shoreline Protection Infrastructure.

Green Alternatives	Descriptions
Vegetable only	Roots hold soil in place to reduce areas and breaks small waves.
Edging	Structure to hold the toe of existing or vegetated slope in place. Protects against shoreline erosion.
Sills	Parallel to existing or vegetated shoreline, reduces wave energy and prevents erosion. A gapped approach would allow habitat connectivity, greater tidal exchange, and better waterfront access.
Sediment replenishment	Large volume of sand added from outside source to an eroding beach. Widens the beach and moves the shoreline seaward.
Sediment replacement and vegetation	Helps anchor sand and provide a buffer to protect inland area from waves, flooding, and erosion.
Gray Alternatives	**Descriptions**
Breakwater	Offshore structure intended to break waves, reducing the force of wave action and encouraging sediment accretion. Can be floating or fixed to the ocean floor, attached to shore or not, and continuous or segmented. A gapped approach would allow habitat connectivity, greater tidal exchange, and better waterfront access.
Groin	Perpendicular, projecting from shoreline. Intercept water flow and sand moving parallel to the shoreline to prevent beach erosion and break waves. Retain sand placed on beach.
Revetment	Lays over the slope of a shoreline. Protects slope from erosion and waves.
Bulkhead	Parallel to the shoreline, vertical retaining wall. Intended to hold soil in place and allow for a stable shoreline. **(Not Recommended)**
Seawall	Parallel to shoreline, vertical or sloped wall. Soil on one side of wall is the same elevation as water on the other. Absorbs and limits impacts of from land. **(Not Recommended)**

Source: (3,4)

The gray alternatives to shoreline protection (including groins and revetments) were grouped as one element since these structures are similar in concept, potential costs, and life span. The analysis for these structures to bay-facing shorelines is complex and requires site-by-site analysis.

PROPOSED GIWW-FACING SHORELINE PROTECTION: EXAMPLE MCFADDIN

Any shoreline protection project to be developed on the shorelines of the GIWW will have to consider navigation safety and the potential of rocks or debris that can end up within the navigation channel (Seth Jones, USACE, personal communication, 2018). During the analysis conducted for the historical solutions dedicated to mitigating or reducing shoreline erosion along the GIWW, it was identified that one specific project has successfully performed as a wave attenuation, sediment retention, and shoreline stabilization feature after its construction. This project, located within the McFaddin Wildlife Refuge in Jefferson County, was developed by the GLO in 2000 in partnership with US Fish and Wildlife Service. The project was developed under the Coastal Erosion Planning and Response Act (CEPRA) managed by the GLO. Other rock shoreline protection projects have partially failed in the GIWW and did not retain enough sediment for shoreline stabilization as part of the performance.

McFaddin General Project Criteria

The report produced for the McFaddin project shows the criteria that need to be considered for installing breakwaters along the GIWW. The uniqueness of this project is that it allowed for the retention and the capture of sediment behind the breakwater (Figure 35). This is the only project discovered in this research that developed shoreline protective features along the GIWW with the goal of retaining sediment as part of the performance criteria of the project, and to concurrently act to attenuate barge and vessel waves. The retention of sediment serves to restore and preserve marshes and prevent shoreline retreat.

Figure 35. Location of Shoreline Protection Project Developed by GLO and USFWS on South Side of GIWW in Jefferson County.
Source: Google Earth and USACE DMPA Database

This project followed several recommendations identified in NOAA’s LS strategies (*4*) before they were formally published. Figure 35 displays the location of the project (Latitude: 29°44'44.69"N; Longitude: 94° 4'36.69"W). The project consisted of more than 3,000 ft of shoreline rock breakwaters along south side of the GIWW.

The methodology applied to this project can serve as the basis for the future development and implementation of shoreline protection structures for DMPAs, with considerations given to:

- **Analysis for potential soft soils.** The geotechnical survey explored and evaluated soil and groundwater conditions along the proposed project alignment to provide recommendations for the behavior of potential soft soils below the shoreline protection structures.

- **Analysis of potential settlement of soft and hard soils.** Once the crest height was zeroed, there was an analysis of short-term and long-term settlement to ensure the project will end up with the correct long-term elevation.
- **Water level and wave height criteria.** Vessel-induced hydrodynamics and water level analysis for flooding conditions were critical factors in the selection of the type and height of the breakwater and potential implementation of low-spots at an interval within the breakwater system for systematic sediment capture from overflow.
- **Hydrodynamics of vessel waves.** In the GLO McFaddin Report (*9*), three analyses were conducted on this section of the GIWW (extreme events were not included):
  - Vessel Pressure Field Impacts.
  - Vessel Wake Impacts.
  - Vessel Prop Wash Impacts.

The following barge-induced wave parameters (passing vessels) were established:

- Deck barge trains range in length from one (200 ft) to five (1000 ft) barges.
- Deck barge beams are—40 ft.
- Deck barge drafts are generally—9 ft.
- Deck barges generally run at speeds less than 7 knots (8 mph).
- Deck barge trains generally run along the channel centerline.

The pressure field long-period waves created near the passing vessel in the channel are shown in Figure 36 for barge trains ranging from one deck barge (200 ft) to five deck barges (1000 ft) in length passing at 7 knots in the center of the channel. The report concluded that the smaller barge trains create slightly larger drawdowns, and the periods of the drawdowns are much shorter.

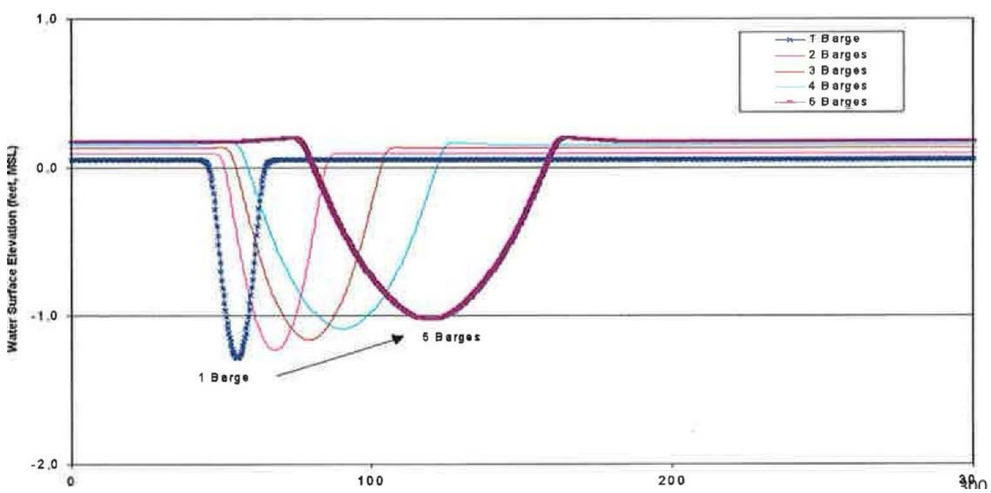


Figure 36. Water Surface Deflections in GIWW Due to Pressure Fields Created by 200- to 1000-ft Barge Trains.

Source: GLO McFaddin Report (9)

This information is important since it can be used and adapted for any shoreline along the GIWW. The design pressure field conditions were long-period waves, generated by the relatively large vessels and barge trains passing through the GIWW. The pressure field impacts on channel bank erosion vary for each event based on vessel parameters (length, beam, draft), vessel passing speed and position, and the channel configuration (width, depth, side slopes).

Pressure field wave propagation from the deep channel design depth of 12 ft toward the shallow bank (depth less than 6 ft) results in the transformation of long-period wave energy into cross-shore motions of a significant mass of water. These motions may consist of several phases:

- Phase 1—original slight movement onshore.
- Phase 2—significant outflow toward the channel when the bottom slope can be exposed far from the shoreline.
- Phase 3—return water flow in the form of a bore that results in a rapid increase in water level.
- Phase 4—propagation of short-period waves on top of the return flow.

The occurrence of these phases of motion depends on the pressure field parameters. For small pressure field waves, some of these phases of motion may be so insignificant that they cannot be observed or recorded by standard measuring equipment.

The pressure field effects and forces created by motions of the pressure field wave on the shallow bank are investigated for Phase 3 in terms of wave run-up and bottom flow velocities. It is assumed that this phase generates the maximum forces and impacts to the shoreline and shoreline structures.

Vessel wakes are also important for design of erosion protection structures along waterways. In the GIWW, it is estimated that the tug, barge, and pleasure craft/small boat traffic is capable of frequently producing vessel wakes with heights and periods up to approximately 2 ft and 5 seconds, respectively. Under extreme conditions, vessel wake heights could exceed 2 ft.

McFaddin Project Preliminary Design Criteria

For the McFaddin project, engineering criteria were developed to evaluate each of the alternatives in a comparable manner. The following preliminary design criteria were established to assist in the development and evaluation of the alternatives:

- Design Water Surface Elevations — Mean Higher High Water El +1.96.
- Max Water Surface Elevations — 5.07 ft.
- Long Term Subsidence — up to 1.5 ft (25-year period).
- Short Term Settlement — negligible at most locations.
- Design Life — 25 years.
- Vessel Wake — 3-ft height.
- Pressure Field Bore Speed — 8 ft per second.
- Salinity Concentrations — 2.5 ppm in the freshwater wetlands, 25 to 30 ppm in the GIWW.
- Detached breakwaters to be installed outside of the USACE GIWW Right-of-Way.
- Selection of the rock breakwaters as long-term solution.

After several comparisons, a rock breakwater was considered the best long-term solutions for the shoreline retreat on this section of the GIWW (Shane Phillips of Mott McDonald, personal communication). As a concept, the breakwater is considered a rubble mound structure that is designed to absorb wave forces and protect a stretch of shoreline from erosion. The detached rock breakwater is considered a shore parallel structure that is designed to reduce the amount of wave energy reaching the protected segment of shoreline. The breakwater is designed to allow for some overtopping to facilitate deposition of suspended sediments within the area between the existing shoreline and the breakwater.

The breakwater was coupled with a geotextile filter fabric layer, an armor rock layer, and toe protection. The geometry of the breakwater consisted of top elevation at +4 ft, a top width of 3 ft and side slopes of 2.5H:1V. The total height of the structure varies from 4 to 6 ft depending on the location along the proposed project site.

Based on the established design criteria, the median stone size for the breakwater is estimated to be 250 lb. The gradation for the rip rap would range from a minimum of 50 lb to a maximum of 1,000 lb.

DESIGN RECOMMENDATIONS BY THE USACE GALVESTON DISTRICT

The USACE Galveston District and the U.S. Army Engineer Research and Development Center Coastal Modeling System (USACE Team) addressed the GIWW sedimentation problem in West Galveston Bay. The USACE Team approached the problem as a sediment management strategy (*6*). They identified several sediment management options to prevent DMPA bay-facing berm or shoreline erosion, including the stabilization of local bay inlets and the reduction of channel shoaling.

Townsend et al. (*6*) simulated physical processes connected to the GIWW and some DMPAs. The models include waves, currents, sediment transport, and morphology changes. The results of the modeling facilitated the selection of potential solution alternatives on bay-facing berms or shorelines along the GIWW focused on shoaling reduction and erosion mitigation on the land barriers or the DMPAs. Important considerations for a recommended alternative are that it will have to be economically feasible and be positively received by resource agencies. Also, the inclusion of BU of dredged sediment from the GIWW as the main alternative will be the preference.

Recommendation for GIWW-Facing Shorelines

Based on the alternatives analysis and a cost comparison per linear foot, a rip rap revetment (see Figure 37) was found to be the lowest cost acceptable alternative for structures adjacent to channels (*6*). Pre-fabricated breakwater concrete units were not selected, although cheaper, due to the potential for damage from barges, which would compromise their functionality and require significant repair to the revetment. A full breakwater would be a more expensive alternative to a sole revetment.

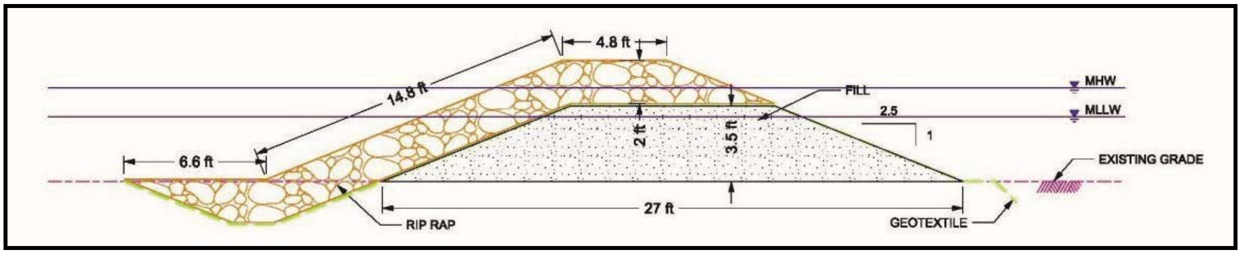


Figure 37. Typical Cross Section for Rip Rap Revetment.
Source: (*7*).

Recommendation for Bay-Facing Shorelines

The study found that oyster castles are the lowest-cost alternative for bay-side structures and structures adjacent to channels (Figure 38). This was also found to be the most constructible alternative for these areas, as this material is anticipated to be delivered to the construction site on small, shallow-draft boats and can be hand assembled, requiring no heavy equipment. However, since the USACE Galveston District has no experience in the implementation of oyster castles, the study recommended a demonstration project using this technology in mild erosion environments to observe performance.

