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Coastal Protection and Restoration Authority
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2013 Operations, Maintenance, and Monitoring Report

for

Terrebonne Bay Shore Protection Demonstration (TE-45)

State Project Number TE-45
Priority Project List 10

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For
Terrebonne Bay Shore Protection Demonstration
(TE-45)

Table of Contents

Preface

This report includes monitoring data collected through December 2012, and annual Maintenance Inspections through March 2013.

The 2013 report is the 2nd report in a series of three OM&M reports. For additional information on lessons learned, recommendations and project effectiveness please refer to the 2010 Operations, Maintenance, and Monitoring Report on the CPRA web site (Melancon et al. 2010).

I. Introduction

The Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) of 1990 (PL 101-646, Title III) authorized the Terrebonne Bay Shore Protection Demonstration (TE-45) project as part of the 10th Priority Project List approved on January 10, 2001. The TE-45 project is located southeast of Chauvin, Louisiana in Terrebonne Parish along the rapidly eroding northwest shore of Lake Barré, which is part of the Terrebonne Basin system (Figure 1). The project was federally sponsored by the United States Fish and Wildlife Service (USFWS) and locally sponsored by the Coastal Protection and Restoration Authority of Louisiana (CPRA) under CWPPRA. The project evaluates three fabricated structures placed along the shore for their effectiveness in abating shoreline erosion, and for their ability to develop and sustain an oyster reef. The project is distributed along three (3) shoreline sites, Reach A, Reach B, and Reach E (Figures 2-4). The TE-45 demonstration project's monitoring life is eight (8) years.

The soils in the TE-45 project area are composed of a Timbalier-Muck association. This soil is a very poorly drained organic soil that is found in saline marsh habitats. The organic layer extends approximately 1.5 m (5 ft) below the ground surface. Below this layer, lies a very fluid clay substratum (USDA 2007). *Spartina alterniflora* Loisel. (smooth cordgrass) dominates the vegetation community in the project area soils. *Juncus roemerianus* Scheele (needlegrass rush), *Salicornia bigelovii* Torr. (dwarf saltwort), *Sporobolus virginicus* (L.) Kunth (seashore dropseed), *Borrichia frutescens* (L.) DC. (bushy seaside tansy), and *Batis maritima* L. (turtleweed) have also been found to inhabit Timbalier-Muck association soils (USDA 2007). Eustis (2002) discerned that the soils at Reach E have a thicker organic layer and a lower bearing value than the other Reaches.

The TE-45 project consists of three shoreline protection features; ReefBlk structures (foreshore), A-Jack structures (onshore), and Gabion Mat (onshore) structures. All three features and a reference area were installed at Reach A, Reach B, and Reach E in 91 m (300 ft) lengths (Figures 1-4). In addition, Reach A and Reach B were only separated by one structure length, 91 m (300 ft), (Figure 1) due to high land loss rates in the previous Reach B location. The placement of the treatments was randomly selected and the structures fronted a continuous 305 m (1000 ft) of shoreline at each Reach. Tie-in units were used to attach the foreshore treatment (reef block) to the shoreline (Figures 2, 3, and 4). The tie-in units were constructed with the A-Jack structures. The ReefBlk structures, the A-Jack structures, and the

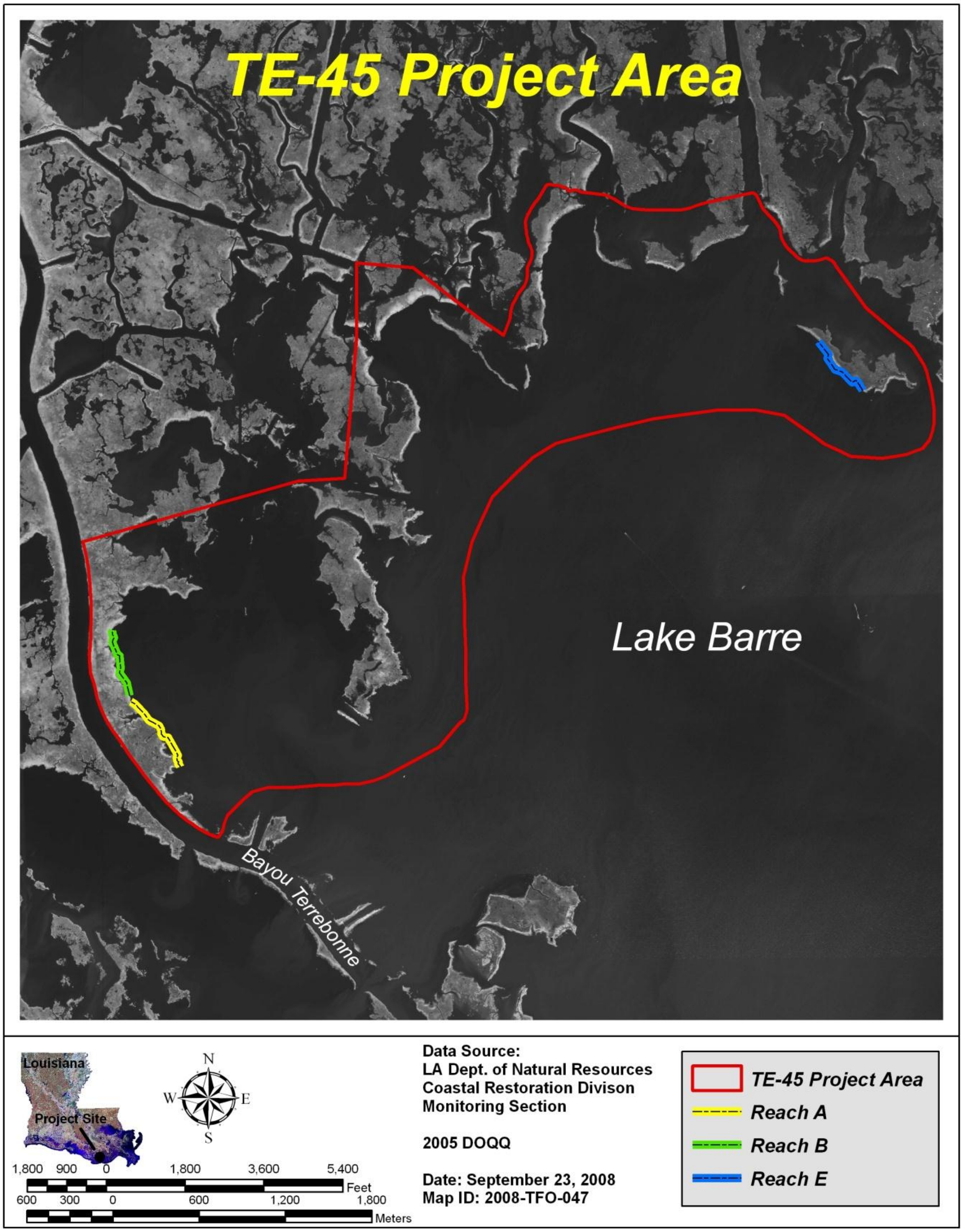

Figure 1. Location of the Terrebonne Bay Shore Protection Demonstration (TE-45) project area with the delineated shoreline Reaches investigated and selected for protection.

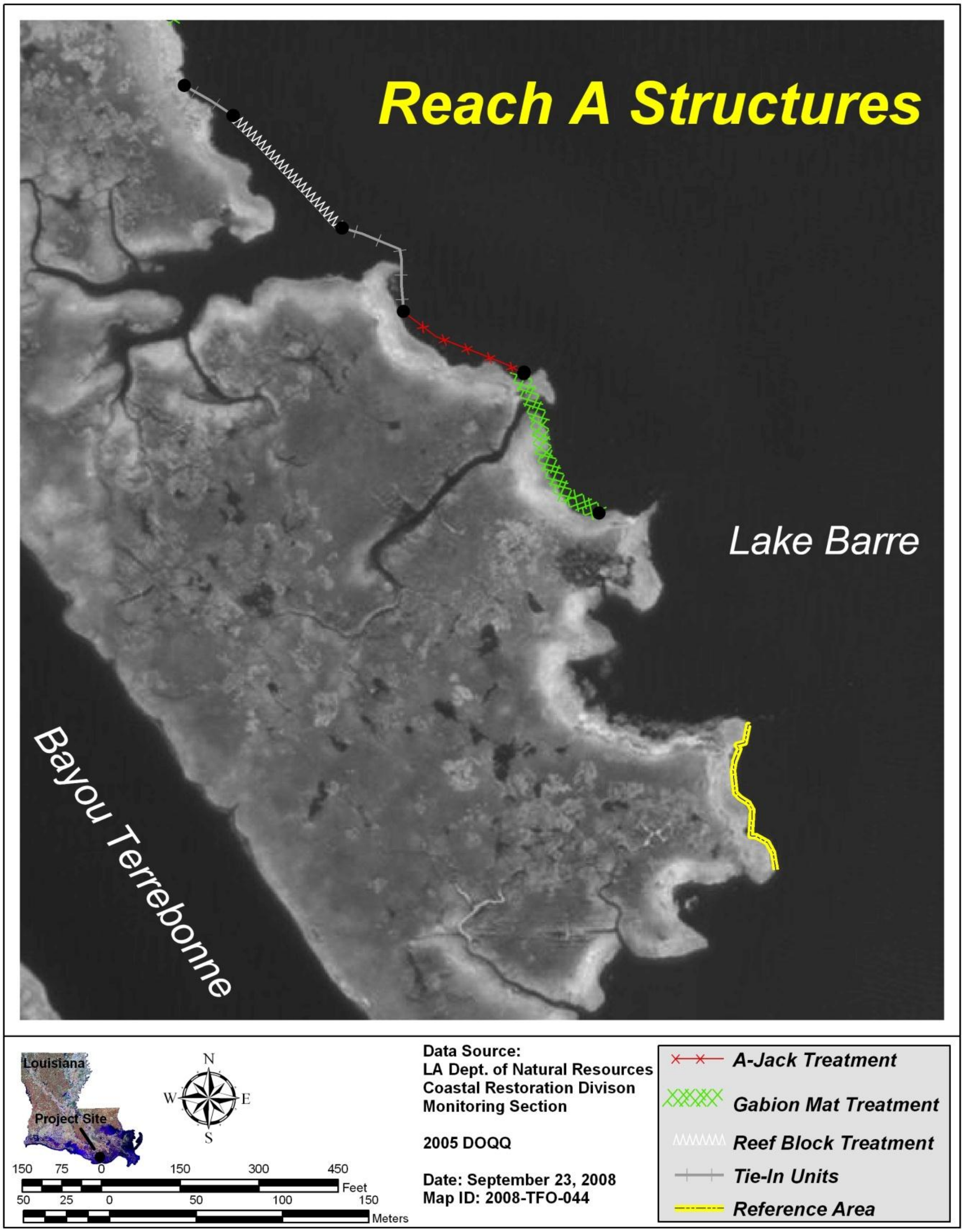

Figure 2. Location of the Reach A project features (structure treatments) at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

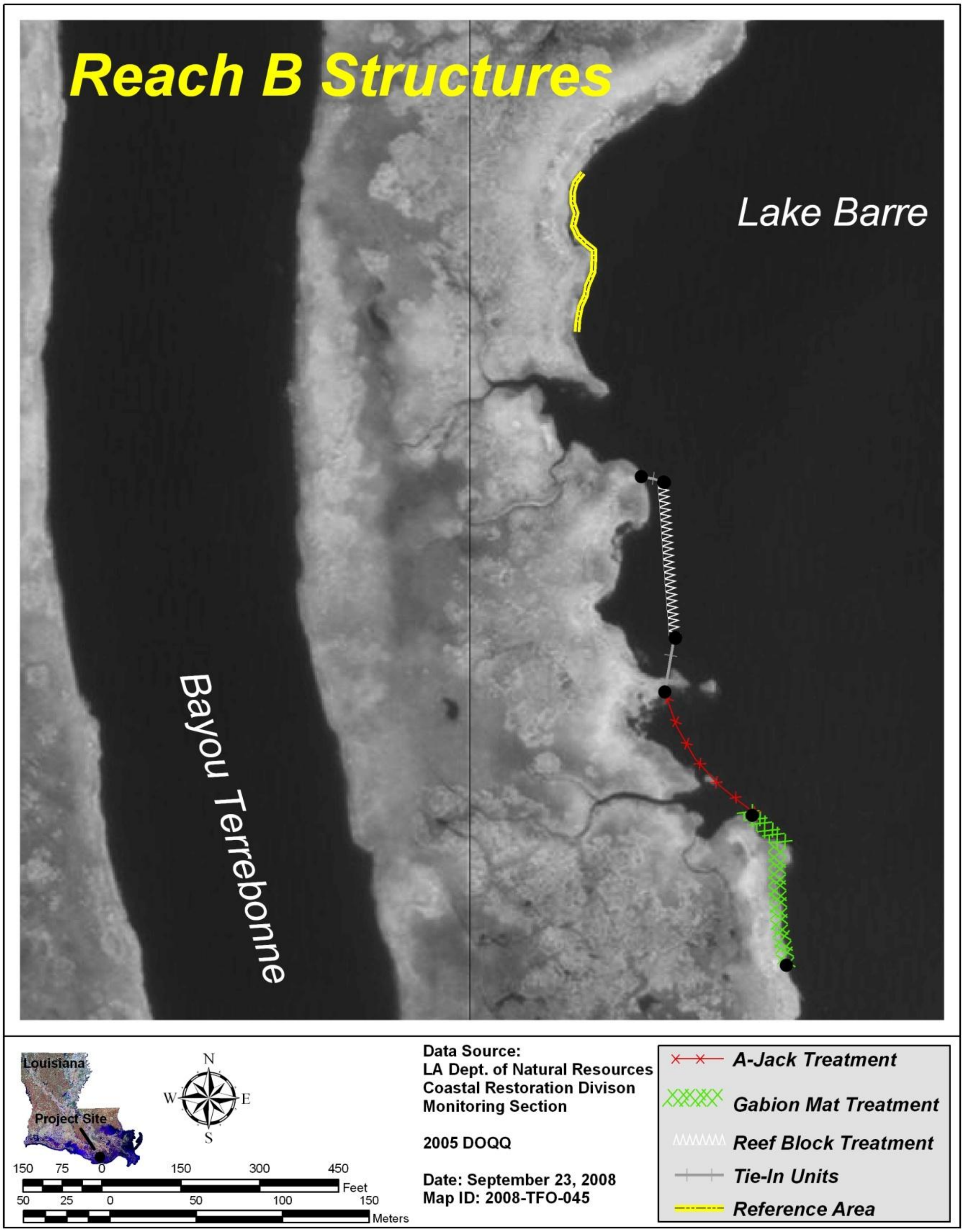

Figure 3. Location of the Reach B project features (structure treatments) at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

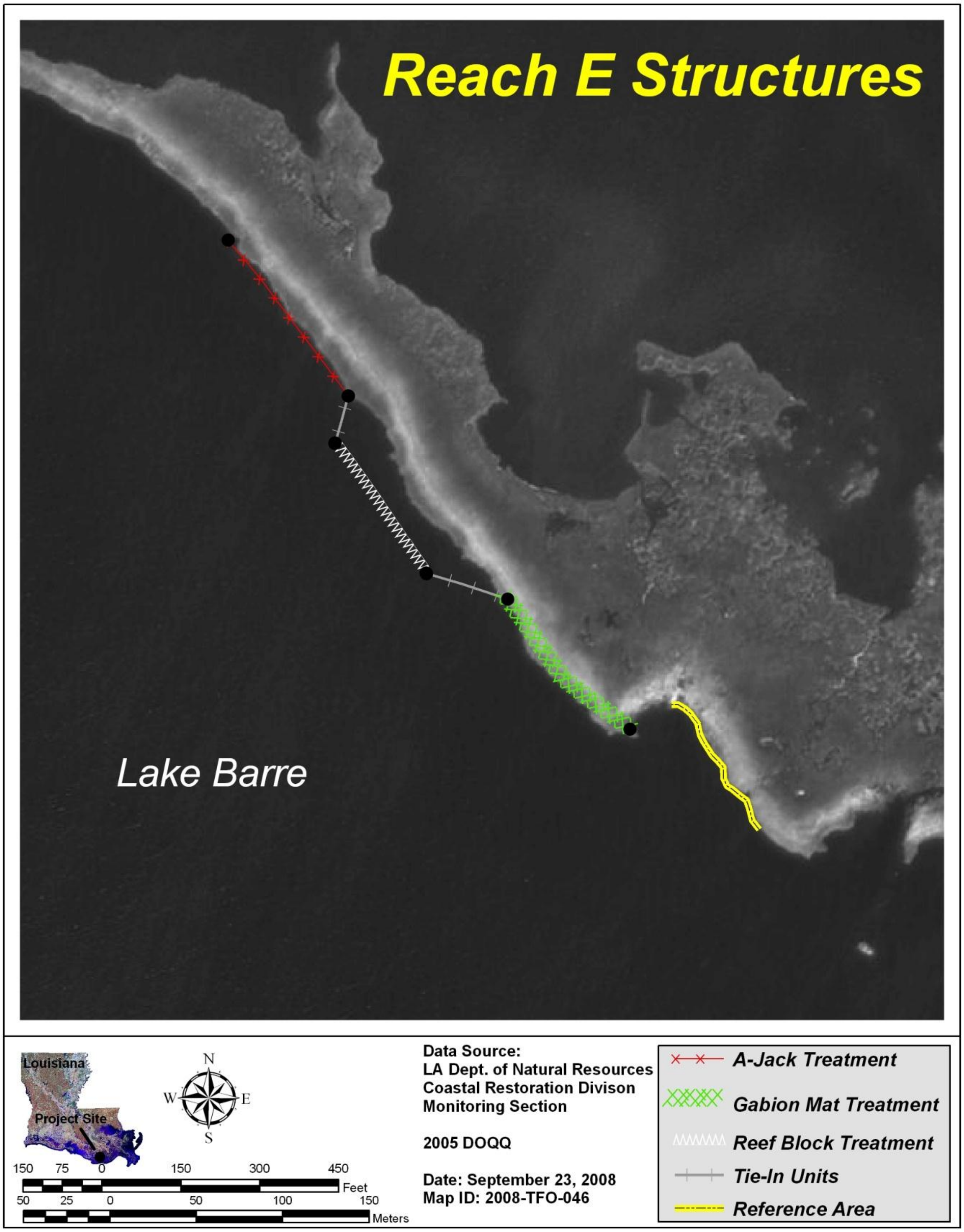

Figure 4. **Location of the Reach E project features (structure treatments) at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

tie-in units were built on top of a geogrid and crushed stone foundation and were anchored at 3 m (10 ft) intervals while the Gabion Mat structures were laid directly on top of the existing marsh and bay bottom and were not anchored (Appendix A, Figures A-1 and A-2). The ReefBlk structures were constructed by welding triangle shaped metal frames together. The outer perimeters of the frames were fitted with mesh bags that were filled with oyster shells (Appendix A, Figure A-3). The ReefBlk treatment was installed to a minimum elevation of 0.3 m (1.0 ft) NAVD 88 (Appendix A, Figure A-1). The A-Jack structures were fabricated by forming concrete into an A-jack shape (Appendix A, Figure A-4). The A-Jacks used for the TE-45 project were 0.6 m (2 ft) tall and were lashed together with steel cables (Appendix A, Figures A-1 and A2). The Gabion Mat structures were manufactured by constructing a mattress shaped mesh frame with 6 m (20 ft) x 1.5 m (5 ft) x 0.3 m (1 ft) dimensions. The Gabion Mats were filled with ASTM class #1 stone and sealed by braiding 0.3 m (1 ft) thick geogrid tabs to the mesh frame (Appendix A, Figure A-5). The Gabion Mats were laid 2 m (7 ft) into the marsh while the remaining 4 m (13 ft) of the mats rested on the bay bottom (Appendix A, Figures A-1 and A2). Construction of the TE-45 structures began on September 6, 2007 and was completed by December 19, 2007.