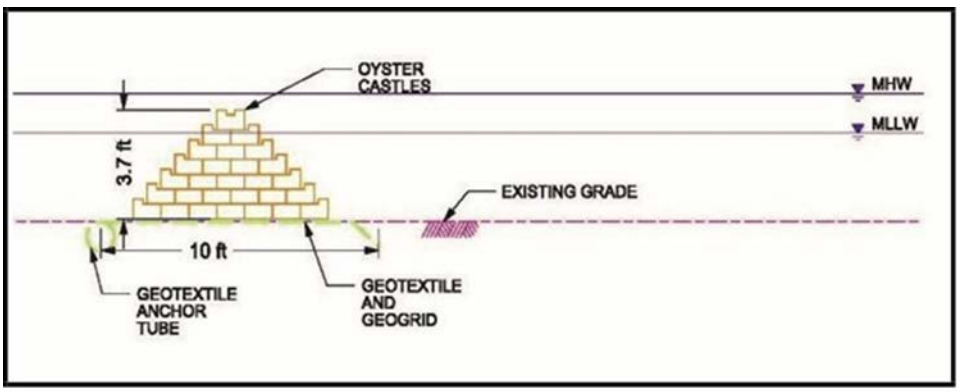


Figure 38. Typical Cross Section for Oyster Castle Breakwater.
Source: (*7*)

Therefore, the USACE study recommended the implementation of sacrificial berms in addition to the hard structures (Figure 39) for bay-facing berms or shorelines of the bay barrier islands to serve as training dikes and allow for the continued placement of dredge materials. The sacrificial berm also functions as re-nourishment mechanism to maintain the island/DMPA features.

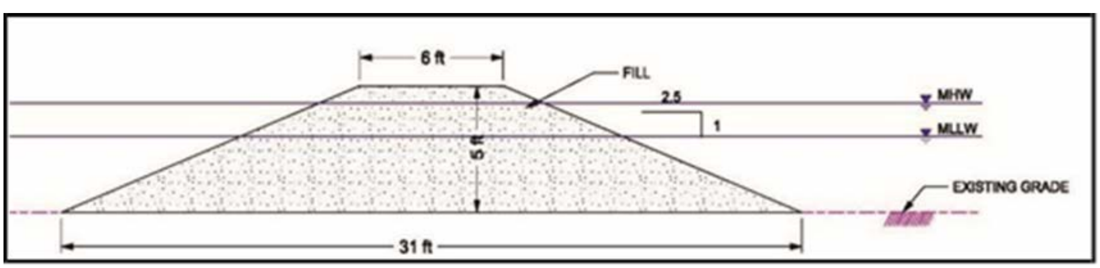


Figure 39. Typical Cross Section for Sacrificial Berm.
Source: (*7*)

DESIGN CONSIDERATIONS FOR GIWW-FACING SHORELINE PROTECTION SOLUTIONS

Rock breakwaters are recommended for GIWW-facing shore protection features along the GIWW because wave heights are typically 5 ft or less. Advantages and disadvantages of rock breakwaters include:

- Advantages of the rock breakwaters:
  - Ease and low cost of construction.
  - Flexible structure that can accommodate minor settlement or minor toe scour and still remain functional.
  - High wave erosion protection level for shoreline.
  - Allows some overtopping to aid in sedimentation of leeside for re-establishment of aquatic plants.
  - Assists in retaining deposited sediments.
  - Proven and reliable performance with minimal maintenance.
- Disadvantages:
  - If not placed correctly, could pose an indirect hazard to navigation and therefore likely require installation of aids to navigation. Breakwaters should be constructed outside the USACE GIWW right-of-way limits, so navigation in the area of the proposed breakwater should not be anticipated.
  - High quality stone sources are located a long distance from the project site resulting in higher construction costs.

The rock breakwater/dike alternative is recommended for construction as shoreline protection. Rock breakwaters provide the highest level of protection, lowest construction cost, and lowest level of maintenance cost with the lowest risk. In the McFaddin Report (*9*), the type and morphology of breakwaters were analyzed for each type of shoreline based on geometry of the shoreline to provide the biological function for marsh creation (Figure 40 and Figure 41).

Crest Elevation of Breakwater

This elevation must be established to mitigate wave erosion of the shoreline but still allow overtopping to facilitate suspended sediment accumulation behind the breakwater (during flood events), which would help in smooth cord grass establishment.

Low-Crested Breakwater Analysis

This analysis is necessary to optimize the reduction of wave energy to acceptable levels versus still allowing floodwater overtopping and sediment to be allowed to enter the backside between the breakwater and the shoreline:

- Too high = limited sediment for plant growth.
- Too low = too much energy and potential scour and continued loss of shoreline due to erosion.

Figure 40 presents an example of the rock breakwater used for the GIWW McFaddin project.

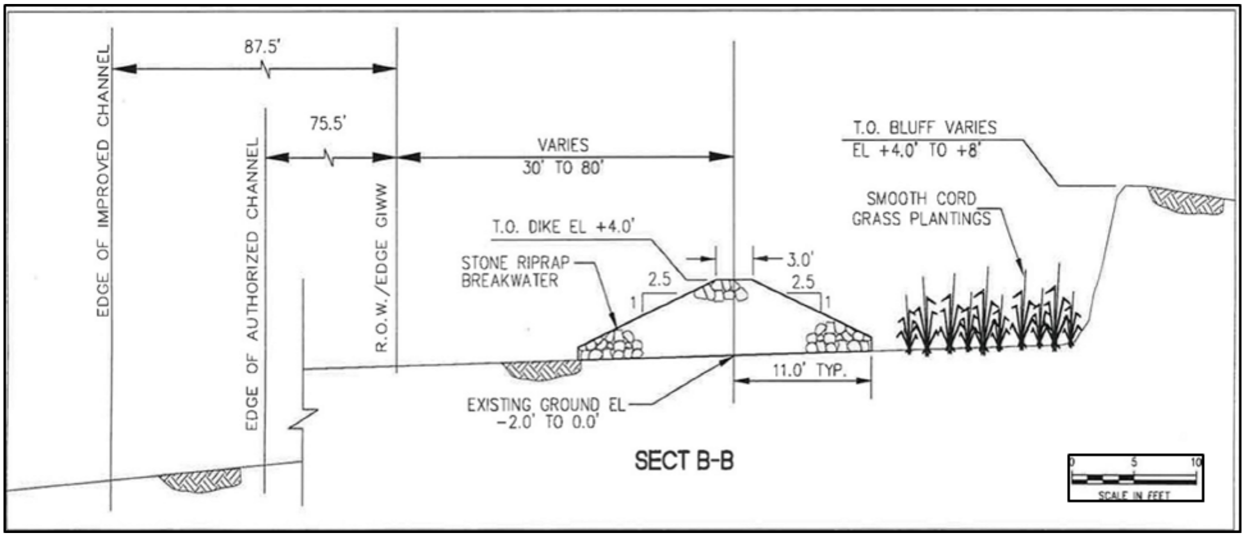


Figure 40. Cross Section of Design for Shoreline Rock Breakwater/Dike Alternative Designed for GIWW McFaddin Refuge Shoreline Protection Alternative.

Source: (9)

Figure 41. Sediment Distribution Pattern between Rock Breakwater and Shoreline at GIWW McFaddin Refuge Shoreline Protection Project Site in 2010.

Source: Google Earth

DESIGN CONSIDERATIONS FOR BAY-FACING SHORELINE PROTECTION SOLUTIONS

Rip Rap Stone Revetment/Breakwater

Rock revetments are recommended for bay-facing shorelines as a long-term shoreline stabilization alternative. These revetments are recommended for use at locations: 1) where the existing shoreline alignment is nearest to the GIWW, 2) for new recovery shorelines, or 3) for replacing existing shoreline protection infrastructure in need of repairs. Right-of-ways and sufficient space for the rock revetment/breakwater footprint is required for this protection solution.

In general, to protect shoreline features from wave and current erosion, a revetment is lower in cost than a rock breakwater. However, the application of a revetment only applies if an existing shoreline needs to be stabilized in an existing location and the shoreline stability allows for the installation of the revetment. The installation of a rip rap revetment will include foundation preparation, a geotextile filter layer, armor layer, and toe protection. The armor layer consists of graded rip rap stone with sizes specified between a minimum and maximum size. The toe protection is either a launched toe or embedded toe constructed of rip rap.

If the shoreline is to be extended farther bayward to allow placement of dredged material or to allow sediment capture from sediment transport patterns in the bay, a breakwater system should be evaluated. Different options, continuous or segmented and single or dual line concepts, should be evaluated for suitability based on the sediment transport regime and wave impacts from the bay-facing shoreline. Figure 42 shows the location of a specific segmented breakwater option applied in Pensacola Bay, Florida, to harvest sediment that moves naturally on the bay shorelines.

Figure 43 shows the details of the breakwaters. Figure 43a shows different solutions that support the sediment accumulation processes behind the breakwaters. Figure 43a also shows a subset box in yellow illustrating the location of Figure 43b, which shows a detailed diverse set of breakwater systems that can be applied to harvest sediments. The same figure shows a sand bar being accumulated behind the breakwaters.

Figure 42. Location of a Segmented Breakwater System in Pensacola Bay, Florida.
Source Google Earth

Figure 43. Segmented Breakwater Systems in Pensacola Bay, Florida.
Source Google Earth

Design Considerations

An appropriate design wave height, wave period, and water surface level are the basis for the design of a rip rap revetment cross section. The data from the water level analysis, causes of erosion analysis, and the design criteria should be used to develop the appropriate structure cross section and rip rap sizes and gradation. Rip rap armor is recommended for revetment shore protection systems located in wave environments with a significant wave height of 5 ft or less (*9*).

Construction Considerations

Selective placement of the rock is required for construction of the shoreline revetments. This placement method involves placing the rock individually with a floating crane bucket to result in a tight-fitting breakwater structure. Individual stones need to be tightly fitted to maximize contact on all sides. Smaller stone can be used to chink the voids of the larger stones. The specified gradation needs to be consistently maintained throughout the structure. Rock materials for the construction of the rip rap revetment have to be imported to the project site via flat deck barges. These barges vary in size from 2,500 to 5,000-ton capacity with drafts varying from 5 to 7 ft fully loaded.

A crane barge is required for the construction of the rip rap revetment. An average crane barge requires approximately 5 ft of water depth for its draft. The minimum distance between the crane barge centerline and the centerline of the proposed structure must be less than 75 ft. In some areas of the project, the horizontal distance from the shoreline to this water depth is greater than the reach of the barge's crane boom. This requires either dredging a barge access channel parallel to the shoreline for rock placement or off-loading rock onto another barge to decrease the draft to gain the required access to these areas. For sites similar to the McFaddin project, it is estimated that a significant amount of access channel dredging may be required for the construction of this alternative. Specifically, for the construction of the shoreline protection at the McFaddin project, the work was accomplished by loading materials and equipment from a barge onto the shore and conducting operations shore-side.

Advantages and disadvantages of rip stone revetments/breakwaters are:

- Advantages:
  - Flexible structure that can accommodate minor settlement or minor damage and remain functional.
  - Ease of construction—low technology required for installation; materials delivered by barge.
  - Ease of maintenance repairs.
  - Less wave run-up and overtopping because of the rough and open face surface.
  - Low cost of installation.
  - Highly durable when high quality stone is used.
- Disadvantages:
  - Requires use of heavy equipment.
  - High quality stone sources are located a long distance from project site that results in high material costs.
  - More susceptible to toe scour from pressure field affect than breakwater structures.

Concrete Articulated Mat Revetment

The USACE has used articulated mat revetments on the GIWW for the protection of DMPAs in EMB and West Galveston Bay. A concrete articulated mat revetment is a structure that consists of geometrically shaped pre-cast concrete blocks connected with cable or nylon cord. The mats function as a permeable shoreline armor to protect the backland from wave attack. These blocks are typically placed on a relatively well-graded, stable slope where the wave climate is slight to moderate. The blocks should be placed on top of geotextile fabric to prevent the loss of fine grained material due to wave run-up and filtration though the blocks. These articulated revetments have had significant failures due to continued scouring.

Design Considerations

Pressure fields/long period waves and wakes generated by vessels navigating through the GIWW reach along the McFaddin National Wildlife Refuge cause most of the shoreline erosion noticed in the area. Pressure fields are hydrodynamic effects caused by vessels moving in narrow/shallow waterways.

Variations in pressure within the channel cause head differentials, and hence cause long-period waves to form. Since the banks of the GIWW are relatively flat, the long-period waves run up the beach in the form of bores. These bores are predicted to run up the beach at 5 to 8 ft/second, depending on vessel dimensions, vessel speed, and channel/bank configurations. The pressure field bores can be approximately represented as 1-ft high long-period waves (bores moving 8 ft/second) and/or an 8-ft/second current moving over the structure (over the concrete blocks).

Vessel wakes could also cause some small impact, especially when combined with a rise in water level at the bank due to pressure fields. Given the distance between the vessels and the revetment, some short period vessel wake energy will be dissipated. However, it should be considered that vessel wakes 0.5 to 3 ft in height and 2 to 5 seconds in period will reach the structure. Proper foundation preparation will be required to minimize potentially large maintenance costs associated with the effects of the pressure field draw down impacts.

Given the severity of pressure field bore impacts at the revetment location, vessel wakes are less critical in the design of the concrete articulated mat revetment. Proper foundation preparation will be required to minimize potentially large maintenance costs associated with the effects of the pressure field/drawdown impacts.

Construction Considerations

For water-based construction, the crane barge laying out the concrete mat must have a minimum of 5 ft of water depth for its draft. In some areas of the McFaddin project, the horizontal distance from the shoreline to this water depth was greater than the reach of the barge's crane boom.

This required dredging a barge access channel parallel to the shoreline for mat placement in these areas or considering a land-based placement. Some land-based activities during water-based construction were required during construction for the clearing, grading, and shaping of the shoreline.

For the McFaddin project, land-based placement alternatives are the same as for rip rap stone revetments/breakwaters. Advantages and disadvantages of concrete articulated mats are:

- Advantages:
  - This method is stable in that all the blocks are connected, and to move one, you must move the surrounding blocks.
  - Structure easily contours to the bathymetry of a site.

    - Allows for the relief of hydraulic forces that take place beneath the structure.
    - Uniform surface allows for easy use by vehicles or pedestrians.
    - Open blocks allow vegetation to grow in between blocks.
    - The blocks can easily be assembled by hand.
- Disadvantages:
    - Foundation preparation is expensive, especially if fill material needs to be imported.
    - Differential settlement of structure crest and face is common for this type of structure under wave attack.
    - Wave run up and overtopping is significantly higher than that for rip rap rock structures.
    - Partial failure could result from the loss of one block, the mechanism that holds the blocks together must be maintained to prevent failure.
    - Maintenance repairs are difficult and more expensive than rubble mound structures.
    - Mats must be connected by hand; labor intensive.
    - Impact from a moving vessel would damage the foundation and cause settlement of the structure.
    - More susceptible to toe scour from pressure field affect than breakwater structures.

Reef Balls

A reef ball is an artificial reef module that mimics the structure and function of a natural reef. Reef balls are ideally suited for a wide-range of aquatic habitats even when used in engineering applications. Concrete made with special additives for reef balls that include a pH like seawater assures compatibility with marine environments and enhances its attractiveness to colonizing organisms. These basic modules and related adaptations are widely used.

Design Considerations

USACE Galveston District in cooperation with GBF has used reef balls in West Galveston Bay and other areas as shoreline protection measures. Several manufacturers provide reef balls. These devices are available in different sizes, forms, elevations, and weights.

Construction Considerations

Site and product specific analysis will be required to evaluate the constructability constraints on a site-by-site and product-by-product basis. Advantages and disadvantages of reef balls are:

- Advantages:
    - Reef balls are stable if they are anchored or connected together.
    - They easily contour to the bathymetry of a particular site.
    - Open reefs allow vegetation to grow in between holes.
    - The reefs can easily be assembled by hand or by barge.
    - Maintenance repairs are easy.
- Disadvantages:
    - Differential settlement is common for this type of device under wave attack.
    - Failure could result from the loss of one on or more reefs; the mechanism that holds the blocks together must be maintained to prevent failure.

- Impact from a moving vessel would damage the reef and cause settlement of the others.
- They tend to be susceptible to toe scour or fast sedimentation from pressure fields and sediment transport.

PROPOSED APPLICATIONS OF SHORELINE PROTECTION SOLUTIONS IN EAST MATAGORDA BAY

Priority Area

Figure 44 represents one of the priority areas where the shoreline protection measures discussed in this report could be used for the protection of the GIWW—specifically, the navigation channel turns adjacent to DMPA 102-C. This area was identified as a priority for navigation safety. Protecting this reach of the GIWW against long-fetch bay-induced wind/wave energies will significantly increase navigation safety and efficiencies and reduce navigation channel shoaling, resulting in reduction of maintenance dredging cycles. The DMPA berm or shorelines along the GIWW will require a rock breakwater as described previously. For the bay-facing berms or shorelines, combination solutions consisting of green and/or gray features may effectively provide multifaceted protection. However, these solutions should be determined case-by-case.

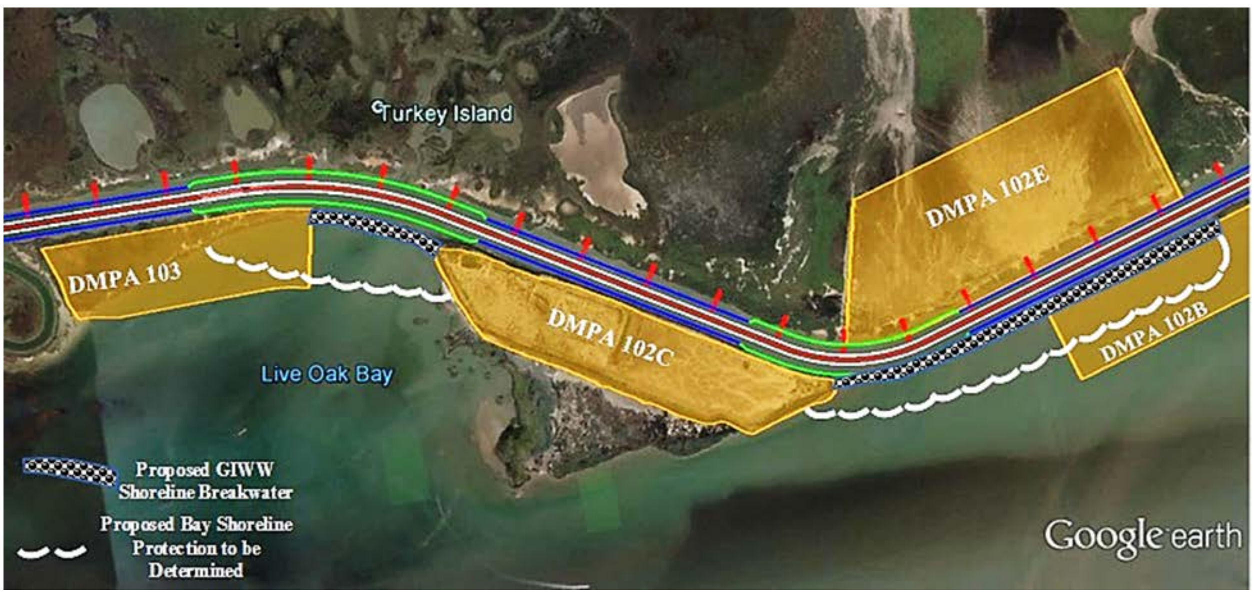


Figure 44. Potential Solutions to GIWW Turns in EMB Next to DMPA 102-C.
Note: The idea is to close the gaps between DMPAs. *Source: Google Earth and USACE DMPA Database*

The concept of a breakwater that allows for sediment accumulation behind the breakwater in combination with other protection features will enhance navigation safety within the GIWW and allow for natural sediment build-up within the DMPA that will convert to a sustainable habitat (Figure 44).

Proposed Improvement Features for the GIWW EMB Region and Associated DMPAs

DMPA proposed improvement features target the above listed priority area and address the identified interconnections between the GIWW and Bay in the EMB region and its DMPAs. There is an extended list of improvement features, considerations, and evaluation options that could be prioritized as shoreline changes are observed or storm-induced waves and shoaling or current/wave-regimes negatively impact navigation safety (see Table 18).

Table 18. Proposed Improvement Features for Evaluated Reach/DMPAs.

DMPA	GIWW-Facing		Bay-Facing	
	Issue	Feature	Issue	Feature
101	GIWW-Facing Shoreline Erosion	a) Breakwater Shoreline Protection (allowing for overtopping and sediment exchange)	Continue Monitoring Shoreline Changes	N/A
West of 101	No Elevated Land between GIWW and Bay causing Shoaling in GIWW	a) Extend DMPA 101 westward for tie-in into Existing Bay Barrier Habitat b) Evaluate the Option of Segmented Breakwaters parallel to GIWW to trap Sediment introduced through Mitchell's Cut	No Elevated Land between GIWW and Bay causing Shoaling in GIWW	a) Extend DMPA 101 westward for tie in into Existing Bay Barrier Habitat b) Evaluate the Option of Segmented Breakwaters parallel to GIWW to trap Sediment introduced through Mitchell's Cut
102-A	No Elevated Land between GIWW and Bay causing Shoaling in GIWW	a) Build up DMPA with Dredge Material b) Evaluate adding Rock Revetment/Breakwater on GIWW side post Dredging	No Elevated Land between GIWW and Bay causing Shoaling in GIWW	a) Build up DMPA with Dredge Material b) Evaluate adding Sacrificial Berm and/or Segmented Reef Balls on Bay Side
102-B	No Elevated Land between GIWW and Bay causing Shoaling in GIWW	a) Build up DMPA with Dredge Material b) Evaluate adding Rock Revetment/Breakwater on GIWW side post Dredging	No Elevated Land between GIWW and Bay causing Shoaling in GIWW	a) Build up DMPA with Dredge Material b) Evaluate adding Sacrificial Berm and/or Segmented Reef Balls on Bay Side
East of 102-C	Predominantly Water - Interconnecting Bay and GIWW	a) Extending DMPA past GIWW Curve via Dredge Material Placement. b) Evaluate adding Rock Revetment/Breakwater on GIWW side post Dredging	Predominantly Water - Interconnecting Bay and GIWW	a) Build up DMPA with Dredge Material b) Evaluate adding Sacrificial Berm and/or Segmented Reef Balls on Bay Side
102-C	Continue Monitoring of Erosion	N/A	Continue Monitoring of Erosion	N/A
Between 102-C & 103	Predominantly Water - Interconnecting Bay and GIWW	a) Extending DMPAs and connect DMPA 102-C and 103 via Dredge Material Placement. b) Evaluate adding Rock Revetment/Breakwater on GIWW side post Dredging	Predominantly Water - Interconnecting Bay and GIWW	a) Build up DMPA with Dredge Material b) Evaluate adding Sacrificial Berm and/or Segmented Reef Balls on Bay Side
103	GIWW-Facing Shoreline Erosion	a) Breakwater Shoreline Protection (allowing for overtopping and sediment exchange)	Bay-side Erosion	a) Evaluate Segmented Reef Balls or Breakwaters on Bay Side
105	Predominantly Water - Interconnecting Bay and GIWW	a) Extending DMPA past GIWW curve via dredge material placement.	Area is predominantly water only - interconnected with Bay and GIWW	a) Build up DMPA with dredge material b) Reef balls on bay side (segmented)

APPLICATIONS TO OTHER AREAS

The concepts applied to this section of the EMB can be used in East Galveston Bay and West Galveston Bay. The shoreline retreat of the GIWW is a major problem across the Texas coast. The shoreline retreat on the bay sides of the DMPAs has been accelerated in many areas due to natural and human induced processes and storms surges. As these natural land barriers have disappeared, bay sediment processes are now affecting the efficiency of the GIWW. The methods proposed here can be used in any section of the GIWW on the northern bays: EMB, West Galveston Bay, and East Galveston Bay.

POTENTIAL SEDIMENT SOURCES

The eastern portion of EMB is located close to two Gulf of Mexico cuts (inlets) that historically have been a source of sediment to the bay. Millions of cubic yards of sediment have been deposited into this section of the bay since the construction of the GIWW in the 1940s as observed by historical aerial photos. There are sediments available for the reconstruction or enhancement of the DMPAs or any land barrier that may be considered as a solution to the sedimentation of the GIWW. These sediments are abundant on the eastern side of the bay.

Sediments coming from the north side of the GIWW through the bayous will continue to be a problem. The main sources of sediment are Caney Creek, Boggy Bayou, Turkey Island Slough, and Live Oak Bayou. Also, the shoreline retreat of the land next to the GIWW will continue to be a source of sediment for the enhancement, protection, and creation of potential land barriers and DMPAs.

One of the objectives of this study was to present sustainable shoreline protection solutions that can harvest or accumulate sediments within the perimeters of the DMPAs. Sediment is the substrate of the coastal habitats (submerged habitats or habitats above the tides). The natural accumulation of sediment should be one of the goals of the protection or restoration of the DMPAs. The harvesting of sediment moving in the system will reduce the dependency on dredging to build natural habitats using BUDMs or dedicated dredging.

The natural resource groups interviewed for this study suggested that any habitat is a good habitat once the sediment has been naturally harvested. The sustainability of the DMPAs will depend on how fast new harvested sediment can restore the retreating shorelines. It took more than 10 years after the construction of the GLO-USFWS McFaddin Refuge shoreline restoration project to harvest enough sediment to build sustainable marshes behind the structures.

As presented earlier, Ravens et al. (*7*) discussed the main reason for shoreline retreat along the shorelines of Galveston Bay (and other bays), including the shorelines of DMPAs on the GIWW and bay sides. The main reason for shoreline retreat is the lack of sediment being returned to the shorelines. Sediment is moving along the shorelines through bay littoral processes or by suspension processes, but sediments are not being accreted in the shoreline system.

For immediate solutions, enough sediment is available in DMPAs 102-C, 102-D, and 102-E if shoreline and energy protection solutions are needed to restore or expand DMPAs to protect the EMB GIWW turns.

PROGRAMMATIC APPROACH TO THE SUSTAINABILITY OF THE DMPAS

Programmatic approaches to contribute to the sustainability of DMPAs along the GIWW can be classified under three primary needs: 1) finance, 2) sediment, and 3) policy.

Financial resources are necessary to develop and implement project features. Leveraging of funding sources with other contributed financial resources is an ideal approach to cost share project development and implementation across various federal, state, and/or local programs. Contributed financial resources could be provided in the form of cash, real property, and/or technical work-in-kind services contributions.

In many instances, ensuring the viability and sustainability of DMPA function and features requires initial placement of large volumes of sediments, followed by future placement of sediments to account for short- and long-term erosion and/or elevation losses. GIWW maintenance dredged material would be the primary sources for sediments; however, DMPAs requiring larger volumes of sediment beyond the quantities generated by routine maintenance dredging may require identifying and designating in-bay areas as sources for sediment harvesting.

Implementation of DMPA and navigation safety improvements are tied to federal and state policies that govern the extent that federal and state agencies may be involved in the modification of DMPA and navigation channel features.

The three programmatic approach categories are further discussed in the following sections.

Financial Resources

Federal Financial Resource

The Texas Gulf Intracoastal Waterway Master Plan (*1*) described the available federal (USACE) authorities and programs available for the GIWW and its infrastructure. Most of the funding is awarded on a nationally competitive basis. Under USACE's Continuing Authorities Program (CAP), certain authorities provide programmatic approaches and responses to the problems that affect the GIWW and the DMPAs. The language used here can be seen in more detail in the Master Plan. Pertinent individual CAP authorities include:

- **Section 204 (Regional Sediment Management) of the Water Resources Development Act (WRDA) 1992, as amended (Section 204) — Implementing Restoration Projects in Connection with Dredging.**
  Section 204 is the most commonly used authority for BU projects using dredged material. It allows the USACE (as part of a regional sediment management plan) to select a disposal method that is not the least-cost option if the incremental costs are deemed reasonable to the environmental benefits to be achieved. Section 204 funding is intended for projects that use dredged material to 1) reduce storm damage to property, 2) protect, restore, and create aquatic and ecologically related habitats, including wetlands, and 3) transport and place suitable sediment. No benefit-cost ratio is required, but the quantity and quality of the protection, restoration, and creation must be reconciled against costs associated with working beyond the dredging project's base plan. Costs above the base

plan are funded via cost-sharing, with 65 percent of costs funded from federal sources and 35 percent of costs funded from non-federal sources (i.e., a local sponsor). The non-federal sponsor must pay 100 percent of all operations, maintenance, and replacement costs once the project is constructed. The federal share of the above-base cost per project is capped at $5 million, with an annual appropriation limit of $30 million for all such projects. Local sponsors must be legally constituted public bodies. When Congress amended Section 204 in WRDA 2007, it also listed 11 regional sediment management priority areas, with Galveston Bay identified as one of the priority areas. As such, the DMPAs located within Galveston Bay and currently functioning or proposed to function as habitat or storm damage reduction features may be eligible for Section 204 funds.