Louisiana's interior bay shorelines are experiencing high rates of erosion and marsh loss. There is significant dual benefit in lessening bay shoreline erosion with the use of fabricated structures that also have the ability to establish oyster populations. Oyster populations can continuously respond to changing environmental conditions such salinity, subsidence and sea level rise with continuous reef growth. For example, Meyer et al. (1997) demonstrated the effectiveness of oyster cultch (shell) to marsh edge stabilization and sediment accumulation, while Gagliano et al. (1997) demonstrated that fabricated vertical structure placed along an eroding marsh shoreline in Louisiana may have significant erosion-control and oyster habitat-developing potential.

Historical Background Information

In Louisiana, coastal land loss has been estimated at approximately 64.7 square kilometers (25 square miles) year^{-1} (Dunbar et al. 1992) to 90.6 square kilometers (35 square miles) year^{-1} (Barras et al. 1994). More specifically, the average shoreline erosion rate for the five proposed Reaches along the north shore of Lake Barre are 1.51 meters (4.95 feet) year^{-1} for the period of 1932 to 1983 (May and Britsch 1987). Due to high rates of erosion along the north shore and salinities conducive for oysters, this project location was chosen to evaluate the effectiveness of the three (3) different structure types.

The eastern oyster, *Crassostrea virginica* (Gmelin), is the dominant reef-building estuarine organism along the northern Gulf of Mexico. Because of Louisiana's climate, it has the ability to spawn almost year round, but usually exhibits bimodal peaks of mass spawning in spring-early summer and again in early-late fall (Butler 1954). When waters are warm in summer, planktonic larvae require less than two weeks to metamorphose through several life stages before they are ready for settlement and a benthic life (Galtsoff 1964). Newly settled oysters often experience high mortalities in the first six months of life (Roegner and Mann 1995). At the time of setting, oyster larvae are usually less than 0.5 mm in size, and are very vulnerable to predation and to burial due to sediment overburden. A hard substrate that provides refuge from predators and provides vertical relief from sediments is of significant importance to assure a chance for survival. Once the larva has set, it will become known as a "spat oyster" until it is 25 mm (1 inch) in shell length. The juvenile stage is short-lived with oysters maturing with functioning gonads within 4-12 weeks of settlement in summer water temperatures (Menzel 1951). Young oysters grow rapidly and may reach 75 mm (3 inches) in shell length within 15-18 months in Louisiana waters. After an oyster is approximately eight years old, somatic tissue growth is insignificant or ceases and the volume of the mantle/shell cavity remains relatively constant (Cake 1983). Oysters in the northern Gulf of Mexico may live for 10 years or longer. The oyster occurs in salinities ranging from 5-40 ppt (Shumway 1996). Optimal growth and survival of commercially viable oyster populations require a salinity range of 5-15 ppt, when coupled with an appropriate temperature regime. This narrow ecological salinity range reduces the abundance of higher-salinity oyster predators and disease while still allowing for physiological functions to continue. When other environmental variables are within acceptable ranges for oyster survival, salinity becomes the overriding factor for sustaining an oyster population (Dekshenieks et al. 2000). Melancon et al. (1998) delineated resource zones where oysters can be found under persistent drought (dry) or rainy (wet) conditions within the Terrebonne estuary; four zones were established, with a mid-bay region referred to as the wet-dry zone where oysters can be found irrespective of wet or dry conditions, and thus allowing for both subtidal and intertidal oyster habitats. This mid region of the estuary is where the majority of naturally productive commercial oyster leases exist today. The location of the TE-45 project is within this wet-dry zone.

The oyster is a gregarious animal that has the ability to develop shallow subtidal and intertidal reef structure along a shoreline that also adds significant ecological value to an estuary. An oyster reef is a 3-dimensional structure created by successive years of larval settlement on adult oysters, while also providing multiple levels of hard surface and interstitial heterogeneity that is rare in the marine ecosystem (Bartol et al. 1999). The oyster becomes the keystone organism for a multitude of invertebrate and vertebrate species in a dynamic estuarine community (Coen et al. 1999), which also includes many recreational and commercial species (Zimmerman et al. 1989).

The location, distribution and physical dimensions of an oyster population depend on many interacting factors which include complex associations of physical, chemical, geological and biological processes (Kennedy et al. 1996). Environmental and biological variables such as predation and disease, food quality and quantity, suitable bottom substrate, adequate tidal flushing, water currents, temperature, salinity, and an array of other variables interact to produce a habitat capable of developing and sustaining an oyster population. For example, Bahr and Lanier (1981), describing intertidal reefs along the South Atlantic coast, identified many important driving forces for oyster survival and reef development, including predation and competition, water current regime, particulate organic matter (food), tidal amplitude, and extreme air temperatures. Bartol et al. (1999), working with intertidal oysters in the Piankatank River of the Chesapeake Bay system, demonstrated the importance of vertical relief and depth of substrate in providing critical intertidal-subtidal zonation and refuge for oyster survival.

Powell et al. (1994) and Dekshenieks et al. (2000), both studying subtidal oysters in the Galveston Bay estuary, developed mathematical models to interpret rates of oyster mortality and population crashes using the forcing functions of salinity, water flow rate, food availability (chlorophyll-a and total suspended solids), turbidity, and water temperature. Lenihan (1999), also working with subtidal oysters, demonstrated that shape influences water flow across a reef and becomes a critical variable to settlement and reef development success. Understanding the environmental variables that provide the necessary infrastructure for an oyster population to survive is fundamental to the TE-45 project's ability to interpret success or failure of reef development.

II. Maintenance Activity

a. Project Feature Inspection Procedures

The purpose of the annual inspection of the Terrebonne Bay Shore Protection Demonstration (TE-45) Project is to inspect the physical condition of each treatment technique and determine if any deficiencies exist that would affect or alter the evaluation of the shoreline protection treatments. The inspection results are then used to produce an annual inspection report containing description of treatments, field inspection findings, an overall project features map, photographs taken during the inspection and an updated operations and maintenance budget for the upcoming three (3) years. The overall project features map can be found in Appendix A, field inspection photographs in Appendix B and a summary of the three (3) year O&M budget in Appendix C.

Since this project is a demonstration project, no provisions were included for operations, maintenance and rehabilitation of any of the project features other than to conduct annual inspections during the eight (8) year demonstration period (O&M Plan 2009). The 2013 inspection was the fifth (5th) of eight inspections performed since the project was completed in December 2007.

The annual inspection of the Terrebonne Bay Shore Protection Demonstration Project (TE-45) took place on March 6, 2013. In attendance were Adam Ledet and Glen Curole from CPRA and Robert Dubois from US Fish and Wildlife Service. The inspection began at approximately 11:00 am at Reach A and ended at approximately 1:00 pm at Reach E. The trip included a visual inspection of the nine shoreline protection structure installations (three treatment types at each of the three reaches), the tie-in units, and all warning signs for the project. Photographs of the structures are included in Appendix B.

b. Inspection Results

<u>Reaches A, B, and E</u>

All of the shoreline protection structures at the three sites appear to be in good condition. All Gabion Mats were intact with no ruptures. The A-Jacks and ReefBlks were upright with no rollover observed. Oyster growth was observed on all three types of structures. Also, the tie-in units (A-Jacks) visible during the inspection did not appear to be damaged. A water level reading of +0.7’ NAVD88 was taken from the staff gauge near Reach E at approximately 1:00 pm. Due to the level of the water, the sections of A-Jacks and ReefBlks on Reach E were submerged and not visible at the time of the inspection. As mentioned in previous inspections, there appeared to be some damage to the marsh on the southern end of Reach E behind the Gabion Mats. It is believed that this damage is due to flanking erosion and not a function of the Gabion Mats. Two warning signs were observed to be damaged, one located on Reach B and another on Reach E.

c. Maintenance Recommendations

i. Immediate/ Emergency Repairs

None

ii. Programmatic/ Routine Repairs

None

d. Maintenance History

No maintenance projects or operation tasks have been performed since completion of the Terrebonne Bay Shore Protection Demonstration Project (TE-45). As a demonstration project, there are no funding provisions in the project O&M budget for maintenance events. Only the costs associated with annual inspections are provided in the project O&M budget.

e. Conclusions and Recommendations

The only structural modifications to the constructed treatments were the settlement of the structures and the loss of oyster shell from the ReefBlks. From our observations, it appears some settlement of the structures has occurred. This is confirmed by an elevation survey conducted in 2011 as shown in Table 2. All of the structures have settled since construction, with the most extreme area being Reach E. In particular, the Reach E A-Jack and ReefBlk structures experienced considerable settlement. No remedial activities are being recommended to correct structure settlement and oyster shell loss. By comparing photographs of previous inspections, the area of water behind the Gabion Mats on the southern end of Reach E appears to be increasing. The Gabion Mats in this area are not adjacent to the shoreline and cannot function as designed since flanking erosion is occurring and has been progressing behind this structure due to wind, wave, and tidal forcing over time. There are no provisions in the O&M Plan to reconnect the end of the Gabion Mats with the shoreline. The damage to the two warning signs appears to be due to high winds or extreme weather. Since there are no funds to replace the signs and the signs are still visible, there are no recommendations for maintenance at this time.

III. Operations Activity

a. Operation Plan

None.

b. Actual Operations

None.

IV. Monitoring Activity

Pursuant to a CWPPRA Task Force decision on August 14, 2003 to adopt the Coastwide Reference Monitoring System-*Wetlands* (CRMS-*Wetlands*) for CWPPRA, updates were made to the TE-45 Monitoring Plan to merge it with CRMS-*Wetlands* and provide more useful information for modeling efforts and future project planning while maintaining the monitoring mandates of the Breaux Act. There are no CRMS sites located in the project area.

a. Monitoring Goals

The specific project strategies of the Terrebonne Bay Shore Protection Demonstration (TE-45) project are (1) to use diverse shoreline protection treatments to reduce erosion within the project boundary, (2) to select shoreline protection treatments which will provide habitat for oyster spat adhesion and growth, and (3) to generate a sound experimental design that will allow for statistical testing and evaluation of the project goals.

The specific measurable goals established to evaluate the effectiveness of the project are:

1. To reduce shoreline erosion while minimizing scouring to the bay bottom adjacent to each shoreline protection treatment.

2. To quantify and compare the ability of each of the shoreline protection treatments to reduce erosion and enhance oyster production.

3. To quantify and compare the cost-effectiveness of each shoreline protection treatment in reducing shoreline erosion and enhancing oyster production.

b. Monitoring Elements

The following monitoring elements will provide the information necessary to evaluate the specific goals listed above:

<u>Elevation</u>

Topographic and bathymetric surveys were employed to document elevation and volume changes along the Terrebonne Bay Shore Protection Demonstration (TE-45) project Reaches (Reach A, Reach B, and Reach E). Pre-construction (August 2007), as-built (February 2008), and post-construction (February 2011) elevation data were collected using traditional cross sectional transects and real time kinematic (RTK) survey methods. The pre-construction survey was surveyed perpendicular to baselines at 31 m (100 ft) intervals while the as-built and post-construction surveys were surveyed perpendicular to the structures at 23 m (75 ft) intervals. The latter 2 surveys also established elevations on the upper surface of the structures to document structure heights and settlement over time. All survey data were established using or adjusted to tie in with the Louisiana Coastal Zone (LCZ) GPS Network. The Reach A, Reach B, and Reach E reference areas were not surveyed during the pre-construction period

(August 2007). During the following spatial analysis, Reaches A and B were combined into a single grid model because of their close proximity while Reach E was analyzed separately.

The August 2007, February 2008, and February 2011 survey data were re-projected horizontally to the UTM NAD83 coordinate system and vertically to the NAVD 88 datum in meters using Corpscon® software. The re-projected data were imported into ArcView® GIS software for surface interpolation. Triangulated irregular network models (TIN) were produced from the point data sets. Next, the TIN models were converted to grid models (2.0 m^2 cell size), and the spatial distribution of elevations were mapped. The grid models were clipped to the TE-45 shoreline polygons to estimate elevation and volume changes.

Elevation changes from August 2007-Feburary 2008 and February 2008-Feburary 2011 were calculated by subtracting the corresponding grid models using the LIDAR Data Handler extension of ArcView® GIS. After the elevation change grid models were generated, the spatial distribution of elevation changes along the TE-45 shorelines were mapped in quarter meter elevation classes. Lastly, volume changes along the shorelines were calculated in cubic meters (m^3) using the Cut/Fill Calculator function of the LIDAR Data Handler extension of ArcView® GIS. Note, these elevation and volume calculations are valid only for the extent of the survey area.

In addition to the holistic analysis of the elevation grid models, the TE-45 treatments were also partitioned into windward (the area fronting the structures and reference areas) and leeward (the area immediately behind the structures and reference areas) grids to delineate the effects of coastal structures and the shoreline planform on sedimentation patterns near the treatments. The windward and leeward subdivisions utilized the previously created grid models (February 2008 and February 2011) and were clipped with 232 m^2 (2,500 ft^2) polygons (Figure 5). The small areal extent of the polygons was necessitated because of spatial constraints imposed by the elevation grid models. Next, elevation and volume changes were calculated for each subdivision for the February 2008-Feburary 2011 interval using the aforementioned method. Sedimentation analyses consisted of one-way ANOVA's. The statistical package used was JMP (v10).

The elevation points taken on the TE-45 structures during the February 2008 and February 2011 surveys were used to determine structure settlement over time. New elevation grid models (0.25 m^2 cell size) were created for all structure replicates and these grids were clipped with their matching structure polygons. Structure elevation changes were calculated by subtracting the February 2008-Feburary 2011 structure grid models using the methods described in the previous paragraphs. Volume changes were not calculated for the structures because structure settlement was the parameter investigated. Structure settlement analyses consisted of one-way ANOVA's. The statistical package used was JMP (v10).

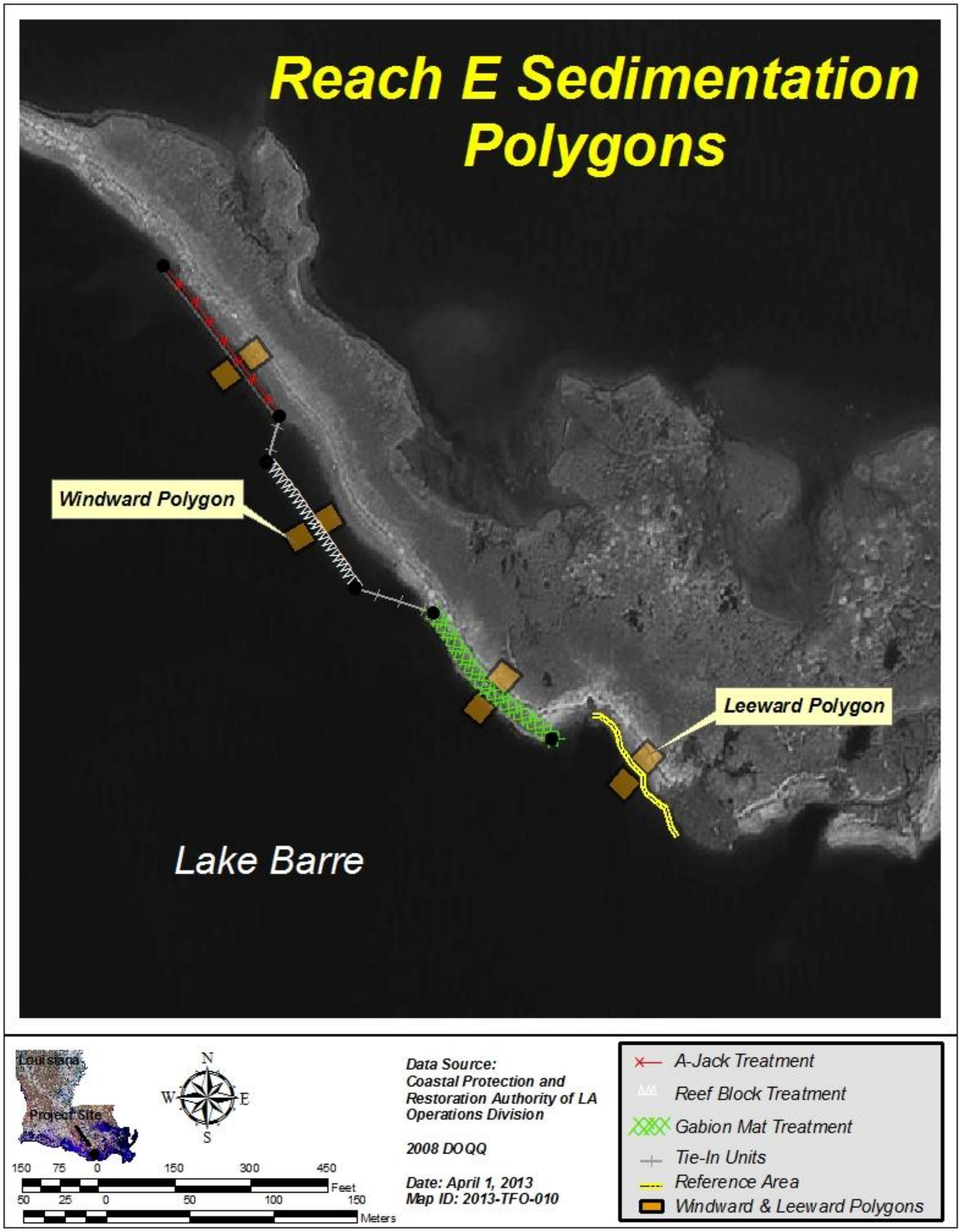

Figure 5. Layout of the windward and leeward sedimentation polygons at the Terrebonne Bay Shore Protection Demonstration (TE-45) project. Although only the Reach E polygons are shown, the layout is the same for Reaches A and B.