- **Section 206 (Aquatic Ecosystem Restoration) of WRDA 1996.**
  Section 206 authority is intended to restore degraded ecosystem structure, function, and dynamic processes, usually through manipulation of hydrology. Projects must improve the quality of the environment, be in the public interest, and be cost effective. No relationship to a USACE project is required. No benefit-cost ratio is required, but the project's ability to improve the environment must be qualified and quantified. The federal share of the above-base cost per project is capped at $5 million, with an annual appropriation limit of $25 million for all such projects. Cost sharing allows for 65 percent federal funding and 35 percent non-federal funding. Work in-kind can constitute part or all the non-federal 35 percent funding for the project, with the exception that work-in-kind is not applicable to the feasibility study phase of the project.

  The non-federal sponsor (in this case TxDOT) will be responsible for 100 percent of operations, maintenance, and replacement costs once the project is constructed. Local sponsors must be legally constituted public bodies. Because this authority relates to aquatic ecosystem restoration, proposals associated with shoreline nourishment or erosion protection will usually not qualify under this authority unless aquatic ecosystem benefits are clearly demonstrated as a result. This authority enjoys a high demand within both coastal and non-coastal USACE districts and, consequently, there is strong nationwide competition for the limited funds appropriated each year.

- **Section 1135 (Project Modification for the Improvement of the Environment) of WRDA 1996, as amended.**
  Section 1135 is intended for restoration of degraded ecosystem structure, function, and dynamic processes. Categories include modification of existing USACE projects, restoration where existing USACE projects contributed to environmental degradation, or restoration where construction or funding by the USACE or another federal agency contributed to degradation of the environment. All Section 1135 restoration projects must have some connection to a USACE project. No benefit-cost ratio is required, but the project's ability to improve the environment must be qualified and quantified. No more than $5 million of project costs may come from federal funding, and there is an annual appropriation limit of $25 million for all such projects. Cost sharing allows for 75 percent federal funding and 25 percent non-federal funding. The non-federal sponsor will be responsible for 100 percent of operations, maintenance, and replacement costs once the project is constructed. Non-federal sponsors may be public agencies, national non-profit groups, and private interests. DMPAs may be eligible for Section 1135 funding in the

case where a DMPA has served concurrently as an ecosystem structure and has experienced degradation induced by operational elements of a USACE project.

NOTE: One downside of working with the authorities listed above is the uncertainty of the federal budgeting process. Use of these authorities requires advanced planning to allow the USACE to include the funding in its budgeting process, which is normally two years in advance.

TxDOT's Role in BUDM Projects

Under Title 43, Part 1, Chapter 2, Subchapter F, Rule §2.132 of the Texas Administrative Code (TAC), TxDOT can participate in BU projects that use dredged material from the main channel of the GIWW-T. TxDOT's role is limited to the acquisition of property to be used as a BU site. Such projects are initiated because of proposals submitted by the USACE. If the commission decides to act on a disposal proposal or BU proposal related to the GIWW-T, TxDOT will assist Corps with the preparation of the environmental review document under 42 U.S.C. §§4321 et seq. and applicable federal rules. TxDOT will also assist with any public participation process that the USACE conducts.

If the commission decides to participate in the cost of a project to BUDM that requires the acquisition of an interest in real property, the procedures it must follow are set out in the TAC. As part of this process, the commission will establish an eligible cost of the proposed BU project by calculating the total estimated cost of the project in excess of the established federal standard for dredged material disposal. As a rule, the department's financial participation in the project will not exceed 50 percent of eligible cost. Details of the BUDM projects are presented in Kruse et al. (*1*).

The commission may authorize participation at levels exceeding 50 percent if the members determine that the additional participation will result in extraordinary environmental or economic benefits, or the costs are reasonably comparable to the costs of providing property to accommodate traditional upland disposal. Department funding may not be used for maintenance or operation of a BU project. This authority would be very appropriate if partnerships with stakeholders can be developed.

Sediment Resources

Sediment resources are discussed in detail in the previous section titled Potential Sediment Sources.

Policies

Beneficial Use of Dredged Material

A key element to allow for the improvements and sustainability of DMPA features is to foster the BUDM for DMPA habitat enhancement and shoreline stabilization. As discussed earlier in the Financial Resources section of this report, the most commonly used authority for BUDM is Section 204 of WRDA 1992, as amended by Section 2037 of WRDA 2007, and is implemented under the USACE's CAP. Although the authority is applicable to both construction and maintenance dredging projects, it is mostly used with maintenance dredging projects. This authority allows the incremental costs for protecting, restoring, or creating aquatic and ecologically related habitat to be cost shared at 65 percent federal and 35 percent non-federal. The federal share per project is not to exceed $5 million, and the program's annual appropriation is limited to $30 million per year for all such projects.

WRDA 2007 Section 2037 changed the BUDM Section 204 authority, by re-naming the authority as "Regional Sediment Management," recognizing the need to manage sediment resources through regional strategies. With this language change, USACE is now authorized to develop, at federal expense, regional sediment management plans in cooperation with appropriate federal, state, regional, and local agencies, for sediment obtained through construction, operation, or maintenance of an authorized federal water resources project. The regional sediment management plans are expected to identify projects for transportation and placement of sediment to reduce storm damages to property and protect, restore, and create aquatic and biologically related habitat (including wetlands). The revised language also authorizes USACE to cooperate with the state in preparing a comprehensive state or regional sediment management plan within the boundaries of the state and submitting to Congress reports and recommendations with respect to appropriate federal participation in carrying out the plan.

Therefore, development of a regional sediment management, or BUDM plan, for the improvements and sustainability of DMPAs that concurrently function to provide biological habitat and/or storm damage protection are potentially eligible to receive Section 204, as amended, funds.

However, as noted earlier, the Section 204 program's annual authorized appropriation capacity is limited to $30 million per year, with projects competing for the appropriated funds at a national level. As such, the availability of Section 204 funds may be limited for any given year.

Beneficial Use of Dredged Material – Texas GIWW DMPAs

To address the appropriations limitations of the aforementioned Section 204 program, a new federal legislative authority for BUDM specifically tailored to the Texas GIWW DMPAs could be considered through a future WRDA, similar to the Louisiana Coastal Area Beneficial Use of Dredged Material program as authorized by WRDA 2007. The authorized intent of the Louisiana Coastal Area Beneficial Use of Dredged Material program is to cost-effectively increase the BUDM from federally maintained waterways at a total cost of $100 million, with program funds to be cost-shared at 65 percent federal and 35 percent non-federal, consistent with Section 204 cost-sharing.

Broader support for a dedicated BUDM program for the Texas GIWW DMPAs could be achieved by expanding the proposed legislative authorization to incorporate the coastal restoration needs and programs of the Texas GLO and TPWD. An advantage of such an expansion would be the ability to promote the leveraging of resources and programs among GLO and TPWD.

Section 5 Navigation Channel Bend Easing

Under Section 5 of the River and Harbors Act of 1915, USACE has discretion with respect to modification of completed navigation projects to better serve navigation without requiring new authorization. This discretion extends to USACE's authority to increase dimensions of navigation channels beyond those specified in project authorization documents at entrances, bends, sidings, and turning places as necessary to allow free movement of vessels. Under this authority, USACE is permitted to study the need for such modifications with operations and maintenance funding. For GIWW navigation channel turns and bends exposed to significant wind/wave energies, the Section 5 authority may be considered as a mechanism to modify bends bends/turns for navigation safety purposes.

Financial Resources That Can Be Leveraged for Ecological Restoration and Infrastructure

The federal and state stakeholders and non-profit organizations that participated in the needs assessment for the environmental benefits of the restoration of DMPAs demonstrated that these groups are interested in the sustainability of the DMPAs as part of the coastal natural resources and habitats of Texas. According to their inputs, DMPAs are substrate for habitats. The restoration of DMPAs or the protection of the shorelines of the GIWW is connected to natural ecosystems that are being affected by barge waves, bay waves and energies, and other processes such as relative sea level rise. The DMPAs act as a natural protection to these ecosystems, mainly those on the north side of the GIWW. Some of the mentioned groups own or manage natural resource areas that are being affected by the mentioned processes on the GIWW (TNC, TPWD, GBF, USFWS, etc.).

The restoration of DMPAs or the protection of the GIWW shorelines can be combined with habitat restoration efforts and partnerships can be developed under those ecological and protection of the natural resources principles. Although TxDOT and USACE have their own sources of funding for the restoration of the DMPAs, other sources of funding can be incorporated into these efforts. This study has provided a list of these funding sources as leveraging resources for the management and sustainability of the DMPAs and its natural resources involved.

The Deep Water Horizon Oil Spill Settlement Funds

The Deep Water Horizon (DWH) oil spill began with the explosion of the Macondo exploratory well off the coast of Louisiana on April 20, 2010, causing one of the largest oil spills in American history. The DWH oil spill and its aftermath created a unique set of opportunities for the funding of Gulf of Mexico restoration projects. The funds will be paid by the Responsible Parties for the spill as natural resource damage fines stemming from Clean Water Act violations or criminal penalties (*10*). From this tragic event, Texas has an opportunity to access three funding sources to be applied toward natural resources and economic restoration and recovery across the Texas Gulf Coast region (*11*).

These funding sources are collectively referred to in this document as the "Texas RESTORE Program," and include the following coastal restoration funding sources:

- Resources and Ecosystems Sustainability, Tourist Opportunities and Revived Economies of the Gulf States Act of 2012 (*10*).
- National Fish and Wildlife Foundation (NFWF) Gulf Environmental Benefit Fund (GEBF).
- Natural Resources Damage Assessment (NRDA).

In 2014, the State of Texas activated RestoreTheTexasCoast.org, a dedicated online resource that serves as a single portal to submit project proposals for funding consideration by the three Texas RESTORE Program coastal restoration funding sources.

The following sections summarize each coastal restoration funding source, including information on project eligibility requirements, review criteria, and objectives.

RESTORE Act

RESTORE Act Funding Categories

There are five buckets of funds designated under the RESTORE Act:

- **Bucket 1.** Thirty-five percent of the fines collected will be allocated to the five Gulf States in equal shares for ecological and economic restoration. Bucket 1 funds can be used for restoration; mitigation of damage to fish, wildlife, and natural resources; workforce development and job creation; improving state parks in areas impacted by the oil spill; infrastructure projects benefitting the economy; coastal flood protection; and promotion of tourism and seafood in the Gulf Coast region. There is $65.45 million in Bucket 1 funds currently available to Texas. Over the next 15 years, Texas will receive an additional $308 million from Bucket 1 (*11*).
- **Bucket 2.** Thirty percent of the fines collected will be allocated to the Gulf Coast Ecosystem Restoration Council (Gulf Council). The Gulf Council is an organization created with representatives from the five Gulf Coast states and federal representatives (Federal Council) from the Secretary of Interior, Secretary of Army, Secretary of Commerce and Agriculture, the U.S. Environmental Protection Agency (EPA) Administrator, and the Secretary of the Coast Guard. The projects funded under Bucket 2 will be selected under a competitive process based on a prioritized list of specific projects approved by the Gulf Council. There is $26.3 million in Bucket 2 funds currently available to Texas. Over the next 15 years, an additional $1.32 billion will be distributed by the Gulf Council on a competitive basis to the Gulf states and Federal Council members (*11*).
- **Bucket 3.** Thirty percent of the fines collected will be allocated to the five states using on an impact-based formula in the RESTORE Act that considers the overall number of miles of shoreline in each state compared to the number of shoreline miles that experienced oiling, the inverse proportional distance from the DWH rig, and the average population of coastal counties bordering the Gulf of Mexico. There is $21 million in Bucket 3 funds currently available to Texas. Over the next 15 years, Texas will receive an additional $100.5 million from Bucket 3 (*11*).
- **Bucket 4.** Five percent of the fines collected will be to the Gulf Coast Ecosystem Restoration Science, Observation, Monitoring and Technology Program (RESTORE Act

Science Program). The mission of the RESTORE Act Science Program is to carry out research, observation, and monitoring to support, to the maximum extent practicable, the long-term sustainability of the ecosystem, fish stocks, fish habitat, and the recreational, commercial, and charter-fishing industry in the Gulf of Mexico (*12*).

- **Bucket 5.** Any interest on the Trust Fund holding the fines will be divided evenly between the Gulf Coast Ecosystem Restoration Science Observation, Monitoring, and Technology Program and Centers of Excellence research grants. There is $21 million in Bucket 5 funds currently available to Texas. Over the next 15 years, Texas will receive an additional $22 million from Bucket 5 (*11*).

RESTORE Act Funding Priorities

In general, RESTORE Act funding eligibility and priorities include projects that primarily benefit the Gulf Coast Region and that provide for one or more of the following project activities:

- Restoration and protection of the natural resources, ecosystems, fisheries, marine and wildlife habitats, beaches, and coastal wetlands of the Gulf Coast Region.
- Mitigation of damage to fish, wildlife, and natural resources.
- Implementation of a federally approved marine, coastal, or comprehensive conservation management plan, including fisheries monitoring.
- Workforce development and job creation.
- Improvements to or on state parks located in coastal areas affected by the DWH oil spill.
- Infrastructure projects benefitting the economy or ecological resources, including port infrastructure.
- Coastal flood protection and related infrastructure.
- Planning assistance.
- Administrative costs of complying with the RESTORE Act.
- Promotion of tourism in the Gulf Coast Region, including recreational fishing.
- Promotion of the consumption of seafood harvested from the Gulf Coast Region.

NOTE: The restoration of the DMPAs and the ecosystems connected to them and maritime activities qualify for this funding source.

RESTORE Act Selection Criteria

According to the RESTORE Act scoring criteria displayed in Table 19, the categories described below are some areas where the restoration of DMPAs and its habitats may help TxDOT to qualify for this funding source (*10*). Although the GIWW is considered federal infrastructure, the DMPAs are considered state environmental assets due to the habitats that have been developed around them.

Table 19. RESTORE Act Scoring Criteria.

Priority Category	Points	Priority Activities
Economic Benefits	25	• Job Creation and Retention • Benefits Economy through Infrastructure Projects • Promotes Economic Resiliency • Beneficial Impacts to Local and Regional Economy • Promotes Tourism, Eco-Tourism, Recreation and Wildlife Tourism • Promotes Gulf Seafood Marketing
Environmental Benefits	25	• Restores, Conserves and Preserves Habitat • Protects or Enhances Rare and Threatened Resources • Replenishes and Protects Living Coastal & Marine Resources • Restores and Protects Water Quality and Quantity • Contributes to Landscape Level Environmental Enhancement
Comprehensive Factors	20	• Complements Other Projects • Promotes Community Resiliency • Promotes Ecological Resiliency • Part of a Federal, State or Local Coastal Plan • Promotes Recreational, Historical, Cultural and Educational Uses
Project Logistics	20	• Project Readiness and Planning • Likelihood of Success • Long-term Operation and Management • Success Criteria and Monitoring • Based on Best Available Science • Cost-Effectiveness
Community Engagement	20	• Public Support and Participation • Financial Partners and Funding

Note: The issues connected to the restoration of the DMPAs are underlined.

National Fish and Wildlife Foundation Gulf Environmental Benefit Fund

NFWF GEBF was established in early 2013 because of two plea agreements resolving the criminal cases against BP and Transocean after the 2010 DWH oil spill. The agreements direct a total of $2.544 billion to NFWF over a five-year period. These funds are to be used to support projects that remedy harm to natural resources (habitats and species) where there has been injury to, or destruction of, loss of, or loss of use of those resources resulting from the oil spill (*13*).

NFWF GEBF Priorities

NFWF GEBF program funding priorities include, but are not limited to, projects that contribute significantly to the following natural resource outcomes (*13*):

- Restore and maintain the ecological functions of landscape-scale coastal habitats, including barrier islands, beaches, and coastal marshes, and ensure their viability and resilience against existing and future threats, such as sea level rise.
- Restore and maintain the ecological integrity of priority coastal bays and estuaries.
- Replenish and protect living resources including oysters, red snapper, and other reef fish, Gulf Coast bird populations, sea turtles, and marine mammals.

A list of potential actions that might be considered to advance these outcomes can be found at the following NFWF GEBF website: http://www.nfwf.org/gulf/Pages/fundingpriorities.aspx.

NFWF GEBF Selection Criteria

According to NFWF (*13*), GEBF program funds that are available for projects in Alabama, Florida, Mississippi, and Texas may only be used to support projects that remedy harm to natural resources (habitats and species) of a type that were impacted by the DWH oil spill. Additional evaluation and selection criteria emphasize projects that:

- Advance priorities in natural resource management plans, such as those called for under the RESTORE Act.
- Are within reasonable proximity to where impacts from the oil spill occurred.
- Are cost-effective and maximize environmental benefits.
- Are science-based.
- Produce measurable and meaningful conservation outcomes to habitats and species of a type impacted by the oil spill.

Natural Resources Damage Assessment

NRDA is a scientific and legal process to determine natural resource damages and hold responsible parties accountable. Certain government agencies are charged with trusteeship of natural resources and act on behalf of the public with Responsible Parties to assess damages and implement restoration associated with the oil spills. In Texas, TPWD, GLO, and Texas Commission on Environmental Quality act as state natural resource trustees. There are also federal agencies designated as trustees for natural resources, including NOAA and the Department of the Interior. For the DWH NRDA, EPA and U.S. Department of Agriculture are also designated as trustees. Federal law requires the responsible parties to compensate for the injury to natural resources caused by the DWH oil spill (*10*).

In April 2016, a negotiated settlement among the Trustees and BP (Responsible Party) to address natural resources injuries stemming from the DWH oil spill was approved in the amount of $8.8 billion (*14*).

For Texas, NRDA early restoration funding for projects has amounted to $50.35 million to date. An additional $238 million will be available for NRDA projects in Texas. State and federal trustees for NRDA-DWH will distribute a plan to distribute those funds (*11*).

The following restoration types are prioritized for current Texas NRDA restoration planning efforts: 1) restore and conserve wetland, coastal, and nearshore habitats; 2) restore water quality through nutrient reduction (nonpoint source); and 3) replenish and protect oysters.

NRDA Priorities

The NRDA Trustees have prepared and finalized a Programmatic Damage Assessment and Restoration Plan and Programmatic Environmental Impact Statement (The Plan) (*15*). The Plan provides guidance for identifying, evaluating, and selecting future restoration projects. The Plan identifies five priority goals to achieve restoration of Gulf Coast region resources. Listed below are the Plan's priority goals:

- Provide for monitoring, adaptive management, and administrative oversight to support restoration implementation.
- Restore and conserve habitat.
- Restore water quality.
- Replenish and protect living coastal and marine resources.
- Provide and enhance recreational opportunities.

NRDA Selection Criteria

Selection of projects to be funded by NRDA-DWH will be driven by project work elements that offer to restore wetlands and other coastal habitats, reduce nonpoint source pollution, and restore coastal and marine resources injured by the DWH oil spill, such as oysters, birds, and sea turtles. NRDA-DWH funds are allocated to 13 different restoration types to achieve the priority goals as outlined in The Plan. The 13 restoration types that address a broad range of impacts at both regional and local scales (*16*) include:

- Wetlands, coastal and nearshore.
- Habitat projects on federally managed lands.
- Nutrient reduction.
- Water quality.
- Fish and water column invertebrates.
- Sturgeon.
- Submerged aquatic vegetation.
- Oysters.
- Sea turtles.
- Marine mammals.
- Birds.
- Mesophotic and deep benthic communities.
- Provide and enhance recreational opportunities.

NOTE: The underscored restoration types are connected to the protection of DMPAs in parallel to restoration of habitats. The creation or restoration of the GIWW DMPAs should be part of the restoration and enhancement of specific coastal habitats. A key consideration for selection of Texas NRDA projects will be features that protect and restore federal and state-listed threatened and endangered species. Specifically, GIWW DMPAs have been connected to specific habitats for piping provers, whooping cranes, and red knots. Restoring DMPAs will enhance marsh habitats, seagrasses, and bird habitats. Shoreline solutions on the bay sides can include LS and oyster reefs. Partnerships with natural resources groups will allow TxDOT to reach out to these funding sources in a win-win situation where habitats are enhanced and restored and the DMPAs are protected.

GLO Coastal Erosion Planning and Restore Act

The purpose of the CEPRA Program is to implement coastal erosion response projects and related studies to reduce the effects of and to understand the processes of coastal erosion as it continues to threaten public beaches, natural resources, coastal development, public infrastructure, and public and private property. Under CEPRA, GLO implements erosion response projects and studies through collaboration and a matching funds partnership with federal, state, and local governments, non-profit organizations, and other potential project partners. (*17*)

If the legislature appropriates funding, the CEPRA program provides funding on a biennial basis for the following types of projects and studies, with priority given to projects that include construction of an erosion response solution during the biennium. The underlined types in the list below apply to the protection of DMPAs having TxDOT as a direct applicant or as a partner in the application for these funds:

- Beach nourishment on both Gulf of Mexico and bay beaches.
- <u>Shoreline stabilization.</u>
- <u>Habitat restoration and protection.</u>
- Dune restoration.
- <u>BUDMs for beach nourishment, habitat restoration, etc.</u>
- Coastal erosion related studies and investigations.
- <u>Demonstration projects.</u>
- Structure relocation and debris removal.

Several of these types of solutions can be used to justify funding through CEPRA for the sustainability of the DMPAs and the habitats adjacent to them. Several projects on the shorelines of the GIWW have been developed using CEPRA funds. These projects include McFaddin Refuge-GIWW shoreline protection project, Mad Island shoreline protection project, and Port Aransas-GIWW shoreline protection project.

Gulf of Mexico Energy Security Act of 2006

This grant program will be administrated by GLO and will include the Phase II of the Gulf of Mexico Energy Security Act (GOMESA II) funding source, which is already available and is anticipated to end in 2055, for projects that benefit restoration, conservation, and hurricane protection. The processes and protocols to apply for GOMESA funds have yet to be established for Texas.

As reported under the Bureau of Ocean Energy Management (*18*), GOMESA (Public Law 109-432) established permanent sharing of federal revenues from oil and natural gas leasing and production on the Gulf of Mexico Federal Outer Continental Shelf with the states of Alabama, Mississippi, Louisiana, and Texas and their Coastal Political Subdivisions (CPS). Under the law, 50 percent of offshore drilling royalties is directed to the U.S. Treasury, 37.5 percent goes to Alabama, Louisiana, Mississippi, Texas, and the CPS, and the remaining 12.5 percent is allocated to the Land and Water Conservation Fund (LWCF). GOMESA funds are to be used for coastal conservation, restoration, and hurricane protection.

The GOMESA statute provided for two phases of revenue sharing. Revenues from a subset of leases were shared beginning with the 2009 disbursements under Phase I of GOMESA. For GOMESA II, a revenue sharing cap of $500 million per year for the four Gulf producing states (GPS), their CPS and the LWCF applies from fiscal years 2017 through 2055. GOMESA II revenues are primarily dependent on the prices of crude oil and natural gas; therefore, annual revenues to be shared with the GPS and their CPS are highly variable. Of the shared revenue, 75 percent (maximum $375 million) is payable to the four GPS and their 42 CPS, and 25 percent (maximum $125 million) to the LWCF. Of the share to the states, 80 percent is to be paid directly to the GPS themselves while the remaining 20 percent directly to the CPS.

TxDOT, as a state agency, qualifies to leverage GOMESA funds with state funds for the protection of the habitats or other public infrastructure available on the DMPAs. The reconstruction of DMPAs can also be justified as a hazard protection for infrastructure or natural resources areas located inland of the area of interest.

CHAPTER 5: APPLICATION OF FINDINGS TO OTHER AREAS

INTRODUCTION

The conditions around the entire set of GIWW placement areas are not the same throughout the entire Texas coast. Some GIWW placement areas are now in a critical stage for the protection of navigation safety. Other regions will become critical in the future since wave action and shoreline retreat will continue to be strong. As part of this research project, researchers developed a tool to enable analysts to apply the findings of this research to a broader set of potentially critical areas along the GIWW.

To be relevant and useful, such a tool must be able to evaluate various feasible solutions based on consideration of multiple criteria such as lifecycle costs, safety, and environmental sustainability. Due to the limitations of the existing tools for decision-making processes related to assessing the sustainability of placement areas, there is a need for quantitative analytical tools that incorporate various economic, technical, and environmental criteria to assist in decision-making processes. To this end, researchers used the AHP method to develop a tool to facilitate the use of the information collected in this study in formulating the decision-making problem (i.e., objectives, strategies, structural alternatives, and criteria). The tool is spreadsheet-based to provide flexibility to add and modify the criteria and alternatives for other areas.

ANALYTIC HIERARCHY PROCESS

AHP is a structured technique enabling multicriteria decision-making. The AHP organizes various criteria into an orderly, interrelated pairwise structure. A hierarchy serves to combine alternatives, criteria, and goals and represent the structure of the problem in an intuitive way.

Figure 45 illustrates AHP. It is a structured technique for organizing and analyzing complex decisions and has been successfully adopted in various transportation decision-making problems. The approach used in this study specifies whether each criterion favors a specific solution and then assigns a score for each alternative in each criterion on a scale of 1–9 where 1 represents low significance and 9 high significance.

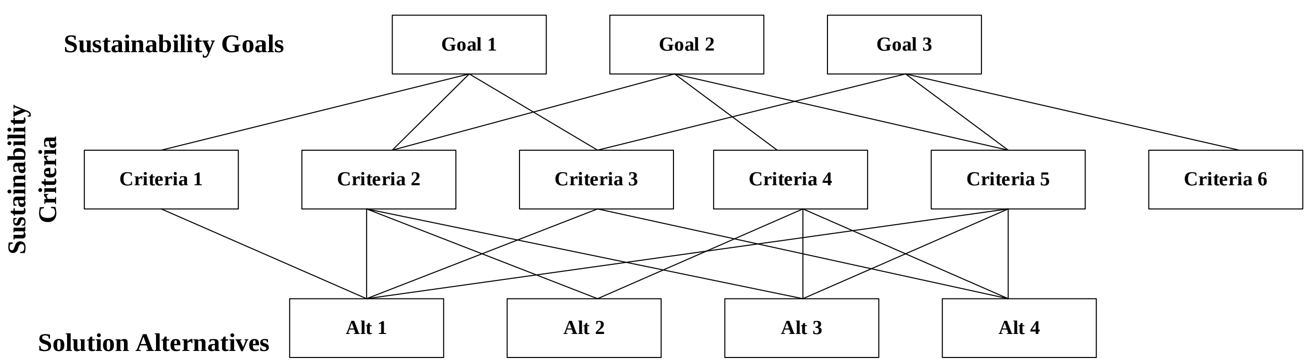


Figure 45. Schematic Structure of AHP for Evaluation of Feasible Solutions.

In simple terms, the tool performs the following functions:

1. Establishes a hierarchical structure that starts with a goal, criteria, subcriteria, and alternatives by decomposing the decision problem.
2. Collects data from experts or decision-makers corresponding to the hierarchical structure.
3. Organizes pairwise comparisons of various criteria.
4. Calculates relative weights based on the judgement of subject matter experts.
5. Checks the consistency ratio, which is a measure of how consistent judgments are across a set of choices.
6. Identifies highest-ranking alternatives.

Table 20 shows the feasible solutions that have been identified for placement area restoration or strengthening.

Table 20. Feasible Alternatives for Placement Area Restoration or Strengthening.