Shoreline Change

Shoreline position data were analyzed to estimate shoreline changes in the Terrebonne Bay Shore Protection Demonstration (TE-45) project and reference areas using the Digital Shoreline Analysis System (DSAS version 2.1.1) extension of ArcView® GIS (Thieler et al. 2003). Shoreline positions were determined by digitizing aerial photographs at a 1:800 scale as per the Steyer et al. (1995) method, which defines shoreline position as the edge of the live emergent vegetation. The resulting polylines established the shoreline positions in UTM NAD 83 coordinates. Pre-construction and post-construction aerial photographs were acquired over a thirteen year period to discern the A-Jack, Gabion Mat, and ReefBlk structures effect on shoreline erosion rates. Pre-construction aerial photographs were collected on January 28, 1998 and November 1, 2005 while post-construction aerial photographs were captured on September 16, 2007 (as-built), October 30, 2008 (1 year post-con), July 12, 2010 (3 years post-con), and October 28, 2012 (5 years post-con). All images were georectified using UTM NAD 83 horizontal datum.

The January 1998 and November 2005 shorelines were created in ArcView® GIS software to establish pre-construction shoreline change rates, and the September 2007, October 2008, July 2010, and October 2012 shorelines were created to establish post-construction shoreline change rates. Secondly, offshore baselines were drawn for Reach A, Reach B, and Reach E project and reference areas. Thirdly, the DSAS attribute editor was populated by identifying shorelines and baselines and dating shorelines. Next, 300 m (984 ft) simple transects were cast from the baseline at 10 m (33 ft) intervals producing shoreline change, intersect, and transect shapefiles. Then, these shapefiles were edited by eliminating transects that intersect the shorelines at irregular angles. Finally, shoreline change data were imported into Excel® to calculate average and annual erosion rates for each period and each treatment. Shoreline change rates were assessed and mapped for the ensuing periods January 1998-November 2005 (pre-con), September 2007-October 2008 (post-con), October 2008-July 2010 (post-con), and July 2010-October 2012 (post-con) for the area behind each Reach and each 91 m (300 ft) treatment. Shoreline analyses consisted of one-way ANOVA's. The statistical package used was JMP (v10).

Hydrology

Hourly water temperature, specific conductance, salinity and water level data were collected from two stationary continuous recorders. Initially YSI 6920 data sonde units were deployed. However, on June 1, 2010 the YSI recorders were replaced with Hydrolab MS-5 data sonde units. Each sonde was attached to a wooden post driven into the bay bottom and adjacent to the study sites. Sonde site TE45-H01 was near Reaches A and B, while site TE45-H02 was near Reach E (Figure 6). Calibration of the YSI and Hydrolab data sondes, as well as data corrections, followed the established protocols developed by the CPRA (Folse et al. 2012). Occasionally, when one of the two continuous data sondes malfunctioned, hourly salinity and temperature missing data were calculated using regressions developed between the two sondes using 5-years of hourly data. Predicted salinity (R^2 = 0.73, P<.001) for H01 is Y= 0.79x +

1.61, and for H02 is Y = 0.92x + 3.18. Discrete water data were also taken while in the field using a Hydrolab MS-5 or an YSI-30 meter for comparison to the continuous sonde data.

Clod cards were deployed to assess wave and water energy. While water currents as well as wave activity were reflected in the dissolution rates of the clod cards, relative water motion, as measured by the clod cards, is referred to in this study as wave energy. Cards were deployed for 5-7 days nine times from July 2010 to May 2011. Clod cards were returned to the lab after the period of deployment and dried for 24 hours at 60°C (140°F), before being weighed to determine a final weight (Wall 2004, Barber 2007). The premise is that plaster-of-paris dissolves more rapidly in higher wave energy conditions, and as a result the rate of dissolution can be used to approximate the amount of wave energy in one area relative to another. This method facilitates determination of water energy between locations.

Clod cards were created by pouring DAP™ plaster-of-paris into cylindrical aluminum candle molds with a diameter and height of 10.2 cm (4.0 inch) or a diameter of 7.62 cm (3.0 inch) and height of 10.2 cm (4.0 inch). Clod cards were dried for 24 hours at 60°C (140°F) and weighed prior to deployment. For each deployment clod cards were shaved to within 2 grams of a target weight. For the first four deployments, molds with a 7.62 cm (3.0 inch) diameter were used. However, the smaller molds often completely dissolved before they were able to be retrieved, so the larger molds were used for the last five deployments. A wick pin was inserted through the middle of a clod during curing to allow a cable tie to later be passed through the card. This cable tie was used to secure a clod card to a concrete cinder block for eventual field deployment (Thompson and Glenn 1994, Wall 2004).

Oyster Spat Availability in Project Area

Unglazed quarry tiles with two ends inserted into slotted 1.9cm diameter (3/4 inch) pvc pipe were used to monitor for oyster recruitment (spat set) every 28-45 days from early spring through late fall of each year since 2008. Area of each quarry tile available for spat measured 15 cm by 15 cm square (6 inch x 6 inch) and a minimum of three were placed at each Reach, and often many more than three. Quarry tiles/pvc pipes were strapped horizontally to vinyl-coated wire crab-style cages with a square mesh 3.8 cm (1.5 inch x 1.5 inch). Cages were placed subtidal adjacent to the windward side of the experimental structures. Once retrieved from the cages all tiles were bagged, iced and returned to Nicholls and stored in a walk-in cooler at 3.3°C (38°F) until enumerated for live oysters, barnacles and mussels per tile.

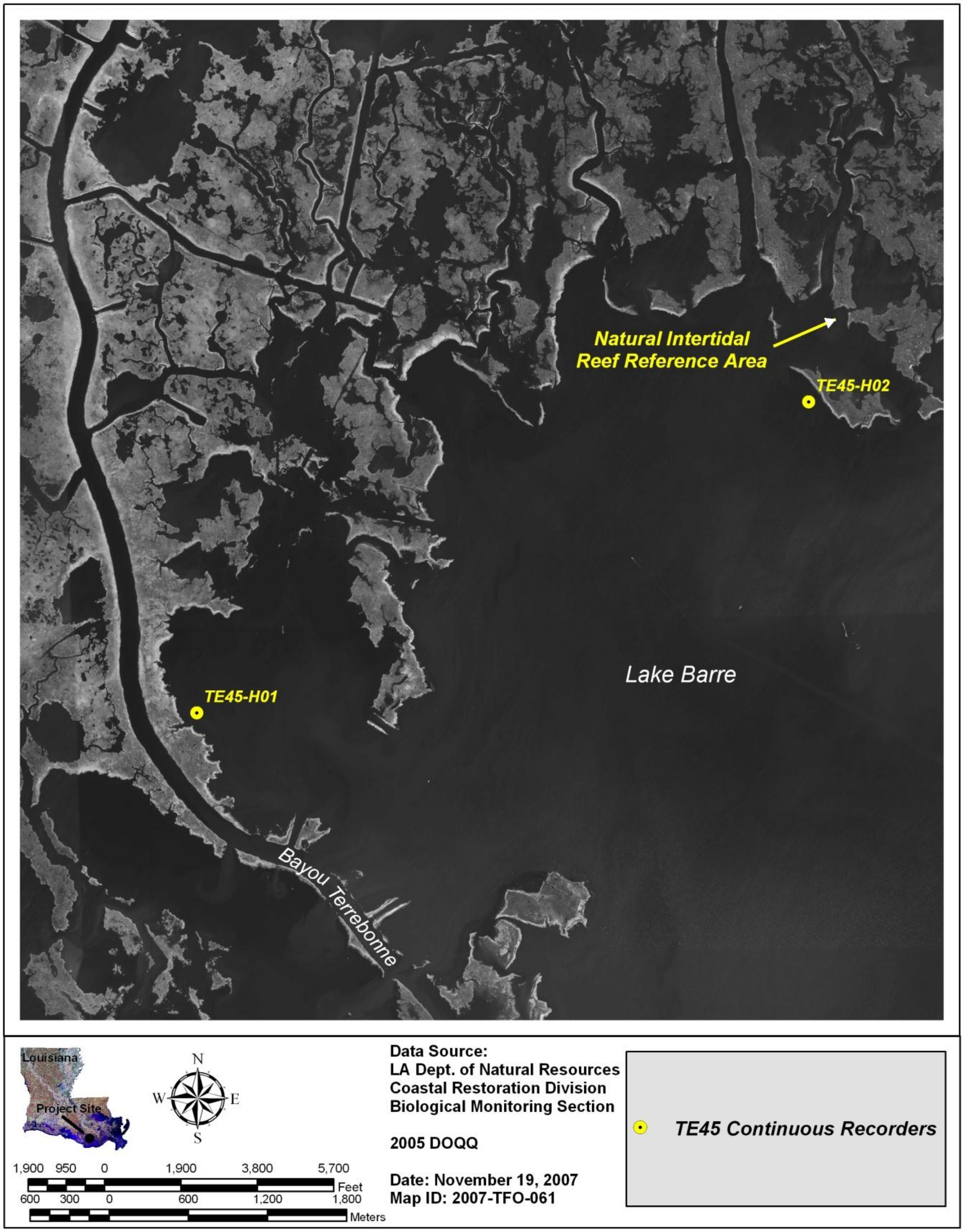

Figure 6. Location of continuous recorder stations and the natural intertidal oyster reef used as a reference to treatments at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

Fauna Recruitment to Experimental Structures

Each structure's shape required placing a pvc quadrat frame in a unique way, and also required measurements to be taken at low tide when exposed. The only time of year when structures were exposed long enough was during the winter months. Winter was also advantageous since all structures had been exposed to traditional oyster spring-through-fall spawning and recruitment cycles.

Each structure type (treatment) was assessed at each Reach by randomly selecting sites along its 91 m (300ft) length by using the uniformly-distributed-random-numbers statistical method (Sigma Stat v3.1). Through three fall-winter-early spring periods, 2010-11, 2011-12 and 2012-13, when tides were lowest and when eastern oyster recruitment peaks were complete, the structures were visually and quantitatively examined. The surficial (surface) layer of attached eastern oysters and its major competitors for space, barnacles (*Balanus spp*.) and mussels (predominantly the hooked *Ischadium recurvum*) were noted during each yearly winter assessment period.

In the winter of 2011-12 quadrat density samples were collected to enumerate oysters, mussels and barnacles. Quadrats were 1/16 m^2 for Gabion Mats and for A-Jacks using a pvc frame to outline the area, but for ReefBlks the quadrat was the entire contents of the middle bag of one side from the top down to a depth of 25 cm (0.82 ft), about half its height. Gabion Mat quadrats were taken at an average distance of 3.9 m (12.95 ft) for Reach A, 3.63 m (11.81 ft) for Reach B and 3.33 m (10.91 ft) for Reach E, all slightly greater than half of a mat's length. Density data collected in 2009-10 (Melancon et al. 2010) indicated that there was no significant difference ($P<.05$) between mid-mat and bottom-mat oyster densities, and therefore one quadrate per mat was taken for this mid-term report in the winter of 2011-12. A-Jack quadrats were taken from windward and leeward arms by using a metal scraper and cleaning an area equivalent to 1/16 m^2, usually the equivalent of three flat sides per arm per site; at each site two arms were from a top orientation of the structure and one was from a vertical orientation. ReefBlk quadrats, as with A-Jack quadrats, took into consideration windward and leeward facing structures when selecting sites for obtaining density samples. Photos of each structure type and how density quadrats were collected can be seen in the Appendix H.

In addition to density quadrat samples, also collected were quadrat samples that calculated the percent of structure covered with oysters and percent of that coverage which was actual consolidated reef. Consolidated reef was defined as those oysters fused into a clump or mass with some having relatively good shell length (height) and relatively good three dimensional structure. Now that the constructed structures are 4-5 years old with multiple age classes of oysters this is a good working definition of consolidated reef. For all three structure types, such a definition confined oysters to the surficial layer; consistently, interior oysters were small, sometimes clumped, but most often singles, and definitely not developed into a mass with significant structure or dimensional relief.

Oyster length frequency data was also collected while collecting surficial and interior density data during the 2011-12 winter. Oysters were classified as live, dead (gaping with articulated, hinged valves intact), or scar (only one oyster valve remaining cemented to the substrate). Only oysters that could be accurately measured to nearest millimeter using a plastic ruler were recorded.

Natural Intertidal Reef Reference Area

A reference site was established on a natural intertidal oyster reef just north of Reach E (Figure 6). The reference site was located in a shallow-water area to prevent commercial harvest that would compromise data comparisons. Oyster density and length frequency data were collected in the winter of 2009 for comparisons to the oyster populations that have recruited to the structures. As typical of natural intertidal oysters in Louisiana, the reef structure is not always continuous along a shoreline, but often patchy in distribution. Therefore, to maximize comparisons to the structures, the 0.25 m^2 (2.7 ft^2) frame was randomly placed on the reference area wherever reef or oyster clusters existed, and not on bare mud habitat.

Fauna Statistics

Analyses (see Appendix D) consisted primarily of paired t-tests, one-way and two-way using the post-hoc Tukey method of pairwise multiple comparison procedures. If the data were not normally distributed, Kruskal-Wallis and Dunn's non-parametric tests were utilized. The statistical packages used were Sigma Stat (v3.1) and PC-SAS (v9.1.3).

Cost-effectiveness

To determine the cost-effectiveness of each structure treatment, construction cost and structure performance were compared. The cost to procure and install the A-Jack, Gabion Mat, and ReefBlk structures were obtained from the TE-45 project completion report (T. Baker Smith 2008). These monetary costs were then assessed in association with structure function to ascertain the cost-effectiveness of each structure treatment. The performance measures applied to quantify structure functioning were shoreline change rate, oyster coverage, consolidated oyster reef, structure settlement, and structure sedimentation. Once the costs and performance measures were evaluated, the cost-effectiveness of the structure treatments was ranked.

CRMS Supplemental

Additional data collected at CRMS-*Wetlands* stations is being used as supporting or contextual information for the TE-45 project. Data types collected at CRMS sites include hydrologic, emergent vegetation, physical soil characteristics, discrete porewater salinity, marsh surface elevation change, vertical accretion, and land/water analysis of 0.4 mi^2 (1.0 km^2) area encompassing the station (Folse et al. 2012). For this report, land/water analysis and vegetation data from two sites situated outside of the project area (CRMS0341 and CRMS0355) will be used to characterize the structure of the project area marshes (Figure 7). In the future, data collected from the

CRMS network over a sufficient amount of time to develop valid trends will be used to develop integrated data indices at different spatial scales (local, basin, coastal) to which we can compare project performance.

Land/Water Classification CRMS0341 and CRMS0355

Land/water analysis was performed on a 1.0 km^2 (0.4 mi^2) portion of the marsh creation area at the CRMS0341 and CRMS0355 sites (Figure 7). The U.S. Geological Survey's National Wetlands Research Center (USGS/NWRC) obtained 1.0 m (3.3 ft) resolution color infrared (CIR) aerial photography to delineate land and water habitats over time. A pre-construction aerial image was captured on November 1, 2005 and a post-construction image was captured on October 30, 2008. These images were analyzed, interpreted, processed, and verified for quality and accuracy using protocols established in Folse et al. (2012). Specifically, habitats in the 1 km^2 (0.4 mi^2) were condensed to a land or water classification. Land was considered to be a combination of emergent marsh, scrub-shrub, wetland forested, and upland habitats. The open water, beach/bar/flat, and submerged aquatics (SAV) habitat classes were considered water. Once grouped into these two classes, the acreages of land and water were calculated. After the analysis was complete, the classification data and the photomosaic were mapped to spatially view the data. The percentages of land and water, the land to water ratios, and annual rates of change were determined to summarize the data.

Vegetation CRMS0341 and CRMS0355

Vegetation data was collected at the CRMS0341 and CRMS0355 sites (Figure 7) to document species composition and percent cover over time. Ten (10) plots were placed inside the 200 m^2 (239 yd^2) square, which is nested within the 1.0 km^2 (0.4 mi^2) square, as per Folse et al. (2012) (Figure 7). Vegetation data were collected in August (CRMS0355) and September 2006 (CRMS0341), August 2007, August 2008, July 2009, June 2010, August 2011, and July 2012 via the semi-quantitative Braun-Blanquet method (Mueller-Dombois and Ellenberg 1974; Sawyer and Keeler-Wolf 1995; Barbour et al. 1999). Plant species inside each 4m^2 (5 yd^2) plot were identified, and cover values were ocularly estimated. After sampling the plot, the residuals within a 5 m (16 ft) radius were inventoried. Mean percent cover was calculated to summarize the vegetation data and was grouped by year. Floristic quality index (FQI) was also estimated using the Cretini and Steyer (2011) protocol. Site FQI assessments were derived using mean percent cover values and coefficient of conservatism (CC) scores.