Alternatives	Descriptions
Vegetable only	Roots hold soil in place to reduce areas and breaks small waves.
Edging	Structure to hold the toe of existing or vegetated slope in place. Protects against shoreline erosion.
Sills	Parallel to existing or vegetated shoreline, reduces wave energy and prevents erosion. A gapped approach would allow habitat connectivity, greater tidal exchange, and better waterfront access.
Sediment replenishment	Large volume of sand added from outside source to an eroding beach. Widens the beach and moves the shoreline seaward.
Sediment replacement and vegetation	Helps anchor sand and provide a buffer to protect inland area from waves, flooding, and erosion.
Breakwater	Offshore structure intended to break waves, reducing the force of wave action and encourages sediment accretion. Can be floating or fixed to the ocean floor, attached to shore or not, and continuous or segmented. A gapped approach would allow habitat connectivity, greater tidal exchange, and better waterfront access.
Groin	Perpendicular, projecting from shoreline. Intercept water flow and sand moving parallel to the shoreline to prevent beach erosion and break waves. Retain sand placed on beach.
Revetment	Lays over the slope of a shoreline. Protects slope from erosion and waves.
Bulkhead	Parallel to the shoreline, vertical retaining wall. Intended to hold soil in place and allow for a stable shoreline.
Seawall	Parallel to shoreline, vertical or sloped wall. Soil on one side of wall is the same elevation as water on the other. Absorbs and limits impacts of from land.

Based on the literature, the primary criteria for placement area alternatives evaluation include economic factors, technical factors, and environmental factors. For this project, a set of 11 criteria is used that address these factors. Table 21 shows the criteria considered for the assessment of solutions for placement areas.

Table 21. Evaluation Criteria for Sustainable Placement Areas.

Criteria	Description
Life-cycle costs	This criterion assesses the unit costs that include initial investment for construction and the cost for sediment dredged to protect and restore degraded DMPAs and habitats within investigated areas. Sedimentation on the channel will increase the costs for maintenance.
Length of coastal protection	This factor affects the post construction monitoring and operations (i.e., ease of management).
Availability of sediment supply	Sediment supplied by some coastal rivers and the continental shelf has naturally diminished because of climatic changes and adjustments of the inner shelf profile. Today the only remaining source of sediment for many coastal compartments is local erosion of nearby beaches and bluffs.
Quality of the sediment materials	Sediments are an essential component of marine ecosystems and should be considered a resource of high ecological and socioeconomic value. This criterion evaluates the sediment and dredged materials for individual compounds and chemical class.
Long-term durability	This criterion is based on the structure design and the sediment volume potentially available as beneficial-use of dredged material for habitat restoration. The sediment sources available for harvesting to protect and restore degraded DMPAs and habitats are important to long-term durability of shorelines.
Navigation safety	This criterion evaluates the capability of reducing sedimentation and energy for safe and efficient navigation such as eliminating sharp bends and reducing channel length. Sediment movements are the key and decisive factors for navigation safety.
Wave energy dissipation	This is wave transformation in the navigation channels and is measured from the Steady-state spectral WAVE model. Stable and optimal shoreline structures are beneficial for wave energy dissipation. So, this criterion is used to evaluate capability of shoreline structures to dissipate wave energy.
High-water protection	This criterion assesses the capability of protecting the shoreline from sea level rising, and it is a day-by-day process for the wave actions.
Flood water storage	Floodwater is caused by the resulting temporary rise in sea level due to the action of wind stress on the water surface and low atmospheric pressure created during storms.
Erosion of adjacent sites and scouring	This is caused by storms, wave action, rain, ice, winds, runoff, and loss of trees and other vegetation. This criterion assesses the resistance of the shoreline structures to the erosion and scouring.
Natural habitats and ecosystem services	Natural habitats and ecosystem include some natural means, such as the creation of natural habitats (marshes, wetlands, oysters, bird islands). It is directly related to shoreline retreat, which affects public and private infrastructure for management of real estate.

These criteria are suitable for a broader set of potentially critical areas. After identifying the criteria for assessment, researchers established a hierarchical structure of the AHP of the optimal solution assessment issue (see Figure 46).

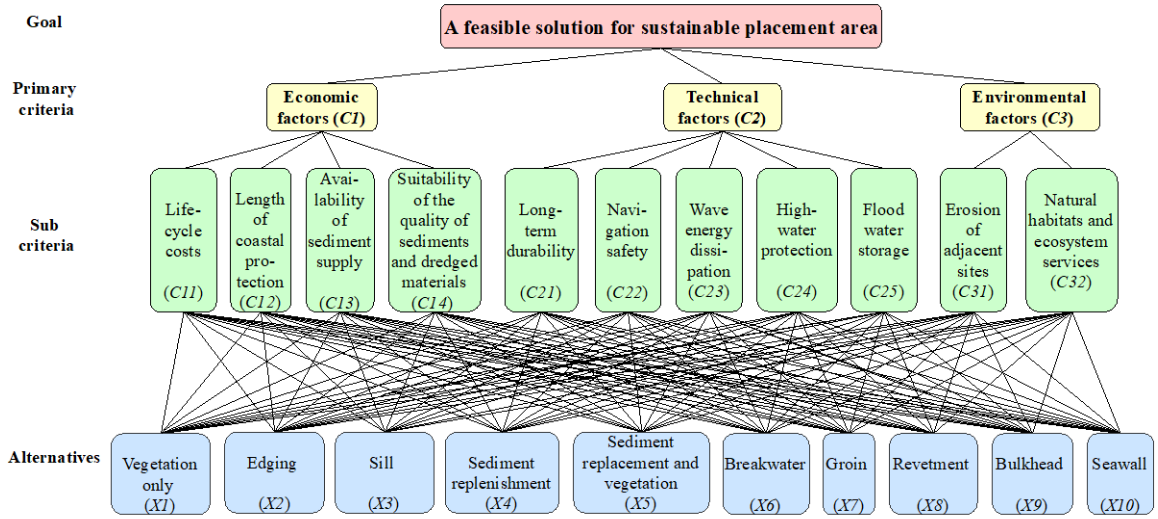


Figure 46. Hierarchical Structure of Optimal Solution Assessment for Sustainable Placement Areas.

The next step is to construct a pairwise comparison matrix to indicate the relative importance of alternatives. Table 22 shows the gradation scale for quantitative comparison of alternatives. For example, if two criteria contribute equally to the objective, they are equal importance and the intensity of importance should be 1. If experience and judgment slightly favor one criterion over another, the favored criterion would receive a score of 3, and so on, for each of the rest of the pairwise comparisons.

Table 22. Gradation Scale for Comparison of Alternatives.

Option	*Numerical value(s)*
Equal	1
Marginally strong	3
Strong	5
Very strong	7
Extremely strong	9
Intermediate values to reflect fuzzy inputs	2,4,6,8

A user guide is included in Appendix B that will walk the user through the various steps of the analysis. It provides examples of typical inputs and outputs.

INTRODUCTION TO USER GUIDE

The user guide in Appendix B incorporates inputs obtained from stakeholders during this project. It is designed to indicate the top three options and their effectiveness scores to facilitate the process of decision-making. It evaluates the 10 possible solutions shown in Table 20.

The tool provides a user interface where the user conducts pairwise comparisons. Then a consistency test is conducted to indicate the degree of logical consistency among the pairwise comparisons. If the consistency ratio does not satisfy the requirement of this approach, the pairwise comparison is modified. The model develops an effectiveness score for each alternative solution. The weight given to each criterion is multiplied by the assigned score given by each user to develop the effectiveness score.

This AHP tool is intended to inform the decision-making process; it does not provide a definitive answer. Since the intent of this study was to provide a generic tool that can be used for different locations and projects, site-specific details and design options were not considered. There are various requirements that could affect the selection and design of DMPAs that are not reflected in this AHP decision support tool. The current tool is intended to be used by a group of individuals that can discuss and determine the scores for pairwise comparisons among different criteria. The group can then determine additional considerations that need to be examined beyond the criteria listed in the current version of the tool.

The user guide includes an appendix that explain how the consistency ratio is calculated.

SPREADSHEET TOOL

A spreadsheet has been developed in a separate deliverable that provides guided inputs, which then lead to the appropriate calculations and outputs. Many of the illustrations in the user guide are snapshots of what the user will see in the spreadsheet.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Based on the knowledge, approaches, and lessons learned summarized in this report, the following are conclusions and recommendations to protect and restore the Texas GIWW DMPAs as natural habitat areas that support and enhance navigation safety for maritime traffic and improve navigation efficiencies by reducing the cycles of dredging.

GEOGRAPHICAL DISTRIBUTION

The formulation and evaluation of potential solutions to protect and restore DMPAs along the Texas GIWW incorporated geographic areas of East and West Galveston Bays and EMB. Ultimately, the evaluation focused on developing DMPA restoration and protection solutions and features within EMB. However, these recommended **solutions are translatable** to other Texas bay systems experiencing similar GIWW DMPA degradation and corresponding GIWW navigation safety issues.

NAVIGATION SAFETY

The protection and restoration of existing DMPAs is important to ensure these DMPAs are available to continue to receive dredged material from the GIWW and that their physical features are further developed to interfere with wave energy originating from open bays. These protected and restored DMPAs will contribute to navigation safety and commodity movement efficiencies by being available to receive shoal sediments dredged from within the GIWW and to further **protect maritime traffic against wind and wave environmental forces**.

It is recommended that navigation channel **reaches at and near GIWW bends or turns be designated as DMPA protection and restoration priority areas** for the reasons described above.

It is further recommended that **longer reaches of the GIWW within bay systems be protected by enhanced or created DMPAs or the enhancement of natural land barriers**, to protect maritime traffic against higher energy impacts from wind and waves associated with longer fetch distances within open water bay environments.

GIWW-FACING ENGINEERED FEATURES

Improvements or restoration of existing DMPAs are **dependent upon the existing conditions of the DMPA, such as the DMPA's environmental location** (within interior marsh or open bay environments); sediment transport processes within the vicinity of the DMPA; and/or, the effects of the DMPA in contributing to GIWW navigation safety and efficiency.

It is concluded and recommended, that in instances where DMPAs require structures to protect and stabilize DMPA's GIWW-facing shorelines, **low crested breakwaters, that allow for wave overtopping and sediment exchange, be considered as the primary option for site specific evaluation** to promote continuous marsh nourishment and enhancement.

BAY-FACING ENGINEERED FEATURES

For DMPAs with bay-facing shorelines, the selection of the shore protection measure depends on the environmental conditions experienced by the DMPA, such as the wave height, bottom depths, the sediment transport and flux, circulation pattern, and foundation or soil conditions at the bay facing rim.

Alternative protection features applicable to the DMPAs with bay-facing shorelines can consist of **sacrificial berms in low energy areas**, and **revetments** consisting of rock or reef balls, **segmented breakwater systems**, **or continuous breakwaters in moderate to high energy areas**.

Potential shoreline protection solutions should incorporate the **harvesting of suspended sediments** induced by vessel wakes and transported within the bay toward the DMPAs. These transported sediments could be captured and retained within the DMPA if the shoreline protection structures consist of low-crested breakwaters. The captured sediments will result in the re-nourishment and stabilization of the DMPAs internal marsh features.

AHP APPLICATION

The AHP application was developed to classify the applicability of an array of soft (green) to hard (gray) shoreline protection solutions for varying environments. These arrays of green-gray solutions have been successfully implemented throughout various coastal systems within the United States and have been applied locally within Texas bays systems.

In the Texas GIWW DMPA case, the AHP application was developed and presented as a decision-making and prioritization tool to identify critical locations and applicable features and measures to protect and restore DMPAs. When coupled with other evaluation criteria and best science, the AHP application can be used as a **support tool to facilitate the prioritization and selection of appropriate solutions** to protect and restore DMPAs along the Texas GIWW. It is not site specific and can easily be adapted to address specific concerns at various locations.

APPENDIX A: AREAS IN VICINITY OF CUTS MENTIONED BY BARGE OPERATOR

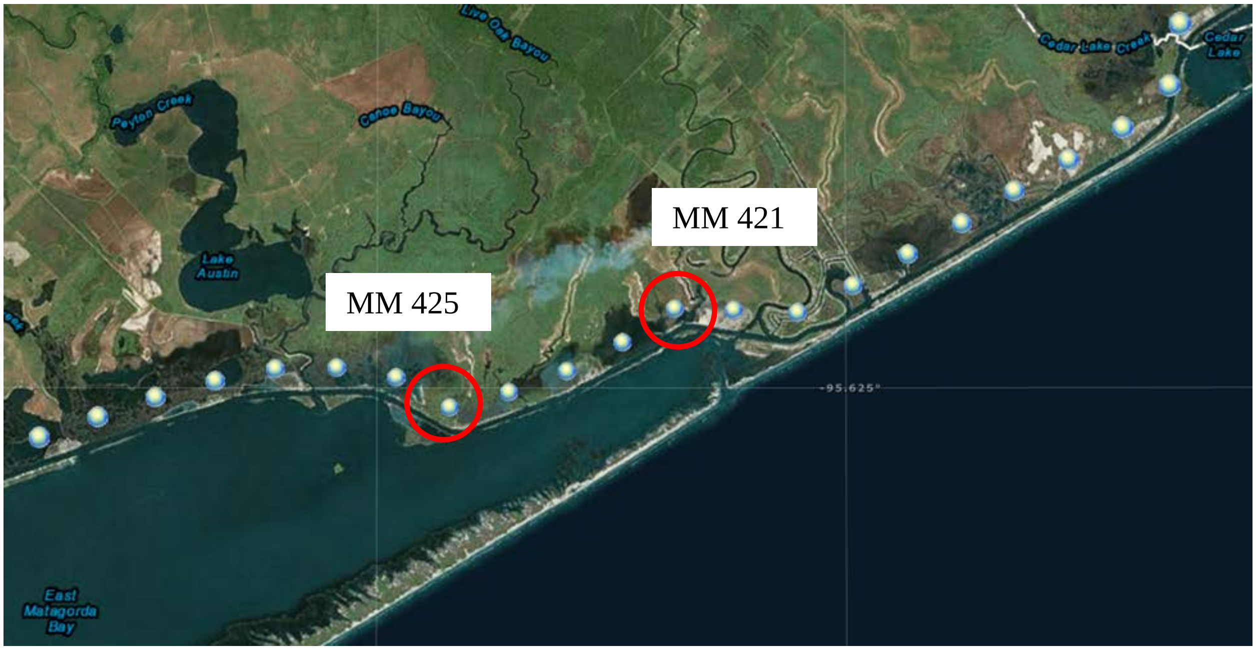


Figure A-1. Mile Marker 421 and Mile Marker 425.

Figure A-2. Mile Marker 435.5.

Figure A-3. Mile Marker 410.

APPENDIX B: USER GUIDE TO AHP TOOL

Analytic Hierarchy Process (AHP) Tool to Identify Optimal Solutions for Sustainable Dredge Material Placement Areas along the Texas Gulf Intracoastal Waterway

USER GUIDE

Date: August 2018

1 General Information

This Analytical Hierarchy Process (AHP) decision support tool is designed to evaluate various feasible solutions based on consideration of multiple criteria such as lifecycle costs, safety, and environmental sustainability for specific US Army Corps of Engineers (USACE) dredge material placement areas (DMPAs) along the Gulf Intracoastal Waterways (GIWW). This approach includes 11 criteria (see Section 5.A) and 10 solutions (see Section 5.B) for users to quantitatively evaluate optimal solutions. This tool will indicate the top three options and their effectiveness scores to facilitate the process of decision-making.

The solutions provided in our AHP tool are recommended by NOAA (NOAA, 2015a, b). Figure 1 shows six techniques in green-softer techniques and gray-harder techniques (NOAA, 2015a). The other four shoreline protection techniques proposed by NOAA are in the intersection between green and gray shoreline techniques. The survey we conducted for obtaining inputs from stakeholders also used those concepts.

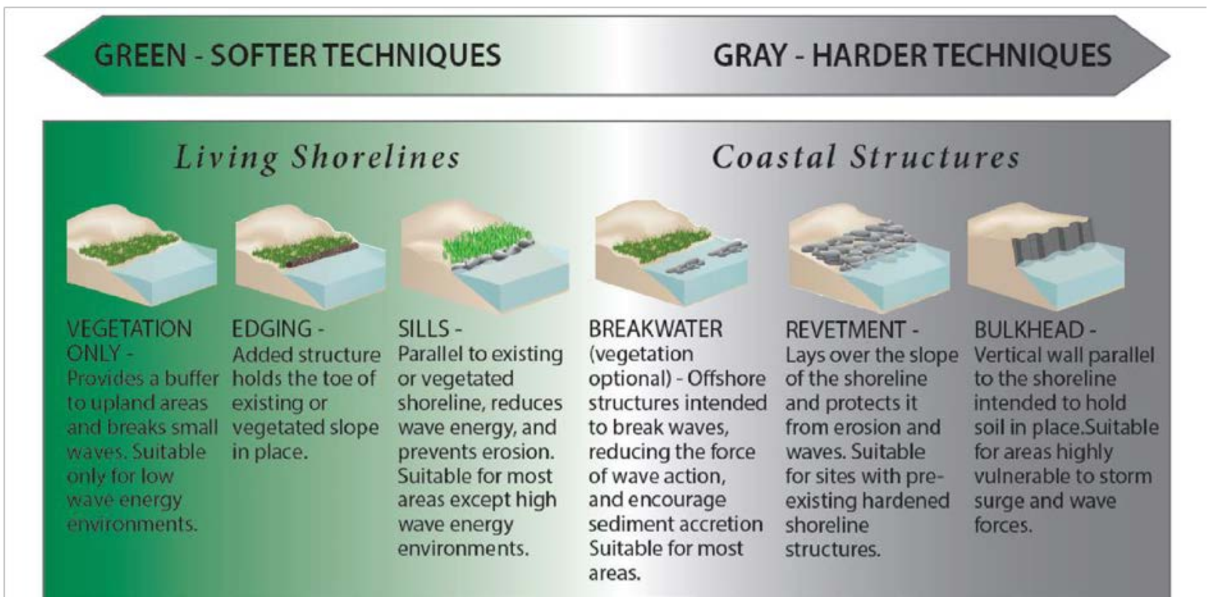


Figure 1. Classification of Living Shorelines and definitions of Green Soft Shoreline Protection and Gray Hard Shoreline Protection Techniques (NOAA, 2015a).

This AHP Tool is an Excel widget; it works on both Mac iOS and Windows.

2 Getting Started

This section provides a general walkthrough of the AHP tool from initiation through exit.

2.1 Tool Interface

There are two parts in the User Input page. The first part is the *pairwise comparison matrix*. This part is developed for users to input the importance of criteria based on specific DMPAs, project objectives, and location characteristics. The details about conducting pairwise comparison will be presented in section 2.2.

The second part in this page is the *consistency test*. This part is developed to inform users about the degree of logical consistency among their pairwise comparisons. If the consistency ratio does not satisfy the requirement of this approach, the pairwise comparison is modified. The details about the consistency test will be presented in section 2.3.

Pairwise Comparison Matrix for the Criteria

Criterion - 1	Your Judgements		Criterion - 2
Life-cycle cost	1	Equal importance	Length of coastal protection
Life-cycle cost	1/9	Absolutely less importance	Availability of sediment supply
Life-cycle cost	1	Equal importance	Quality of the sediment materials
Life-cycle cost	1/7	Demonstratedly less importance	Long-term durability
Life-cycle cost	1/9	Absolutely less importance	Navigation safety
Life-cycle cost	1/5	Essentially or strongly less importance	Wave energy dissipation
Life-cycle cost	1	Equal importance	Highwater protection
Life-cycle cost	1	Equal importance	Flood water storage
Life-cycle cost	1/5	Essentially or strongly less importance	Erosion of adjacent sites
Life-cycle cost	1	Equal importance	Natural habitats and ecosystem services
Length of coastal protection	1/9	Absolutely less importance	Availability of sediment supply
Length of coastal protection	1	Equal importance	Quality of the sediment materials
Length of coastal protection	1/5	Essentially or strongly less importance	Long-term durability
Length of coastal protection	1/9	Absolutely less importance	Navigation safety
Length of coastal protection	1/5	Essentially or strongly less importance	Wave energy dissipation
Length of coastal protection	1	Equal importance	Highwater protection
Length of coastal protection	1	Equal importance	Flood water storage
Length of coastal protection	1/3	Moderately/weakly less importance of one over a	Erosion of adjacent sites
Length of coastal protection	1	Equal importance	Natural habitats and ecosystem services
Availability of sediment supply	9	Absolute importance	Quality of the sediment materials
Availability of sediment supply	5	Essential or strong importance	Long-term durability
Availability of sediment supply	1	Equal importance	Navigation safety
Availability of sediment supply	5	Essential or strong importance	Wave energy dissipation
Availability of sediment supply	9	Absolute importance	Highwater protection
Availability of sediment supply	9	Absolute importance	Flood water storage
Availability of sediment supply	5	Essential or strong importance	Erosion of adjacent sites
Availability of sediment supply	9	Absolute importance	Natural habitats and ecosystem services
Quality of the sediment materials	1/3	Moderately/weakly less importance of one over a	Long-term durability
Quality of the sediment materials	1/9	Absolutely less importance	Navigation safety
Quality of the sediment materials	1/3	Moderately/weakly less importance of one over a	Wave energy dissipation
Quality of the sediment materials	1	Equal importance	Highwater protection
Quality of the sediment materials	1	Equal importance	Flood water storage
Quality of the sediment materials	5	Essential or strong importance	Erosion of adjacent sites
Quality of the sediment materials	1	Equal importance	Natural habitats and ecosystem services
Long-term durability	1/5	Essentially or strongly less importance	Navigation safety
Long-term durability	1	Equal importance	Wave energy dissipation
Long-term durability	5	Essential or strong importance	Highwater protection
Long-term durability	5	Essential or strong importance	Flood water storage
Long-term durability	1	Equal importance	Erosion of adjacent sites
Long-term durability	5	Essential or strong importance	Natural habitats and ecosystem services
Navigation safety	7	Demonstrated importance	Wave energy dissipation
Navigation safety	9	Absolute importance	Highwater protection
Navigation safety	9	Absolute importance	Flood water storage
Navigation safety	7	Demonstrated importance	Erosion of adjacent sites
Navigation safety	9	Absolute importance	Natural habitats and ecosystem services
Wave energy dissipation	5	Essential or strong importance	Highwater protection
Wave energy dissipation	5	Essential or strong importance	Flood water storage
Wave energy dissipation	1	Equal importance	Erosion of adjacent sites
Wave energy dissipation	5	Essential or strong importance	Natural habitats and ecosystem services
Highwater protection	1	Equal importance	Flood water storage
Highwater protection	1/5	Essentially or strongly less importance	Erosion of adjacent sites
Highwater protection	1/5	Essentially or strongly less importance	Natural habitats and ecosystem services
Flood water storage	1/5	Essentially or strongly less importance	Erosion of adjacent sites
Flood water storage	1	Equal importance	Natural habitats and ecosystem services
Erosion of adjacent sites	5	Essential or strong importance	Natural habitats and ecosystem services

Consistency test

Consistency ratio	Judgement	Conclusion
0.0991	<0.1	consistent

Suggestion	Great! Go to the results!

Figure 2. Tool interface for user inputs

2.2 Input Information

The first step for users is to input the judgments on the relative importance of the listed criteria. There is a drop-down table for each pairwise comparison between each two criteria (see Figure 3). All possible pairs are considered in the comparison matrix. The drop-down table has nine scale numbers (i.e., 1, 3, 5, 7, 9, 1/3, 1/5, 1/7, and 1/9) for the pairwise comparison. The definition and explanation of this scale are presented in Table 1. Through the pairwise comparison, users determine the importance of one criterion in comparison with another criterion. In the table, users compare the criteria listed in the Criterion 1 column with the ones listed in the Criterion 2 column. If Criterion 1 were more important for a specific DMPA, the score of pairwise comparison would be greater than 1. Otherwise, if Criterion 2 were more important for a specific DMPA, the score of pairwise comparison would be less than 1. For example, if *Criterion 2*, availability of sediment supply, were absolutely more important than *Criterion 1*, life-cycle cost, for a specific DMPA, users would select 1/9, which means *Criterion 2*, availability of sediment supply, is significantly more important than *Criterion 1*, life-cycle cost. In another example, if *Criterion 1*, life-cycle cost, is as important as *Criterion 2*, wave energy dissipation, we can select 1 in the drop-down menu.

There are 55 pairwise comparisons that need to be done by users in this case.

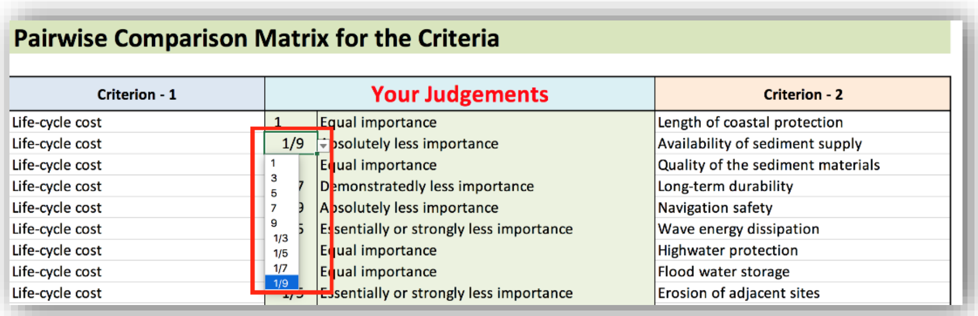


Figure 3. Dropbox of pairwise comparison scales

Table 1. The Scale for Pairwise Comparisons

Scales	Definition	Explanation
1	Equal importance	***Criterion 1*** and ***Criterion 2*** contribute equally to the objective.
3	Moderate/weak importance of one over another	Experience and judgment slightly favor ***Criterion 1*** over ***Criterion 2***.
5	Essential or strong importance	Experience and judgment strongly favor ***Criterion 1*** over ***Criterion 2***.
7	Demonstrated importance	***Criterion 1*** is favored very strongly over ***Criterion 2***; its dominance is demonstrated in practice.
9	Absolute importance	The evidence favoring element over ***Criterion 1*** over ***Criterion 2*** is of the highest possible order of affirmation.
1/3	Moderately/weakly less importance of one over another	Experience and judgment slightly favor ***Criterion 2*** over ***Criterion 1***.
1/5	Essentially or strongly less importance	Experience and judgment strongly favor ***Criterion 2*** over ***Criterion 1***.
1/7	Demonstrated less importance	***Criterion 2*** is favored very strongly over ***Criterion 1***; its dominance is demonstrated in practice.
1/9	Absolutely less importance	The evidence favoring ***Criterion 2*** over ***Criterion 1*** is of the highest possible order of affirmation.
Reciprocals of above nonzero	If a criterion has one of the above numbers assigned to it when compared with ***Criterion 2***. Then ***Criterion 2*** has the reciprocal value when compared with ***Criterion 1***.	
Rational	Ratios arising from the scale	If consistency were to be forced by obtaining numerical values to span the matrix.

2.3 Check Consistency Ratio

The second step is to check the consistency ratio. The consistency ratio indicates the amount of allowed inconsistency (see Section 5.C). Higher numbers mean the comparisons are less consistent (i.e., consistency among different sets of pairwise comparisons). Smaller numbers mean comparisons are more consistent. Since the numeric values are derived from the subjective preferences of individuals, it is impractical to avoid some degree of inconsistency in the matrix of judgments. In this tool, we set the consistency ratio as 0.1. A value of consistency ratio = 0.1 means that the judgments are 10 percent as inconsistent as if they had been given randomly. Hence, in this tool, a consistency ratio of 0.10 or less is acceptable to continue the AHP analysis. However, a consistency ration of up 0.2 would be still acceptable in most circumstances.

If the consistency ratio is greater than 0.10, it is advised to re-evaluate the pairwise comparison to locate the cause of the inconsistency and correct it (see Figure 4). For example, if Criterion A is much more important than Criterion B and Criterion B is much more important than Criterion C, Criterion A should be much more important than Criterion C. However, in some cases, users may input that Criterion A and Criterion C are equally important. Hence, such inconsistency would result in the increase of the consistency ratio, and users should find and revise such inconsistent judgements.