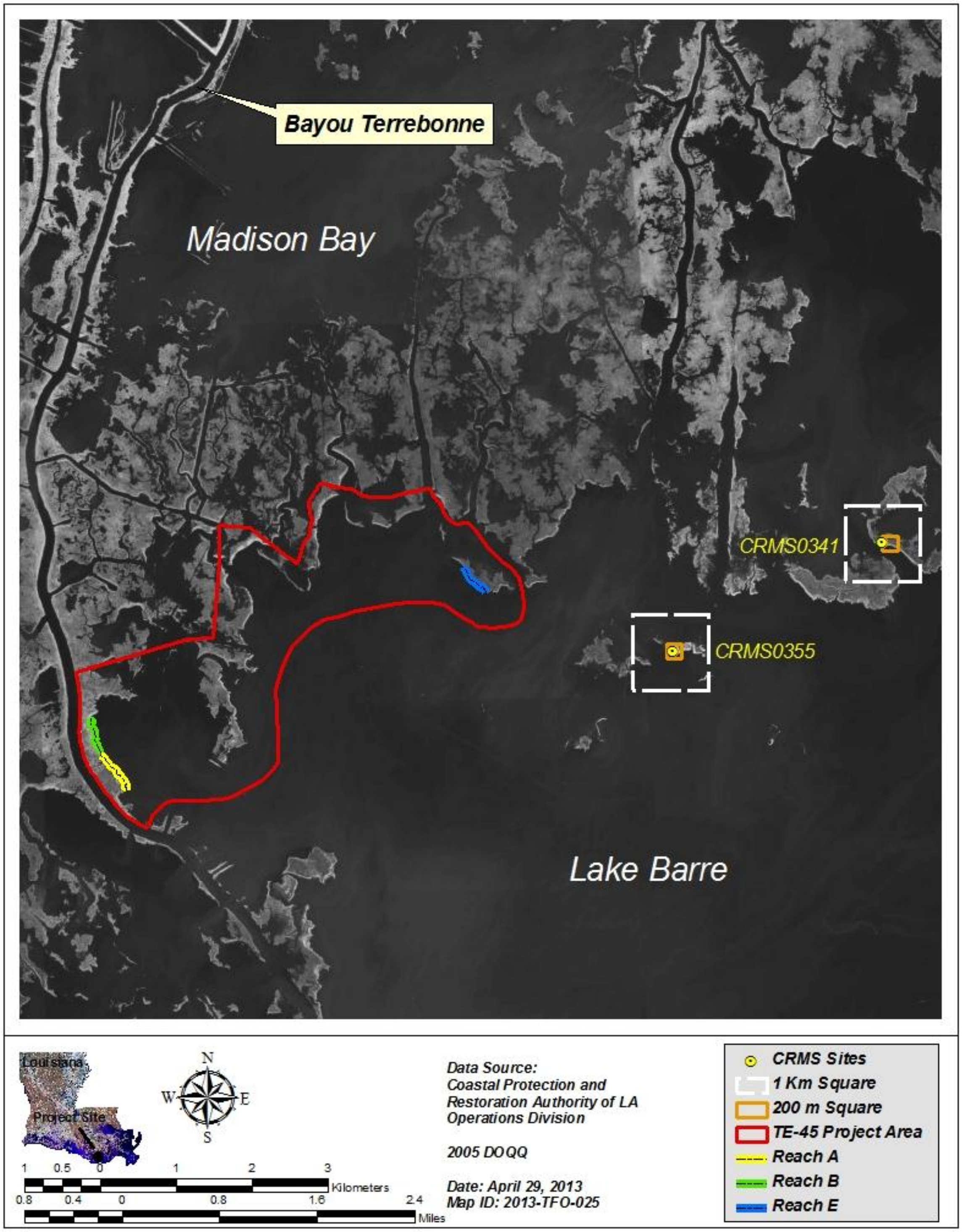

Figure 7. **Location of the CRMS0341 and CRMS0355 sites positioned on the eastern perimeter of the Terrebonne Bay Shore Protection Demonstration (TE-45) project area.**

c. Preliminary Monitoring Results

Elevation

The Terrebonne Bay Shore Protection Demonstration (TE-45) project Reaches experienced volume reductions over time. Elevation change and volume distributions for the August 2007 (pre-construction) to February 2008 (as-built) interval are shown in Figure 8 (Reaches A and B) and Figure 9 (Reach E) while post-construction changes (February 2008-February 2011) are illustrated in figures 10 (A & B) and 11 (E). Elevation grid models for the pre-construction, as-built, and post-construction surveys are also provided in Appendix E (Figures E-1 to E-6). Approximately, 2,449 m^3 (3,203 yd^3) of sediment were removed from the Reach A and B shorelines and 2,194 m^3 (2,870 yd^3) of sediment were removed from the Reach E shoreline for the 6 month pre-construction period (Figures 8 and 9). During the post-construction period, sediment volume decreased by approximately 6,861 m^3 (8,973 yd^3) at Reaches A and B (Figure 10) and 2,435 m^3 (3,185 yd^3) at Reach E (Figure 11). The reference areas also experienced volume losses for the post-construction interval, RA [915 m^3 (1,197 yd^3)], RB [234 m^3 (306 yd^3)], and RE [1,136 m^3 (1,486 yd^3)] (Figures 10 and 11). Because of the different orientation and frequency of the pre-construction and as-built survey transects, the volume loss inside the TE-45 Reaches may be exaggerated. However, post-construction data also exhibited declines in sediment volume. Moreover, the Reach A and B volume loss increased considerably for the post-construction interval. In addition, the Reach A and E reference areas had substantial volume reductions for areas of less than one acre. Figures 10 and 11 provide evidence showing that the volume losses in these reference areas were primarily induced by erosion along their shorelines. All iterations of this elevational analysis suggest that the Reaches are releasing sediment volume through compactional (Morton et al. 2003; Roberts et al. 1994) and erosional mechanisms (Watzke 2004; Stone et al. 1997).

The TE-45 structures and reference areas sustained sedimentation deficits in the interval from 2008 to 2011. Only the Gabion Mat (all Reaches) and ReefBlk (Reach B) structures nominally aggraded contours in the leeward position (Table 1, Figure 5). No structure or reference area experienced sediment volume increases in the windward position. Furthermore, the Reach A reference area was the lone replicate to incur a larger volume loss in the leeward position. The overall mean volume loss in the windward position was -61±8 m^3 (-79±10 yd^3) while the leeward position recorded a mean volume loss of -18±9 m^3 (-23±12 yd^3) (Table 1). These differences were significant ($P < 0.05$). The Gabion Mat replicate and the reference area at Reach E recorded the largest volume reductions in front of the shorelines (windward) whereas the reference areas at Reaches A and E displayed the largest volume reductions behind the shorelines (leeward) (Table 1). Therefore, the volume change in the leeward reference areas was significantly different ($P < 0.05$) from the leeward project areas. As delineated in figures 10 and 11, shoreface and shoreline erosion appear to be the mechanisms inducing change in areas with the greatest volume loss in the windward (Reach E Gabion Mat and reference) and leeward (Reach A and E reference) positions.

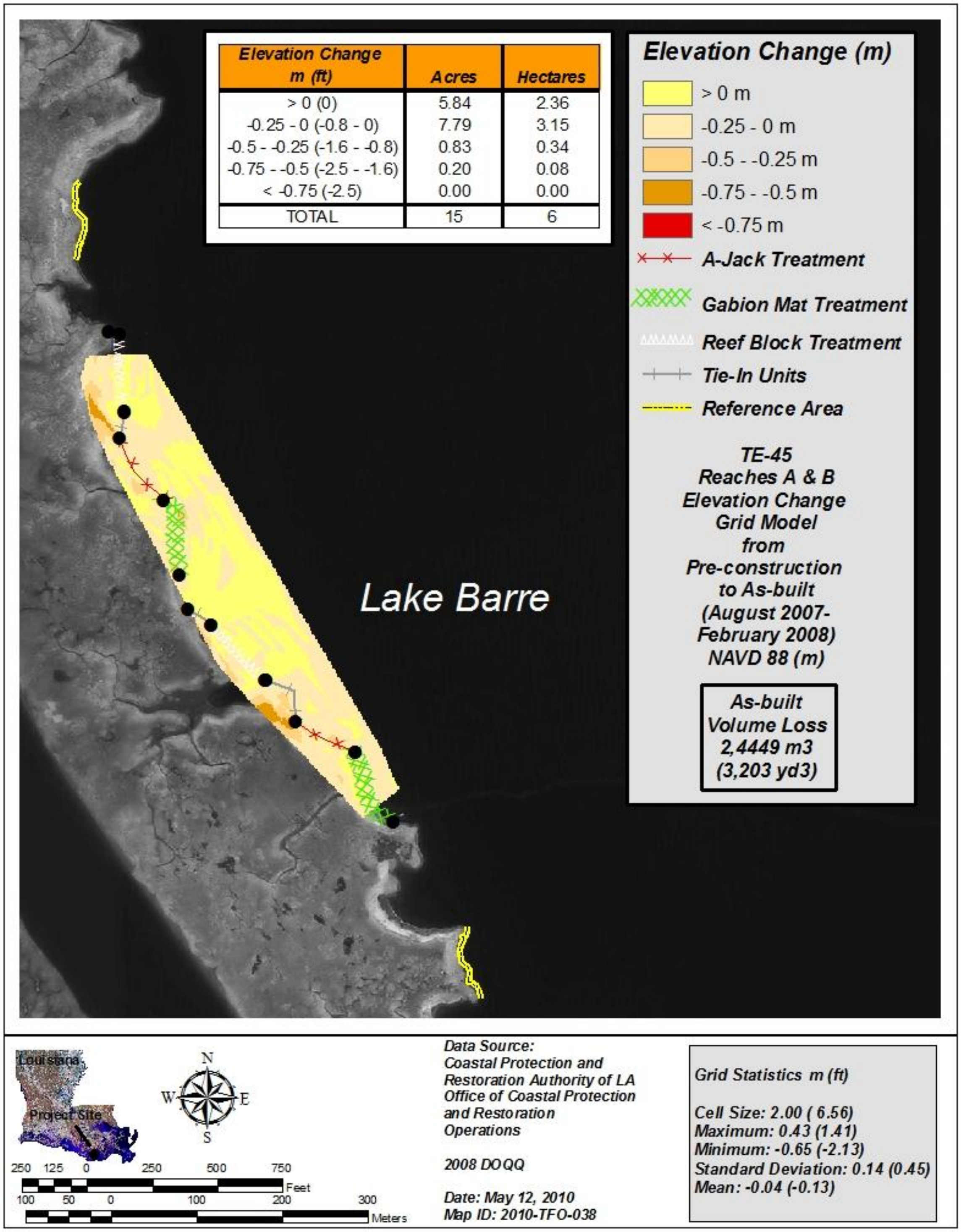

Figure 8. **Elevation and volume change grid model from pre-construction (Aug 2007) to as-built (Feb 2008) for Reaches A and B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

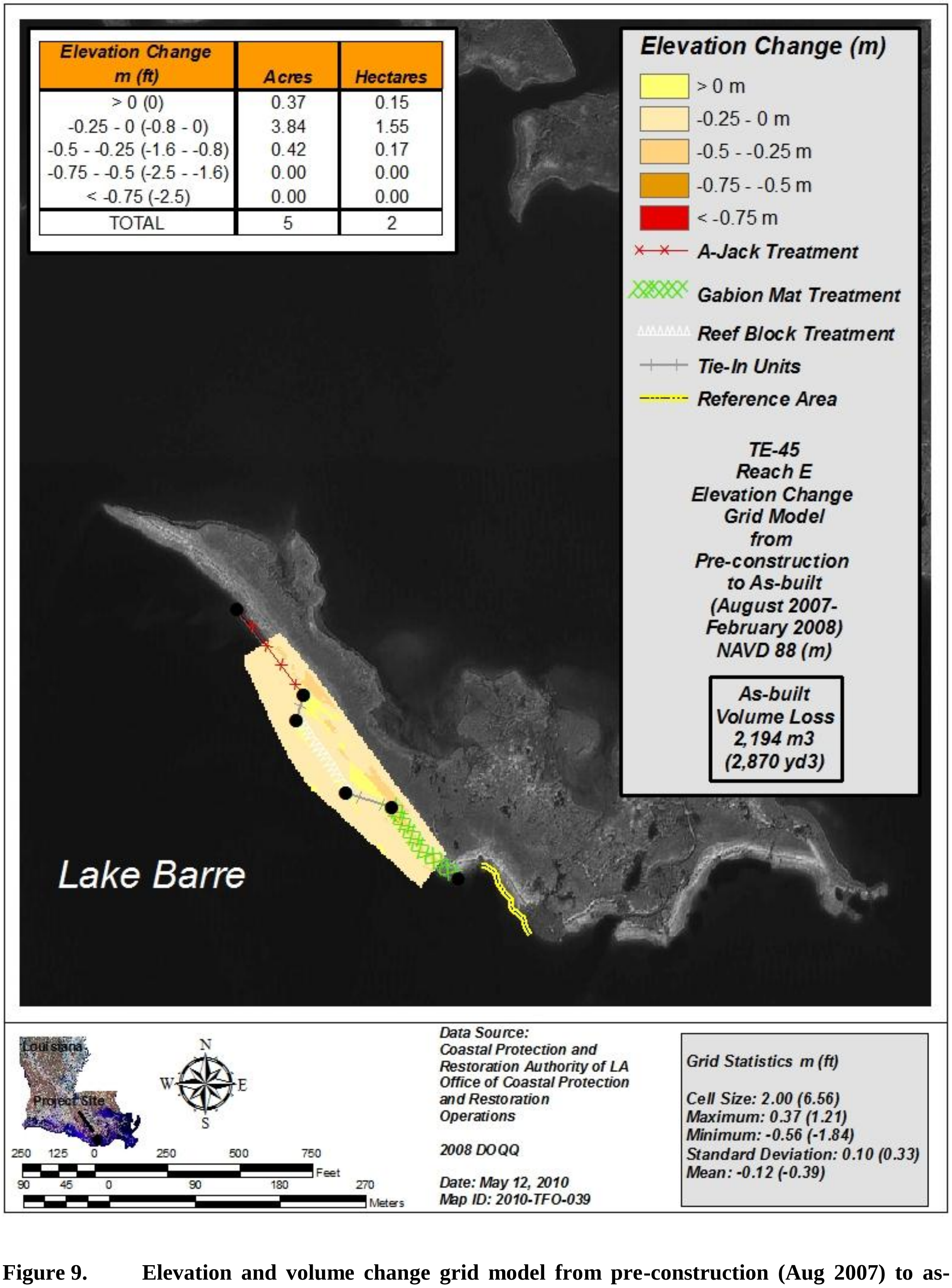

Figure 9. **Elevation and volume change grid model from pre-construction (Aug 2007) to as-built (Feb 2008) for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

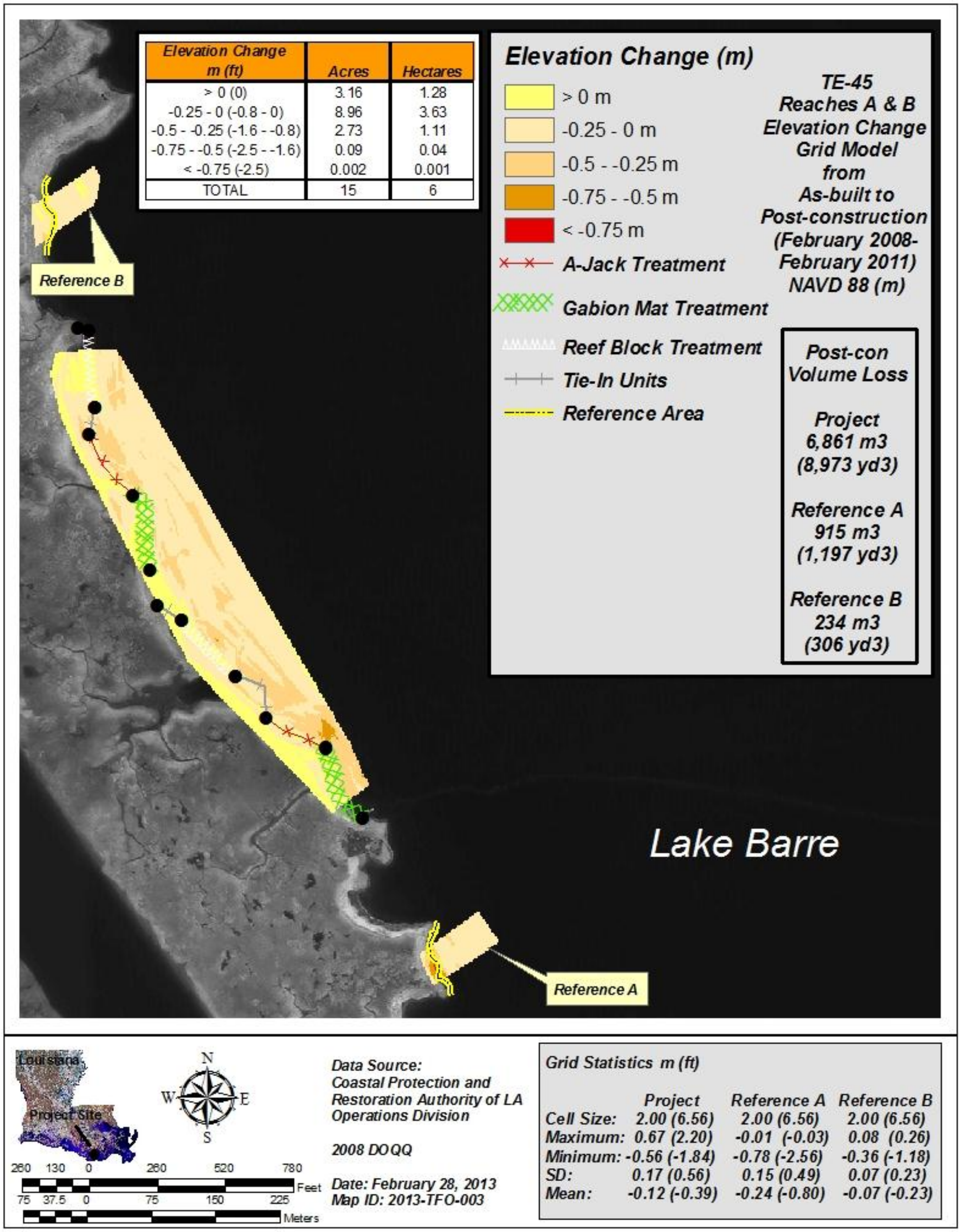

Figure 10. Elevation and volume change grid model from as-built (Feb 2008) to post-construction (Feb 2011) for Reaches A and B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