When the consistency ratio is lower than the acceptable consistency ratio, this tool will suggest the users to go to the result page (see Figure 5). Then, we can see the desirable options and their effectiveness scores.

Consistency ratio	Judgement	Conclusion
0.1110	>=0.1	not consistent

Suggestion	Please check your judgement and make sure your judgement is consistent!

Figure 4. Consistency test – Not consistent

Consistency ratio	Judgement	Conclusion
0.0955	<0.1	consistent

Suggestion	Great! Go to the results!

Figure 5. Consistency test – Consistent

2.4 Get Results

In the result page, we can see that the AHP tool provides three desirable options and their effectiveness scores (see Figure 6). Figure 6 shows that "Sediment replacement and vegetation" has the highest effectiveness score for the DMPA. The effectiveness score of "Revetment" is a little bit lower than the first option, and "Sill" is the third option in this case. The effectiveness score shows that the degree to which the options satisfy the requirement of the objective of the project and the specific location. In other words, the score is the effectiveness of the solution to the sustainable DMPA.

Results

Desirable Options	Effectiveness Scores
Sediment replacement and vegetation	74
Revetment	71
Sill	68

Figure 6. Results window

2.5 Effectiveness Scores

The effectiveness score quantifies the effectiveness of solutions to the sustainable DMPAs for the specific objective of the project and the specific location. In our AHP tool for East Matagorda Bay, 10 feasible solutions and 11 criteria were pre-identified from interviews and conference calls with stakeholders. Then, we conducted a web-based survey using Qualtrics, an online survey provider that enables data collection from stakeholders (e.g., USACE, Texas Mid-coast Refuge Complex, and The Texas General Land Office). In the web-based survey, SMEs evaluated the effectiveness levels (i.e., high effectiveness, medium effectiveness, and low effectiveness) of identified feasible solutions to each criterion based on their knowledge and experience. Once we obtained the responses, we could understand the performance of each solution for each criterion and were able to define the effectiveness score of each solution for each criterion. The effectiveness scores of solutions to specific criterion is determined and embedded in our AHP tool. Users do not need to determine the effectiveness scores when they use this tool.

The final effectiveness score in the results page for the desirable options is calculated by integrating the importance of the criteria toward the objective of a specific project and the pre-determined effectiveness scores obtained from web-based surveys. In this process, the importance of (the weighting to be given to) the criteria is obtained from the inputs of users and converted to a quantitative weight. Then, the final score for each solution is computed by the sum of the product of the pre-determined effectiveness score and the weight of each criterion. Hence, the final score is an integrative indicator associated with the objective of the project and the effectiveness of the solutions.

2.6 Interpretation of Results

Similar to every decision support tool, this AHP tool is intended to inform the decision-making process but does not provide a definitive answer. Since the intent of this study was to provide a generic tool that can be used for different locations and project, site-specific details and design options were not considered. There are various requirements that could affect the selection and design of DMPAs that could not be reflected in this AHP decision support tool. The current tool is intended to be used by a group of individuals that can discuss and determine the scores for pairwise comparisons among different criteria. The group can then determine additional considerations that need to be examined beyond the criteria listed in the current version of the tool.

3 Case Study of East Matagorda Bay

To illustrate the implementation of the AHP tool, we applied it to a case in East Matagorda Bay to evaluate solutions. The pairwise comparison was conducted based on the input from multiple interviews conducted in the earlier steps of the study. Based on the information gathered, the criteria were categorized in three tiers in terms of importance. Tier I group included navigation safety and availability of sediment materials as the two most important criteria for the placement area in East Matagorda Bay. The project is planned to restore and construct dredged material placement areas to act as barriers against energies impacting navigation infrastructure.

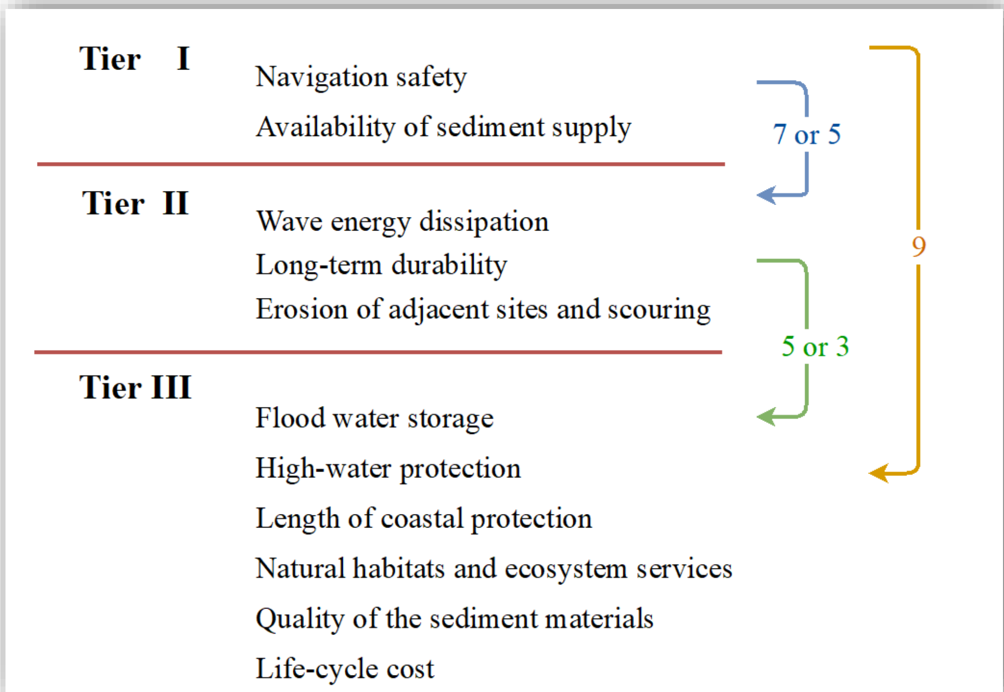


Figure 7. Three tiers of priority of criteria for East Matagorda Bay

Wave energy dissipation, long-term durability and erosion of adjacent sites, and scouring are in Tier II, and the rest of the criteria are placed in Tier III. Once the criteria were categorized, the pairwise comparisons were conducted according to the following rules. First, the criteria in Tier I are absolutely more important than the criteria in Tier III. Thus, a score of 9 was assigned in the comparisons of any of the criteria in Tier I over any criteria in Tier III. Second, the criteria in Tier II are less important than the criteria in Tier I. So, a score of 7 or 5 was assigned to any criteria in Tier I over any criteria in Tier II. Similarly, a score of 5 or 3 was assigned in the comparison of any criteria in the Tier II over any criteria in Tier III. Finally, the criteria in the same tier are of equal importance. Therefore, we can input 1 in the pair-wise comparison between these criteria. (See Table 1 for the definitions of these scores.) This step can help users reduce the complexity and subjectivity of pairwise comparisons and improve the efficiency of implementing the AHP tool.

Once the pairwise comparisons (see section 2.2) are completed, the consistency ratio is checked to ensure that it is below the acceptable threshold (see Section 5.C). As shown in Figure 8, our consistency ratio is 0.09, which is lower than 0.1. We can directly go to the results page to check out the desirable options for the project in East Matagorda Bay. In the results (see Figure 9), "Sediment replacement and vegetation," "Revetment," and "Sill" are the desirable options based on the computed effectiveness scores. These three options are the most effective options for the objectives of this project and site characteristics. For example, "Sediment replacement and vegetation" is suitable for low-lying oceanfront areas and is good for providing navigation efficiencies. Also, "Revetment" is a hard shoreline structure to mitigate the wave actions and protect slops from erosion.

Consistency ratio	Judgement	Conclusion
0.0991	<0.1	consistent

Suggestion	Great! Go to the results!

Figure 8. Consistency test in our case study

Results

Desirable Options	Effectiveness Scores
Sediment replacement and vegetation	74
Revetment	71
Sill	68

Figure 9. Desirable options for our case study

4 Acknowledgment

This AHP tool is a part of a research project sponsored by TxDOT's Maritime Division and the Texas A&M Transportation Institute focusing on improving the sustainability of some of the DMPAs along the GIWW on the Texas upper coast.

5 Appendix

A. Evaluation criteria for sustainable placement areas

Criteria	Description
Life-cycle costs	This criterion assesses the unit costs that includes initial investment for construction and the cost for sediment dredged to protect and restore degraded DMPAs and habitats within investigated areas. Sedimentation on the channel will increase the costs for maintenance.
Length of coastal protection	This factor affects the post construction monitoring and operations (i.e., ease of management).
Availability of sediment supply	Sediment supplied by some coastal rivers and the continental shelf has naturally diminished because of climatic changes and adjustments of the inner shelf profile. Today the only remaining source of sediment for many coastal compartments is local erosion of nearby beaches and bluffs.
Quality of the sediment materials	Sediments are an essential component of marine ecosystems and should be considered a resource of high ecological and socioeconomic value. This criterion evaluates the sediment and dredged materials for individual compounds and chemical class.
Long-term durability	This criterion is based on the structure design and the sediment volume potentially available as beneficial-use of dredged material for habitat restoration. The sediment sources available for harvesting to protect and restore degraded DMPAs and habitats are important to long-term durability of shorelines.
Navigation safety	This criterion evaluates the capability of reducing sedimentation and energy for safe and efficient navigation such as eliminating sharp bends and reducing channel length. Sediment movements are the key and decisive factors for navigation safety.
Wave energy dissipation	This is wave transformation in the navigation channels and is measured from the Steady-state spectral WAVE model. Stable and optimal shoreline structures are beneficial for wave energy dissipation. So, this criterion is used to evaluate capability of shoreline structures to dissipate wave energy.
High-water protection	This criterion assesses the capability of protecting the shoreline from sea level rising, and it is a day-by-day process for the wave actions.
Flood water storage	Floodwater is caused by the resulting temporary rise in sea level due to the action of wind stress on the water surface and low atmospheric pressure created during storms.
Erosion of adjacent sites and scouring	This is caused by storms, wave action, rain, ice, winds, runoff, and loss of trees and other vegetation. This criterion assesses the resistance of the shoreline structures to the erosion and scouring.
Natural habitats and ecosystem services	Natural habitats and ecosystem include some natural means, such as the creation of natural habitats (marshes, wetlands, oysters, bird islands). It directly relative to shoreline retreat, which affects public and private infrastructure for management of real estate.

B. Feasible solutions

Alternatives	Descriptions
Vegetable only	Roots hold soil in place to reduce areas and breaks small waves.
Edging	Structure to hold the toe of existing or vegetated slope in place. Protects against shoreline erosion.
Sills	Parallel to existing or vegetated shoreline, reduces wave energy and prevents erosion. A gapped approach would allow habitat connectivity, greater tidal exchange, and better waterfront access.
Sediment replenishment	Large volume of sand added from outside source to an eroding beach. Widens the beach and moves the shoreline seaward.
Sediment replacement and vegetation	Helps anchor sand and provide a buffer to protect inland area from waves, flooding, and erosion.
Breakwater	Offshore structure intended to break waves, reducing the force of wave action and encourages sediment accretion. Can be floating or fixed to the ocean floor, attached to shore or not, and continuous or segmented. A gapped approach would allow habitat connectivity, greater tidal exchange, and better waterfront access.
Groin	Perpendicular, projecting from shoreline. Intercept water flow and sand moving parallel to the shoreline to prevent beach erosion and break waves. Retain sand placed on beach.
Revetment	Lays over the slope of a shoreline. Protects slope from erosion and waves.
Bulkhead	Parallel to the shoreline, vertical retaining wall. Intended to hold soil in place and allow for a stable shoreline.
Seawall	Parallel to shoreline, vertical, or sloped wall. Soil on one side of wall is the same elevation as water on the other. Absorbs and limits impacts of from land.

C. Calculation of consistency ratio

Once users complete the Input Section for pair-wise comparison of criteria, this AHP tool converts the inputs into a matrix (*see Figure S1*). This matrix facilitates the calculation of the weight of each criterion and the consistency ratio. The consistency ratio is calculated by:

$$CR = \frac{\lambda_{max} - n}{(n-1) \cdot RI_n}$$

where n is the number of criteria, λ_{max} is the maximum eigenvalue of the pair-wise comparison matrix, is equal to n if and only if the matrix is consistent (and greater than n otherwise), and RI_n is the Random Index, which is an estimation of consistency from a large enough set of randomly generated matrices of size n (see Table S).

Criteria	Life-cycle cost	length of coastal protection	Availability of sediment supply	Quality of the sediment materials	Long-term durability	Navigation safety	Wave energy dissipation	Highwater protection	Flood water storage	Erosion of adjacent sites	Natural habitats and ecosystem services
Life-cycle cost	1	1	0.11111111	1	0.14285714	0.11111111	0.2	1	1	0.2	1
length of coastal protection	1	1	0.11111111	1	0.2	0.11111111	0.2	1	1	0.33333333	1
Availability of sediment supply	9	9	1	9	5	1	5	9	9	5	9
Quality of the sediment materials	1	1	0.11111111	1	0.33333333	0.11111111	0.33333333	1	1	5	1
Long-term durability	7	5	0.2	3	1	0.2	1	5	5	1	5
Navigation safety	9	9	1	9	5	1	7	9	9	7	9
Wave energy dissipation	5	5	0.2	3	1	0.14285714	1	5	5	1	5
Highwater protection	1	1	0.11111111	1	0.2	0.11111111	0.2	1	1	0.2	0.2
Flood water storage	1	1	0.11111111	1	0.2	0.11111111	0.2	1	1	0.2	1
Erosion of adjacent sites	5	3	0.2	0.2	1	0.14285714	1	5	5	1	5
Natural habitats and ecosystem services	1	1	0.11111111	1	0.2	0.11111111	0.2	5	1	0.2	1
SUM	41	37	3.26666667	30.2	14.2761905	3.15238095	16.3333333	43	39	21.1333333	38.2

Figure S1. Converted pair-wise comparison matrix

Table S. RI reference matrix

n	3	4	5	6	7	8	9	10	11
RI_n	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51

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