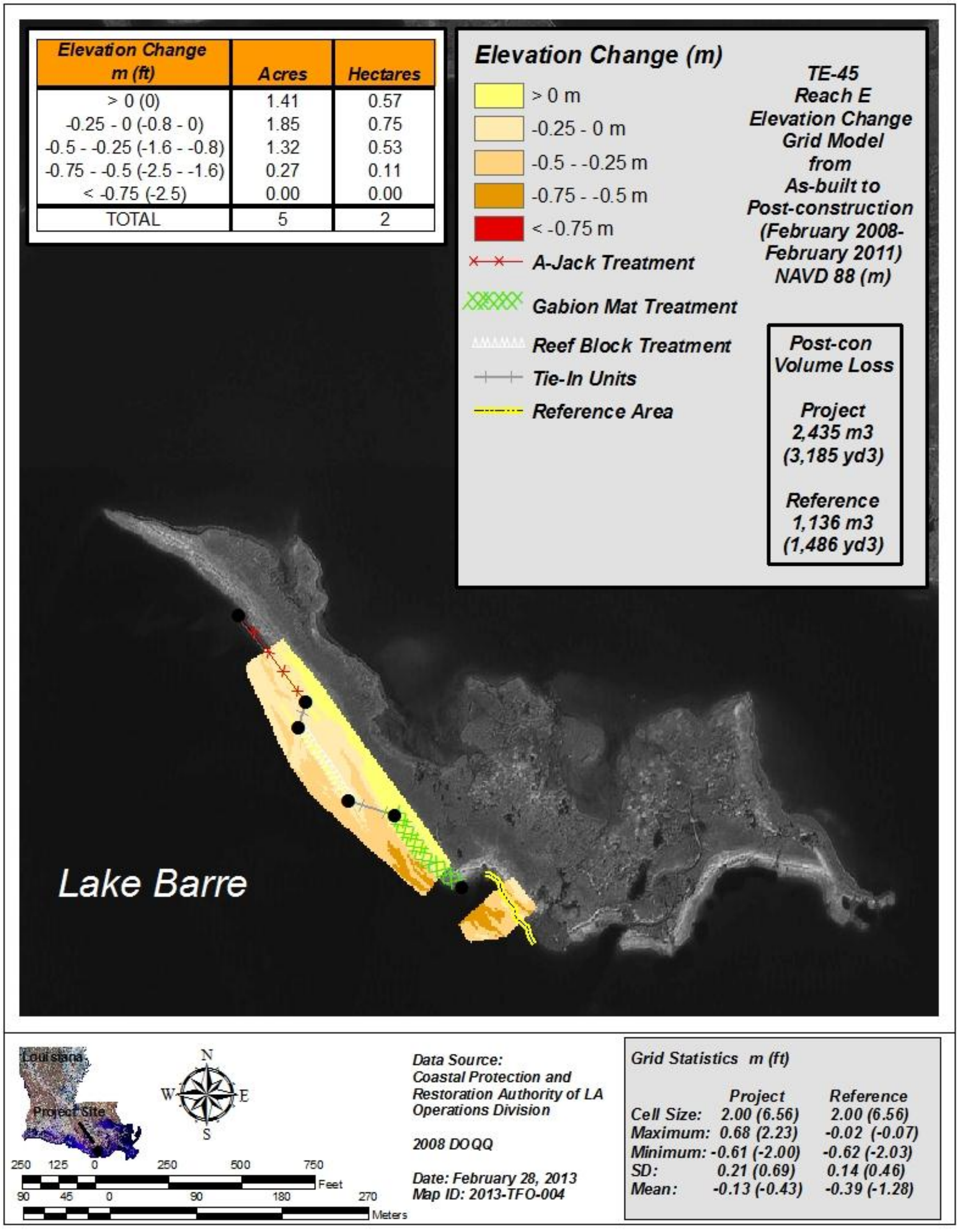

Figure 11. Elevation and volume change grid model from as-built (Feb 2008) to post-construction (Feb 2011) for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

Interestingly, Lear et al. (2011) found that structures fronting shallow embayments facilitated higher rates of sedimentation than structures fronting linear segments of shoreline. Since the TE-45 reaches are relatively linear, the shoreline geometry could be adversely impacting sedimentation rates. Additionally, faulting subsidence (Morton et al. 2003) and intermittent sediment transport (Reed 1989) in the Lake Barre region have been implicated in inducing land-loss and low accretionary rates, respectively. The windward volume losses do not seem to support the goal to reduce shoreline erosion while minimizing scouring. However, these volume losses appear to be independent of the structure treatment because the reference areas also show declines in volume and the structures display a variable response. Therefore, these volume reductions are likely a result of the shoreline geometry, subsidence (Morton et al. 2003; Roberts et al. 1994), and tropical and winter storm forcing (Morton and Barras 2010; Stone et al. 1997; Watzke 2004). In closing, the TE-45 structures have not been effective in capturing and retaining sediments to date.

Table 1 Post-construction volume change in the windward and leeward positions at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

Reach	*Treatment*	*Windward Position Volume Change 2008-2011 m3 (yd3)*	*Leeward Position Volume Change 2008-2011 m3 (yd3)*
A	*A-Jack*	-60 (-79)	-18 (-23)
B	*A-Jack*	-54 (-70)	-10 (-13)
E	*A-Jack*	-49 (-64)	-12 (-16)
A	*Gabion Mat*	-76 (-99)	0.93 (1)
B	*Gabion Mat*	-50 (-65)	3 (4)
E	*Gabion Mat*	-112 (-146)	8 (10)
A	*ReefBlks*	-70 (-91)	-8 (-11)
B	*ReefBlks*	-21 (-28)	15 (20)
E	*ReefBlks*	-76 (-99)	-21 (-28)
A	*Reference*	-46 (-60)	-97 (-127)
B	*Reference*	-18 (-24)	-11 (-14)
E	*Reference*	-97 (-127)	-64 (-84)
Mean	-	-61±8 (-79±10)	-18±9 (-23±12)

The results of the structure settlement analysis reveal that the Reach E structures were established at a lower vertical position and have the highest rate of secondary settlement. The TE-45 structures were initially constructed to a mean elevation of 0.29±0.02 m (0.94±0.06 ft) NAVD 88 (Table 2). However, the Reach E structures were installed to a slightly lower mean elevation, 0.23±0.01 m (0.75±0.03 ft) NAVD 88. From 2008 to 2011, the A-Jack [-0.06±0.01 m (-0.19±0.07 ft)], Gabion Mat [-0.07±0.004 m (-0.22±0.01 ft)], and ReefBlk [-0.08±0.04 m (-0.27±0.13 ft)] vertical positions were diminished as the structures settled (Table 2). Note that the ReefBlk treatment had a variable response to secondary settlement and the Gabion Mat treatment had a more uniform response. While there were no sizeable differences in settlement by treatment, the Reach E structures [-0.10±0.02 m (-0.33±0.07 ft)] settled at a rate greater than the mean [-0.07±0.01 m (-0.23±0.04 ft)] (Table 2). Although notable, these differences are not statistically significant (P > 0.05) and this outcome was predicted in the pre-construction geotechnical assessment (Eustis 2002). However, the lower vertical relief of the Reach E structures is probably influencing the ecology (Lenihan and Peterson 1998) and shoreline protection capacity of the created reefs (Hardaway et al. 2010; USACE 2004). The design elevation of 0.3 m (1.0 ft) NAVD 88 was established using water elevations and wave heights to maximize oyster habitat and shoreline protection (MPH 2003). Currently, the Reach E ReefBlk and A-Jack structures have the lowest vertical profile (Table 2).

Table 2. **Structure elevations (as-built and post-construction) and settlement at the Terrebonne Bay Shore Protection Demonstration (TE-45) project over time.**

Reach	*Treatment*	*Structure Elevation 2008 m (ft) NAVD 88*	*Structure Elevation 2011 m (ft) NAVD 88*	*Structure Settlement 2008-2011 m (ft)*
A	*A-Jack*	0.28 (0.92)	0.23 (0.75)	-0.05 (-0.15)
B	*A-Jack*	0.28 (0.92)	0.24 (0.79)	-0.04 (-0.14)
E	*A-Jack*	0.22 (0.72)	0.13 (0.43)	-0.09 (-0.29)
A	*Gabion Mat*	0.29 (0.95)	0.23 (0.75)	-0.07 (-0.24)
B	*Gabion Mat*	0.35 (1.15)	0.29 (0.95)	-0.06 (-0.20)
E	*Gabion Mat*	0.25 (0.82)	0.19 (0.62)	-0.07 (-0.22)
A	*ReefBlks*	0.30 (0.98)	0.28 (0.92)	-0.01 (-0.04)
B	*ReefBlks*	0.40 (1.31)	0.32 (1.05)	-0.09 (-0.30)
E	*ReefBlks*	0.22 (0.72)	0.07 (0.23)	-0.14 (-0.47)
Mean	-	0.29±0.02 (0.94±0.06)	0.22±0.03 (0.72±0.09)	-0.07±0.01 (-0.23±0.04)

Shoreline Change

Preliminary pre and post-construction shoreline position data indicate that all structures have reduced shoreline erosion rates in the Terrebonne Bay Shore Protection Demonstration (TE-45) project area. Pre-construction shoreline erosion rates averaged -4.7 m/yr (-15.4 ft/yr) in the project area and -5.8 m/yr (-19.0 ft/yr) in the reference area from January 1998 to November 2005 (Figure 12). Post-construction results for the period from September 2007 to October 2008 (1 year post-con) show average erosion rates of -0.5 m/yr (-1.6 ft/yr) in the project area and -3.5 m/yr (-11.5 ft/yr) in the reference area (Figure 13) while erosion rates for the second and third post-construction intervals, October 2008 to July 2010 (3 years post-con) and July 2010-October 2012 (5 years post-con), were -1.5 m/yr (-5.0 ft/yr) and -0.9 m/yr (-2.8 ft/yr) in the project area and -3.6 m/yr (-11.9 ft/yr) and -2.3 m/yr (-7.4 ft/yr)

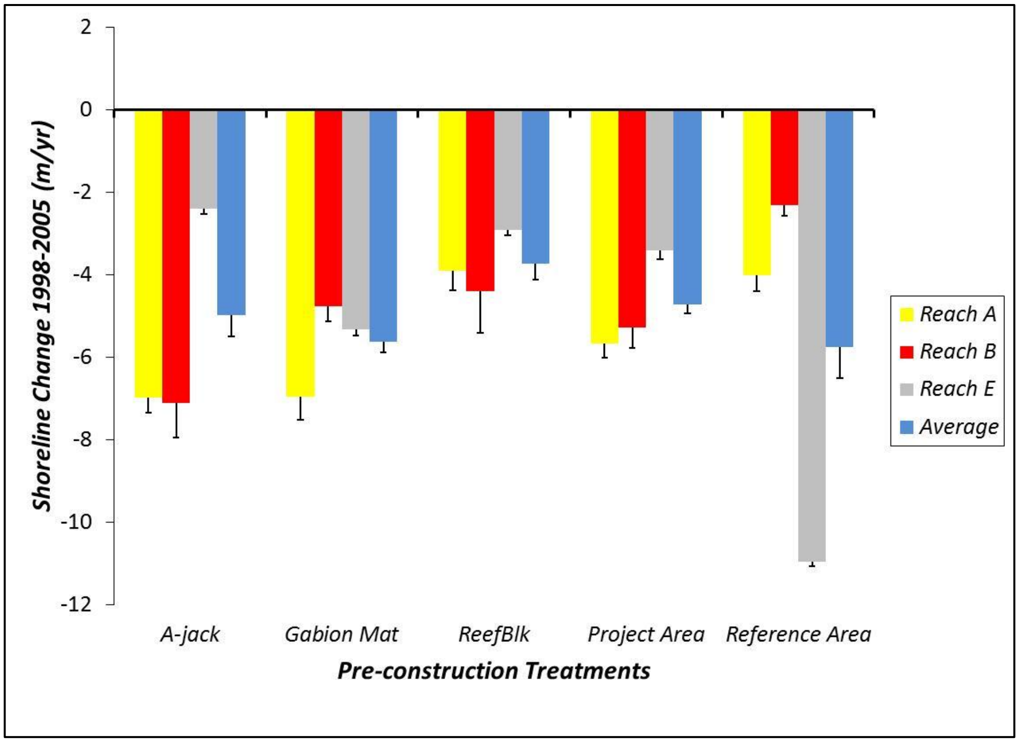

Figure 12. **Pre-construction (1998-2005) shoreline erosion rates for each treatment and each Reach at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

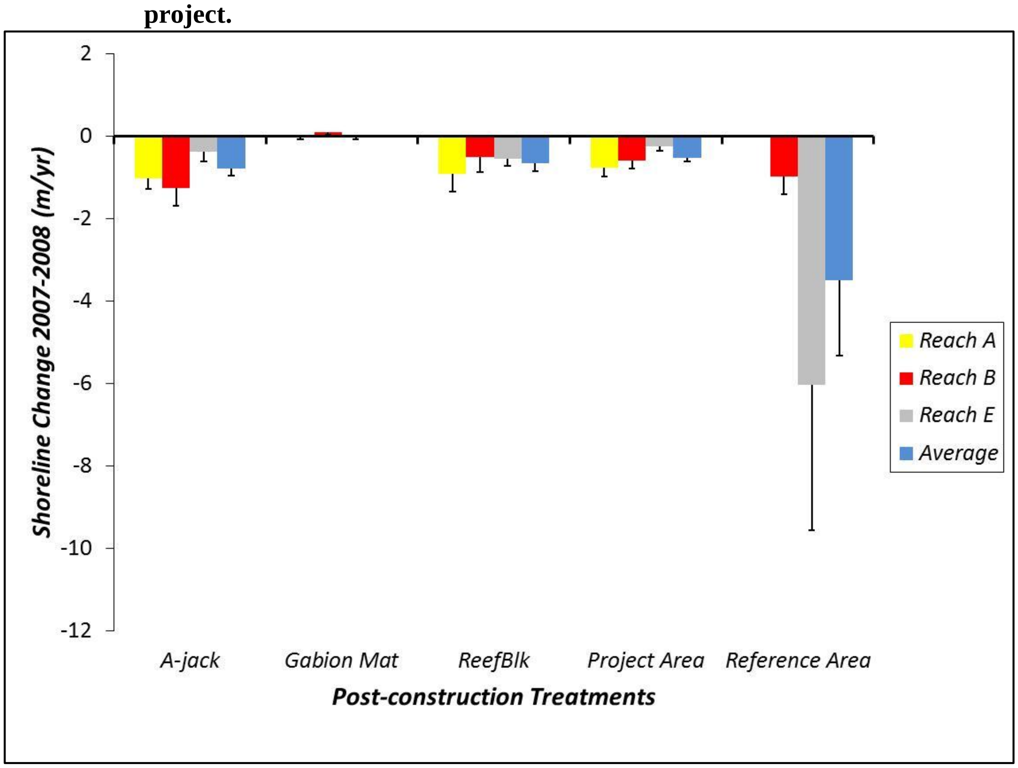

Figure 13. **Post-construction (2007-2008) shoreline erosion rates for each treatment and each Reach at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

in the reference area, respectively (Figures 14 and 15). The decrease in erosion rates behind the TE-45 structures is notable considering that Hurricane Gustav made landfall a few miles southwest of the project area in 2008, and Hurricane Ike (2008), T. S. Lee (2011) and Hurricane Isaac (2012) have also impacted the project area since construction (Figure 16).

Pre-construction data reveals that the Terrebonne Bay Shore Protection Demonstration (TE-45) project (future structure locations) and reference area Reaches were eroding at differential rates. Shoreline change graphics for the pre-construction period are provided in Appendix F (Figures F-1 to F-3). Reach A recorded the highest erosion rate, -5.7 m/yr (-19 ft/yr) while the Reach B and Reach E shorelines eroded at -5.3 m/yr (-17 ft/yr) and -3.4 m/yr (-11 ft/yr) during the 8-year pre-construction interval (Figure 12). Not only did the Reaches erode at differential rates but the shorelines within each Reach and the reference areas also eroded at varying rates. The impending locations of the Gabion Mat -5.6 m/yr (-18.4 ft/yr), A-Jack -5.0 m/yr (-16.4 ft/yr), and the ReefBlk -3.7 m/yr (-12.1 ft/yr) treatments transgressed at asymmetrical rates (Figure 12). Similarly, the reference areas receded at disproportionate rates of -11 m/yr (-36.1 ft/yr) (Reach E), -4.0 m/yr (-13.1 ft/yr) (Reach A), and -2.3 m/yr (-7.5 ft/yr) (Reach B) (Figure 12). Moreover, the Reach E reference area transgressed at a considerably faster rate than the other TE-45 shorelines in the pre-construction period.

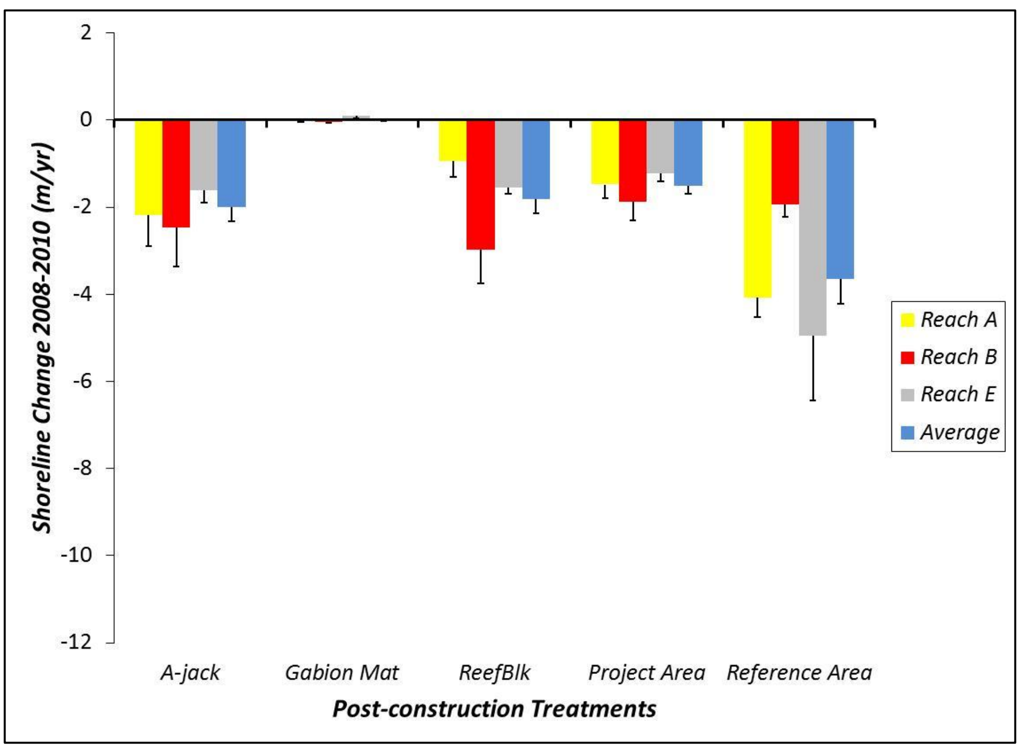

Figure 14. **Post-construction (2008-2010) shoreline erosion rates for each treatment and each Reach at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

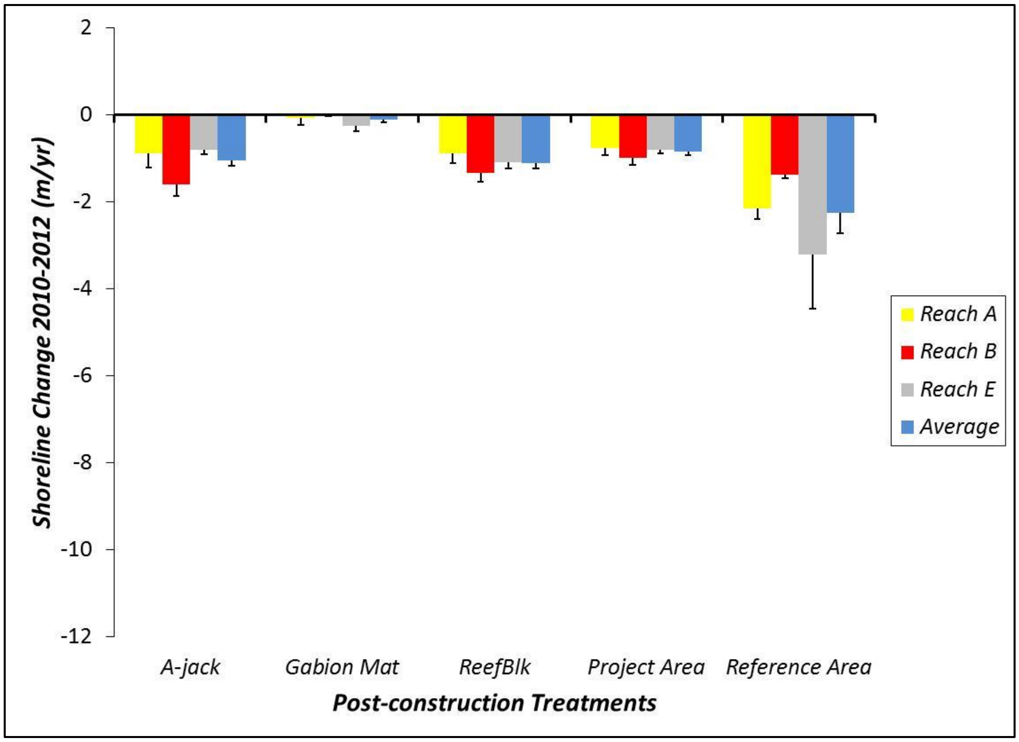

Figure 15. **Post-construction (2010-2012) shoreline erosion rates for each treatment and each Reach at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

Although the pre-construction shoreline erosion rates were a little inconsistent, these differences were not significant (P > 0.05) (Figures 12 and 17). The pre-construction data also illustrates that the TE-45 Reaches were transgressing at a substantial rate before construction. The passage of Hurricane Cindy (July 2005), Hurricane Katrina, (August 2005), and Hurricane Rita (September 2005) probably exacerbated shoreline transgressions in the pre-construction project and reference areas (Figure 16).

The post-construction shoreline analysis suggests that the Gabion Mat, ReefBlk, and A-Jack structures are lowering shoreline erosion rates at all the Terrebonne Bay Shore Protection Demonstration (TE-45) project Reaches. The average shoreline erosion rate behind the structures for the initial analysis (2007-2008) was only -0.5 m/yr (-1.6 ft/yr) significantly less than the -4.7 m/yr (-15.4 ft/yr) rate recorded in the pre-construction interval (Figures 12 and 13). Conversely for the 2008-2010 interval, erosion rates expanded to -1.5 m/yr (-5.0 ft/yr) (Figure 14). While this rate is three times the initial post-construction rate, it is considerably lower than the pre-construction rate. Erosion rates declined during the 2010-2012 interval to -0.9 m/yr (-2.8 ft/yr) (Figure 15). Shoreline change data for all time intervals (pre, post 1, post 2, and post 3) were significantly different (P < 0.05). Shoreline change graphics for the post-construction period are provided in Appendix F (Figures F-4 to F-12).

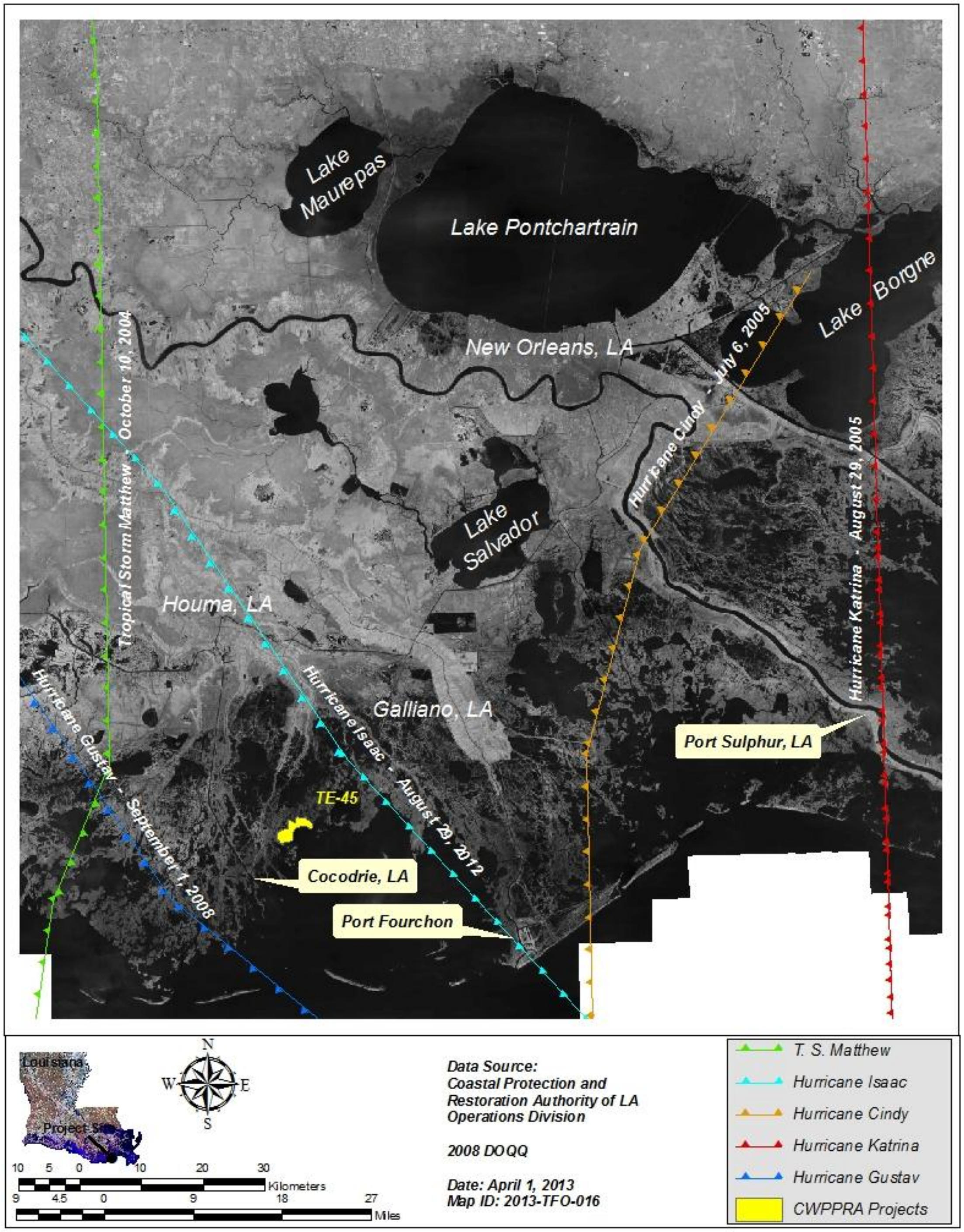

Figure 16. Pre-construction (2004 & 2005) and post-construction (2008 & 2012) tropical storms impacting the Terrebonne Bay Shore Protection Demonstration (TE-45) project area shoreline. Hurricanes Ivan (2004), Rita (2005), Ike (2008), and Tropical Storm Lee (2011) are not shown because the eye wall of these storms traveled further to the south outside the extent of the map.

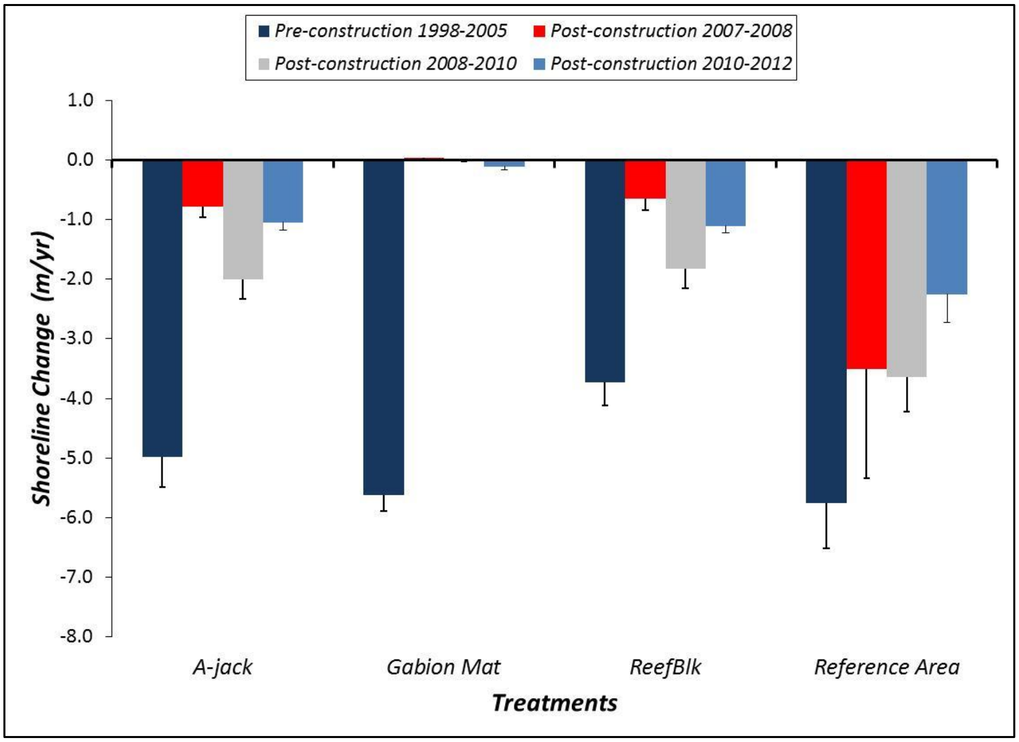

Figure 17. Comparison of shoreline change means for the pre-construction (mean of 8 years) and post-construction (mean of 1, 3, and 5 years) time periods.

Amid the Reaches, Reach A continued to have the highest erosion rate followed by Reach B and Reach E for the 2007-2008 interval. These Reaches had erosion rates of -0.8 m/yr (-2.5 ft/yr), -0.6 m/yr (-1.9 ft/yr), and -0.3 m/yr (-0.8 ft/yr) (Figure 13). Interestingly, the Reaches were positioned in the same order before construction (Figures 12 and 13). However, Reach B [-1.9 m/yr (-6.2 ft/yr)] incurred the greatest erosion rate for the 2008-2010 interval followed by Reach A [-1.5 m/yr (-4.9 ft/yr)] and Reach E [-1.2 m/yr (-4.0 ft/yr)] (Figure 14). Reach B also transgressed at the highest rate for the 2010-2012 interval [-1.0 m/yr (-3.2 ft/yr] while the other Reaches eroded at the same rate, 0.8 m/yr (-2.5 ft/yr) (Figure 15). There were no significant differences ($P > 0.05$) amongst Reaches.

The shorelines below the Gabion Mat treatment documented the lowest erosion rates, 0.04 m/yr (0.1 ft/yr), 0.01 m/yr (0.03 ft/yr) and -0.10 m/yr (-0.33 ft/yr), during all post-construction intervals (Figures 13, 14, 15, and 17). Actually, the first two post-construction intervals showed minimal progradation. However following visual inspections and delineation of the structure edge, it became apparent that the shoreline position differences are probably the result of errors caused by the resolution of the aerial images, scale of digitization, and the placement of the mats on the marsh/water interface. During the 2010-2012 interval, the shorelines behind the Reach A and E Gabion Mat structures incurred their initial transgressions (very minor) since construction (Figure 15). Although not included in the shoreline data, the Reach E Gabion Mats experienced approximately 15 m (50 ft) of flanking erosion (Figure 18). The primary cause of this erosion was the exposure of marshes to wind, wave, and tidal forcing due to the high rate of erosion in the reference area (USACE 2004). The post-construction shoreline transgressions behind the ReefBlk [-0.7 m/yr (-2.1 ft/yr), -1.8 m/yr (-6.0 ft/yr) , and -1.1 m/yr (-3.5 ft/yr)] and A-Jack [-0.8 m/yr (-2.6 ft/yr), -2.0 m/yr (-6.6 ft/yr) , and -0.8 m/yr (-2.6 ft/yr)] treatments were temporally similar (Figures 13, 14, 15, and 17). When comparing pre- to post-construction rates, all structures have appreciably reduced shoreline erosion rates to date albeit the rate behind the ReefBlk and A-Jack structures increased considerably during the 2008-2010 interval. The erosion rates behind these structures declined for the 2010-2012 interval, but they were still considerably higher than the Gabion Mat rate. As a result, the Gabion Mat is clearly the most effective shoreline protection structure at the TE-45 Reaches to date. Moreover, this structure is significantly ($P < 0.05$) so (Figure 17).

The reference area Reaches have continued to erode at differential rates since construction. The Reach A and E reference areas have sustained their high shoreline transgression rates; RE 2007-2008 [-6.0 m/yr (-19.8 ft/yr)], RA and RE 2008-2010 [-4.1 m/yr (-13.4 ft/yr) and -5.0 m/yr (-16.2 ft/yr], and RA and RE 2010-2012 [-2.1 m/yr (-7.0 ft/yr) and -3.2 m/yr (-10.6 ft/yr]; whereas the Reach B reference area has eroded at a lower rate; -1.0 m/yr (-3.2 ft/yr), -2.0 m/yr (-6.4 ft/yr), and -1.4 m/yr (-4.5 ft/yr) (Figures 13, 14, 15, and 17). These spatial differences between Reaches were significant ($P < 0.05$). For the 2007-2008 interval, a post-construction erosion rate could not be determined for the Reach A reference area because a dark spot appeared on the 2007 photography skewing shoreline positions. No temporal significant differences ($P > 0.05$) were found between the post-construction reference areas (2007-2008, 2008-2010, and 2010-2012). In contrast, comparisons between pre- vs. post-construction reference areas and project vs. reference areas were significant ($P < 0.05$) (Figure 17). The high rate of erosion at the Reach A and E reference areas contributed to these significance values. Of particular note, the pre-construction Reach A and E reference areas transgressed at faster rates than most of the other shorelines while the Reach B reference transgressed at one of the slowest rates (Figure 12). This trend has continued during the post-construction period (Figures 13, 14, 15, and 17) and is probably a result of the orientation, geometry, and location of these shorelines (Hardaway et al. 2010).

The results of this analysis show that the TE-45 structures have lowered shoreline erosion rates. The Gabion Mat, ReefBlk, and A-Jack structures have significantly reduced the erosion rates along their shorelines and outperformed the reference areas. Though the ReefBlk and A-Jack structures have produced variable erosion rates, the Gabion Mat treatment is maintaining its shorelines and seems to show the greatest promise as a shoreline protection structure. In addition to the low erosion rates, the structures have maintained their stability and have been successful in recruiting oyster

Figure 18. **November 14, 2012 image depicting flanking erosion behind the Reach E Gabion Mat treatment at the Terrebonne Bay Shore Protection Demonstration (TE-45) project. Image reproduced from Google Earth.**

populations during tropical (Figure 16) and winter storms. Both hurricanes (Morton and Barras 2010; Stone et al. 1997) and cold fronts (Watzke 2004) have been found to erode coastal marshes. Other oyster reefs have reduced marsh erosion in low energy environments (Piazza et al. 2005; Meyer et al. 1997). Therefore, the Gabion Mat, ReefBlk, and A-Jack structures have potential to maintain the TE-45 shorelines. Currently, the TE-45 quantification and reduction shoreline erosion goals are being attained. While the low erosion rates experienced in the first five years after construction is encouraging, only additional temporal data will determine if these low erosion rates behind these structures are sustainable.

Hydrology

Water temperature is highly correlated between the Reaches (A and B combined and Reach E) (Figures 19 and 20), with peak monthly mean water temperatures in the months of July and August of each year at 29-32°C (84-90°F) and lowest mean monthly water temperatures in the months of December to February of each year at 10-11°C (50-52°F). The lowest recorded temperature during the five-year period from 2008-12 that oysters and other reef fauna were exposed to occurred on the same day for both continuous recorder sites, January 13, 2011, with passage of a cold front that pushed out water from the estuary and all structures were exposed to air temperatures. This front produced an air temperature of 2.7°C (36.9°F) at H01 (Reaches A&B) and 3.8°C (38.8°F) at H02 (Reach E). The highest recorded water temperature during the

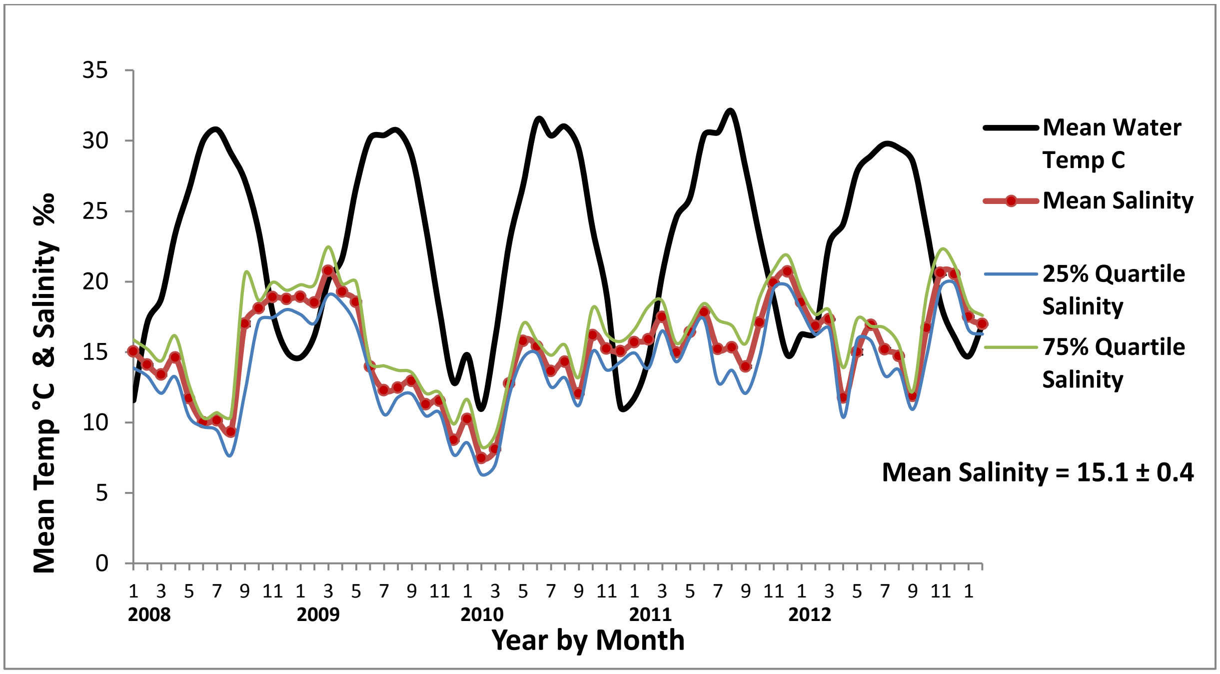

Figure 19. Mean monthly water temperature and salinity from January 2008-January 2013 for Reaches A and B (Site H01).

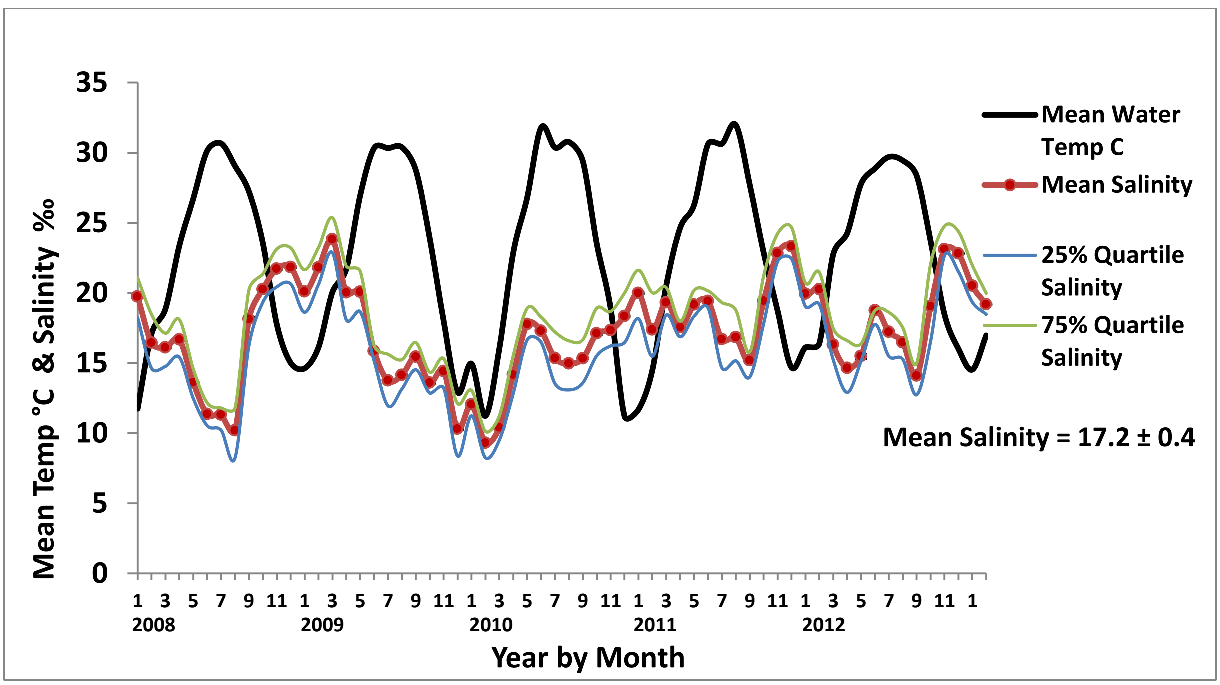

Figure 20. Mean monthly water temperature and salinity from January 2008-January 2013 for Reache (Site H02).

five year period from 2008-12 that oysters and other reef fauna were exposed to also occurred on the same day, August 2, 2010, for both sites. Highest water temperature was 35.9°C (96.6°F) at H01 (Reaches A&B) and 36.0°C (96.8°F) at H02 (Reach E).

Water salinity also correlates well between sites H01 and H02 sites but both exhibited great variability between years and months within a year (Figures 19 and 20). This is typical of an estuary that is wind and tide dominated in a region with over 165 cm (65 in) of precipitation annually (Louisiana Office of State Climatology). What is most important for oyster recruitment and survival is to have salinity at or greater than 8 ppt (Cake 1982) during the late spring/early summer and fall months when oysters are spawning and larvae recruiting as spat to the structures; such conditions occurred each year. Lowest mean monthly salinity at both sites never dipped enough to induce prolonged physiologic and osmotic stress on oysters. Site H02 (Reach E) exhibited an overall mean salinity of 17.2 ppt ± 0.4, while site H01 (Reaches A and B) was slightly lower at 15.1 ppt ± 0.4; both in a good salinity range to protect against major predators and diseases and prolonged physiological stress (Melancon et al. 1998).

The mean plaster dissolution rate for all deployment periods combined (Figure 21) was greater at reach A (3.01 ±0.28 g/hr) and reach E (3.18 ± 0.28 g/hr) than it was at the natural reef site (1.85 ±0.30 g/hr); mean plaster dissolution rate at reach B (2.89 ±0.28 g/hr), although closer in comparison to Reaches A and E did not differ statistically from the natural reef, which is located in a much more sheltered and low-fetch environment than any of the three exposed Reaches with greater fetch and potential for storm-related wave and water energy. The data supports the assumption that Reaches A, B and E are relatively high-energy environments with significant fetch distances across the bay.

Oyster Recruitment

Overall, oyster larvae recruitment, i.e., oyster spat set occurred throughout the period from 2008-2012 at the study sites, with typical bimodal peaks in spring and fall of each year (Figure 21); spring being a consistently higher volume of spat set when compared to fall. The exception to bimodal peaks occurred in the spring of 2010 when a spat failure occurred. Recruitment of oysters at all three Reaches was at an historical low in the spring of 2010. The data represented in Figure 21 is a compilation of all three Reaches within the study area. Although all three Reaches have experienced relatively good oyster spat sets from 2008-2012, there are differences with Reach E having almost three times the oyster spat recruitment success as Reaches A and B (Figure 22). Observations at Reach E throughout the study suggest this area to be more dynamic in biological and physical (water current) conditions than Reaches A and B.

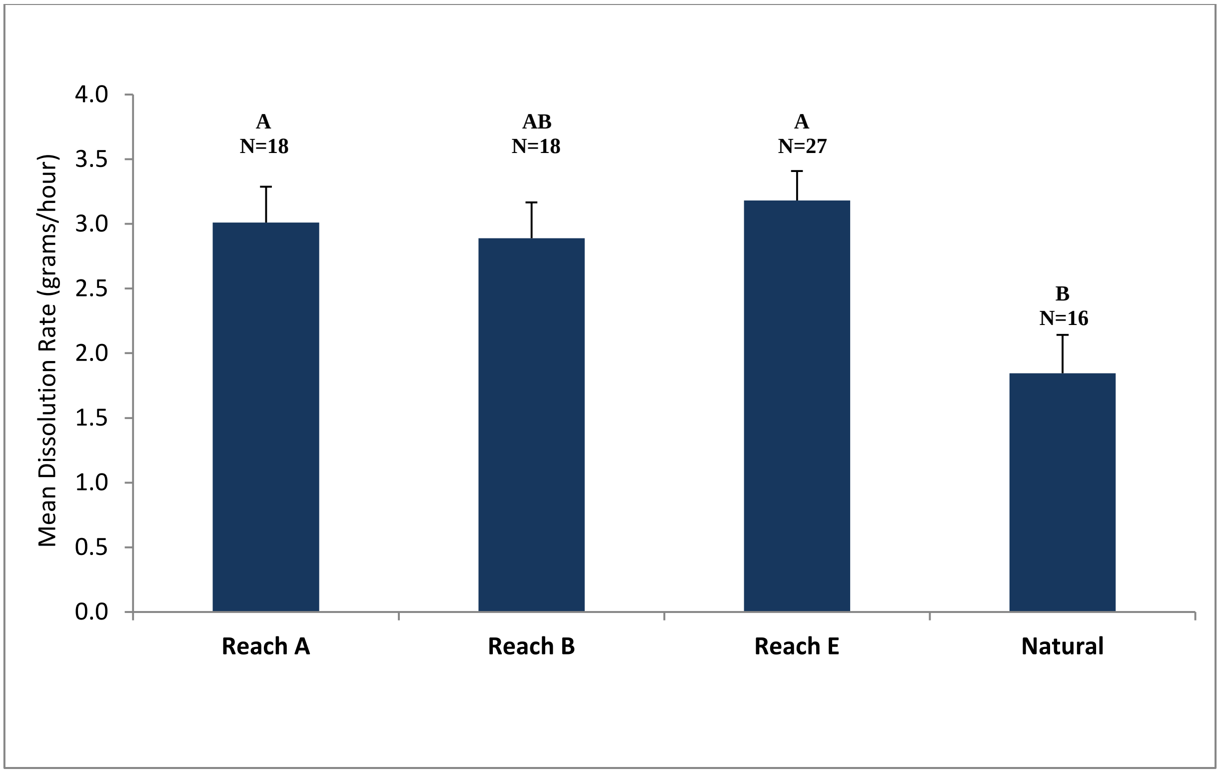

Figure 21. Representation of water energy by the dissolution rate of plaster-of-paris clod cards (+1 S.E) by Reach. Identical letters above the error bars indicate similarity and not significant differences at the P<.05 level or less.

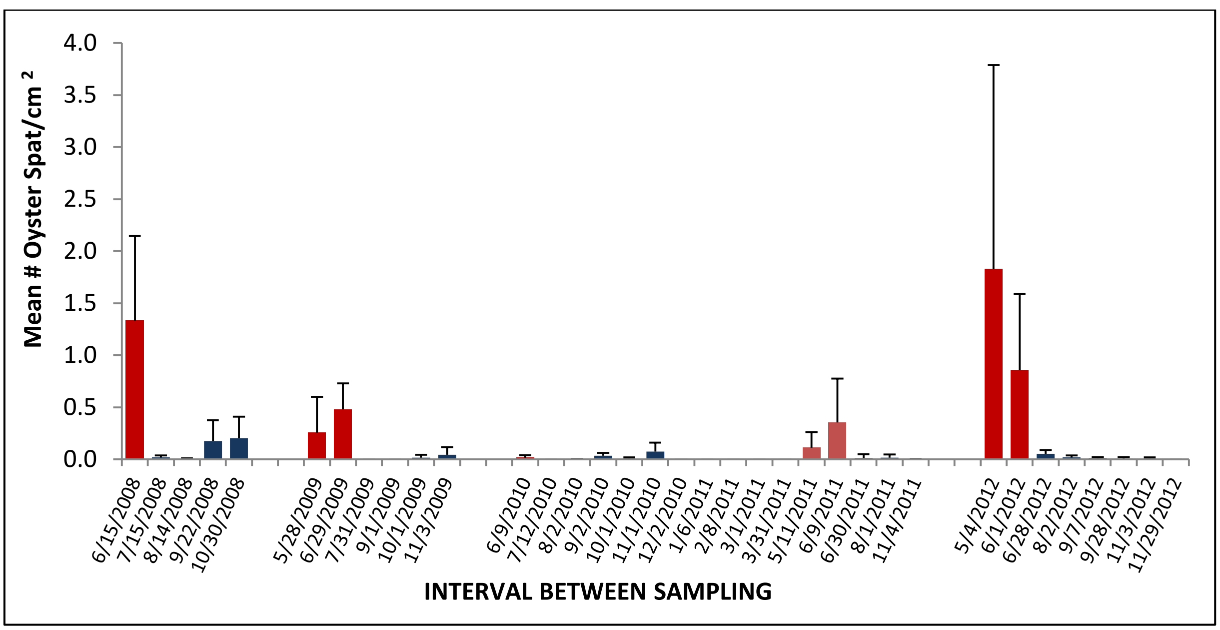

Figure 22. Mean monthly recruitment density of oyster spat by month (+1 S.E) on quarry tiles. Red-shaded bars represent the spring set each year, which is the dominant time for oyster rcruitment. Initial tile deployment each year was as follows: 2008-May 1, 2009-May 1, 2010-May 1 and 2012-April 1.

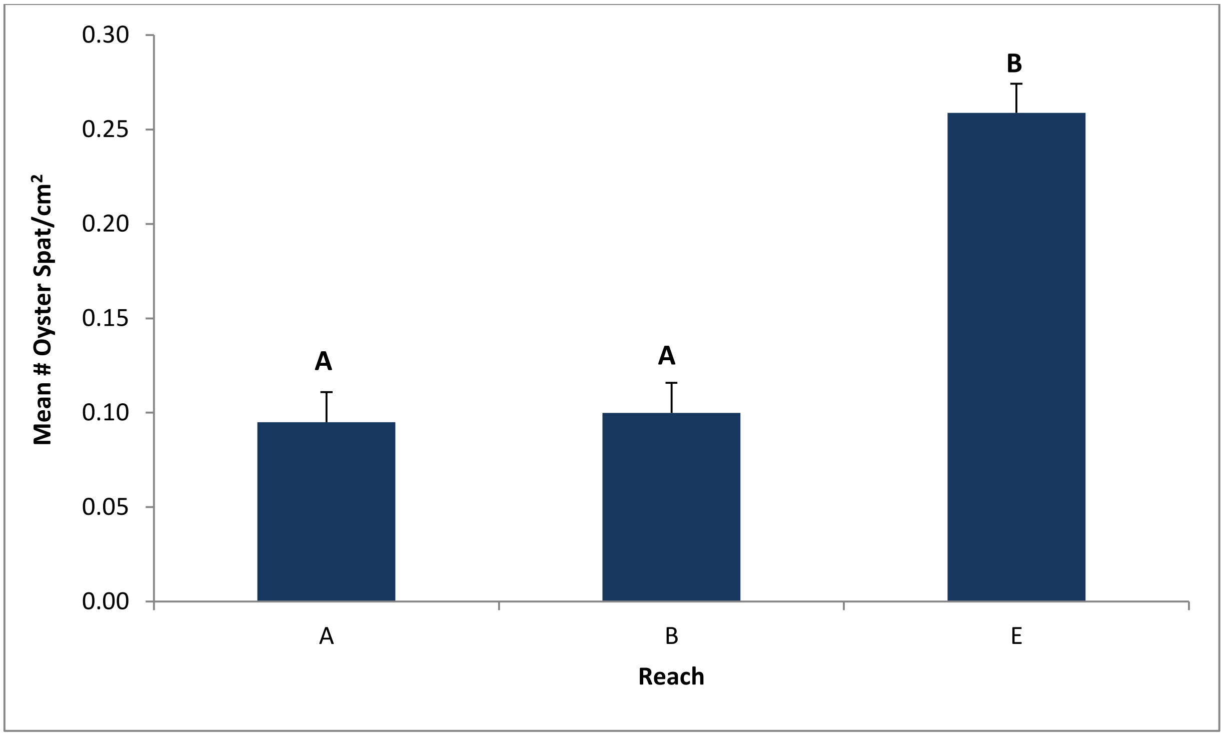

Figure 23. **Mean oyster recruitment density by reach (+1 S.E) for spring-to-fall for the cumulative years 2008-2012. Identical letters above the errors bars indicate similarity and not significant differences at the P<.05 level or less.**

Assessment of Oyster Populations on Experimental Structures

Oyster Population metrics on the three experimental constructed structures used for assessing the success of failure of reef development were percent of oyster coverage, percent of consolidated reef coverage, density (m^2) and live shell length frequency. The data presented primarily reflects oyster status in the winter of 2011-12, which is four (4) years post construction. Where appropriate, comparisons of 4-year post construction data is compared to the 2-year post construction data, which was collected in the winter of 2009-10, which is found in the report of Melancon et al. (2010).

Gabion Mats

Gabion Mats contour the neritic shoreline from the marsh to the bay with sloping elevation and therefore represents differing degrees of daily inundation and aerial exposure dependent on tide and wind influences. These elevation differences produce an oyster population gradient across the length of the 6 m (20 ft) mat (Figure 24). This oyster gradient metric, percent of oyster population coverage on the mats and percent consolidated oyster reef development, is represented in Figure 25. The coverage, i.e., percent presence of surficial oysters, increases with distance from the top of the mat until 3-4 m and then begins to slightly decline. The same pattern was seen in the winter 2009-10 assessment (Melancon et al 2010), with the exception that at 3-4 m distance from the top the percent abundance was asymptotic. The gradual decline with distance past 3-4 m in winter 2011-12 may be due to an number of different reasons; such as, different mats being assessed, a now older mature oyster population that is exposed to the harsh edge of the mat due to scouring, or perhaps to increased predation since this is the most often mat area under water, or unknown reasons. Whatever the reason, the mid zone of the mat continues to be the most dynamic area where oyster populations begin to reach significant numbers.

In the winter of 2011-12 after four years of recruitment the development of consolidated reef was evident and followed the same trend as oyster presence, as would typically be expected (Figure 25). In the winter of 2009-10 the mats were not assessed for consolidated reef development because only two years of post-construction oyster recruitment had occurred by that time.

Percent of consolidated reef on an experimental structure may be the most important overall metric in evaluating the success or failure of oyster colonization. It is consolidated reef, not individual oysters, which will potentially protect the shoreline as a living resource as the experimental structures deteriorate.

Density data indicates that significant differences do exist between Reaches (Figure 26). Gabion mats at Reach E had the highest density of oysters at 1,312/m^2, followed by Reach A with 899/m^2 and then Reach B with 667/m^2. Statistically (Appendix D3), Reach E is significantly different from Breach B, but not Reach A. However, Reach E density was substantially higher than that of Reach A and the power of the performed statistical test was not as robust as needed to not rule out the possibility of Reach E being significantly different from Reach A. Reach E, as mentioned previously, has always appeared to be more dynamic in oyster spat sets and hydrology. In contrast, Reaches A and B are very similar, as perhaps more anticipated since the two are in close proximity to one another. The mean oyster density for this treatment was 960/m^2 (Figure 26). Regardless of Reach, however, all oyster densities were relatively successful and indicate that all Gabion Mats are functioning properly as attractants of oysters in the formation of reef.

Abundance of larger-sized oysters on the Gabion Mats, and therefore ultimately reef development, are primarily surficial processes resulting in a veneer-type of development (Figure 27). The smaller-sized oysters, predominantly within the interior, have limited if any opportunity to build consolidated reef; such conditions are also typical on natural reefs which produce a veneer-type of reef existence.

Comparisons of population shell length frequency distributions are also an important metric in evaluating the development of reef, and also further illustrates how surficial oysters are the dominant players in reef formation for Gabion Mats. All three Reaches had similar length frequency distributions for surficial and interior oysters (Appendix Figures D1 and D2), thus allowing all to be combined (Figure 28). Surficial oysters were about 20-30mm (0.8-1.2 in) larger in shell length than those within the interior of the limestone mats. Gabion Mats are the only experimental structure of the three types

Figure 24. Reach A Gabion Mats showing oyster population gradient from top of mat (to the left in the photo) to the bottom edge of the mat. Photo taken at extreme low tide in winter.

within the study that adequately, and sufficiently, allows for comparisons of shell lengths between surficial oysters to that of interior oysters.

Surficial oyster shell lengths for Gabion Mats were compared between two-year post settlement, winter 2009-10 assessment, and four-year post settlement, winter 2011-12 assessment, to document population shifts (growth) in shell (Figure 29). Population growth occurred with an increase in modal size from 21-30mm in winter 2009-10 to 41-50mm in winter 2011-12, an average of 20mm. This indicates that overall populations on the Gabion Mats continue to survive in adequate numbers to potentially build reef and that recruitment of yearly new cohorts also continues, with the exception of spring 2010 (Figure 22). Winter 2009-10 mid-mat data was collected 3.0 m (9.8 ft) from the top of the mat, as compared to winter 2011-12 mid-mat data which was about 0.5 meters lower on mat; see Monitoring Activities Section IV of this report for winter 2011-12 average mid-mat sites for each Reach.

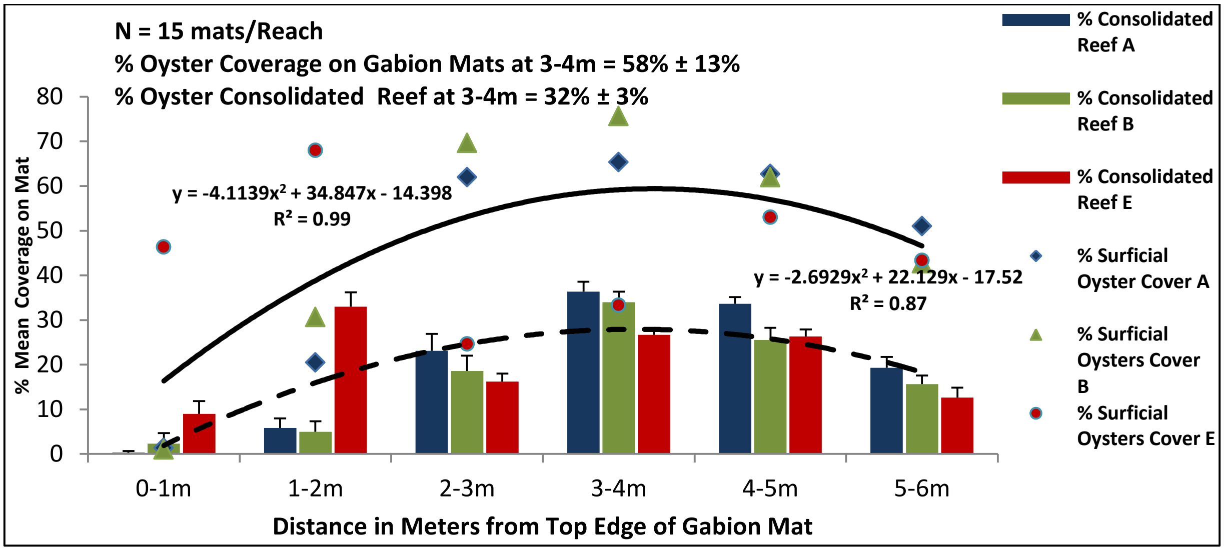

Figure 25. Mean percent coverage (+ 1S.E) by Reach of surficial oysters and consolidated oyster reef with trend lines as found on Gabion Mats in winter 2011-12.

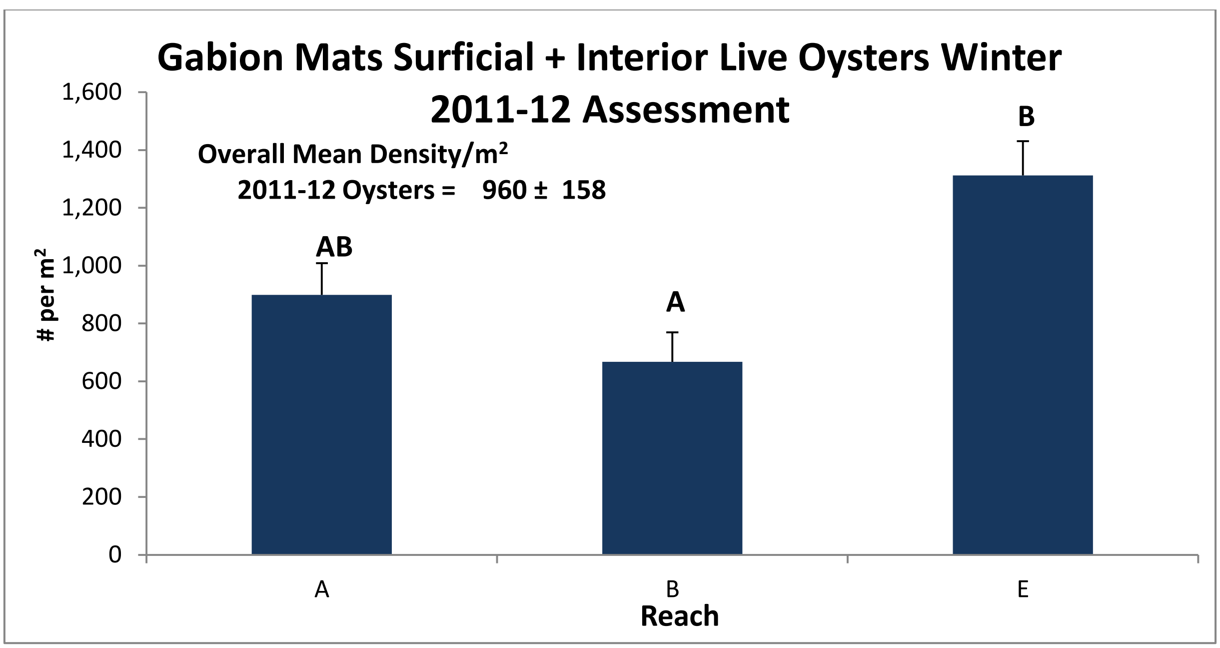

Figure 26. Mean density of surficial + interior oysters (+1 S.E.) by Reach for winter 2011-12. Identical letters above error bars indicate similarity and not significant differences at the P<.05 level or less.

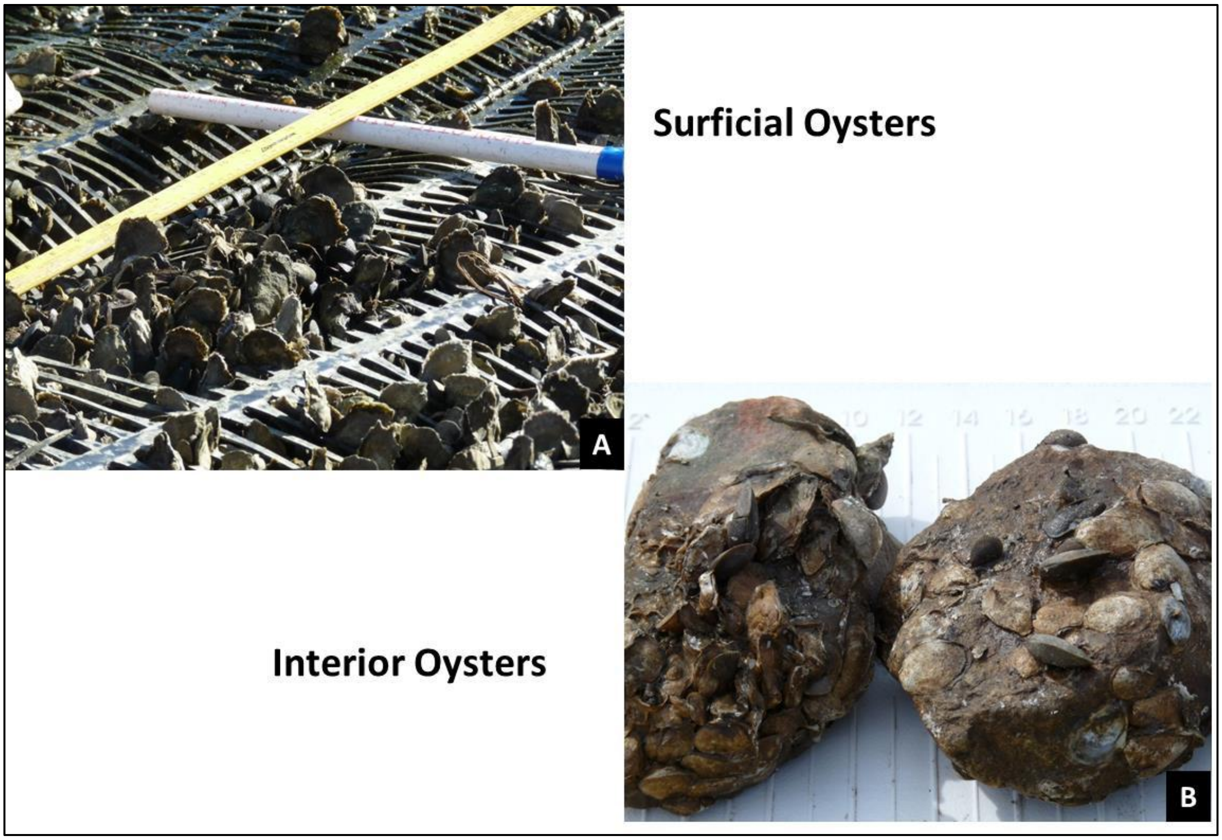

Figure 27. Photos of surficial oysters (A) showing emergent and consolidated reef and small interior oysters (B) on limestone; also notice in both photos the presence of hooked mussels.

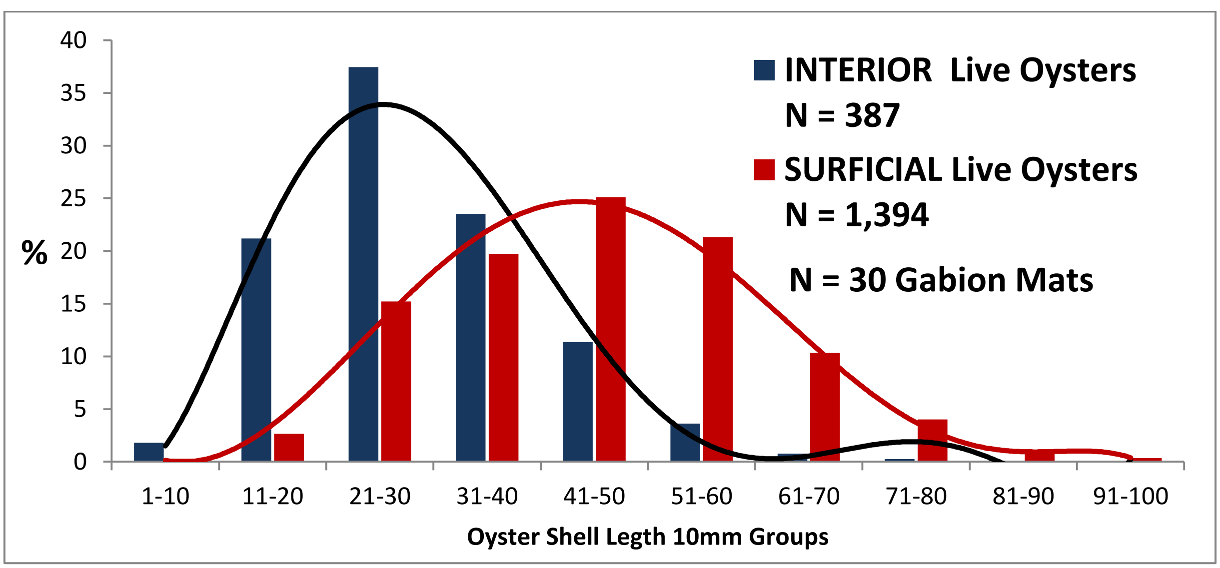

Figure 28. Cumulative surficial and internal oyster shell length frequencies for Gabion Mats combining Reaches A, B and E in winter 2011-12 assessment.

To compare oyster population length frequency complexity to natural oyster populations in intertidal/shallow waters found within the Terrebonne estuary, data were collected by obtaining oysters from two sites. Oysters were randomly collected by hand and tongs during the winter 2009-10 from the TE-45 reference reef site near Reach E (Figure 6) and in February of 2011from an area 37 Kilometers (23 miles) south west of Reach A in bayou Grand Bayou du Large (29°10'51.48"N 90°58'32.36"W). Unlike the weather and wave-exposed shorelines of Reaches A, B and E, the two natural intertidal areas were in more sheltered habitats; the TE-45 reference site in a tidal cut within the marsh, and the Grand Bayou du Large site along a relatively protected shoreline behind a curved spit of marsh. There were no concentrations of oysters to use as reference sites along the exposed shorelines of Reaches A, B and E because of the highly erosional environment.

Winter 2011-12 Gabion Mat oyster length frequency data when compared to the two natural reefs indicated that overall length frequency complexity was similar to the natural intertidal/shallow water population near Reach E that was used for reference (Figure 30), and had a modal peak trend 10 mm greater. However, Gabion Mat population length frequency complexity was still much lower than the Bayou du Large site. Such differences in population length frequency complexity between reference sites is a demonstrates how site-specific oyster population complexity can become.

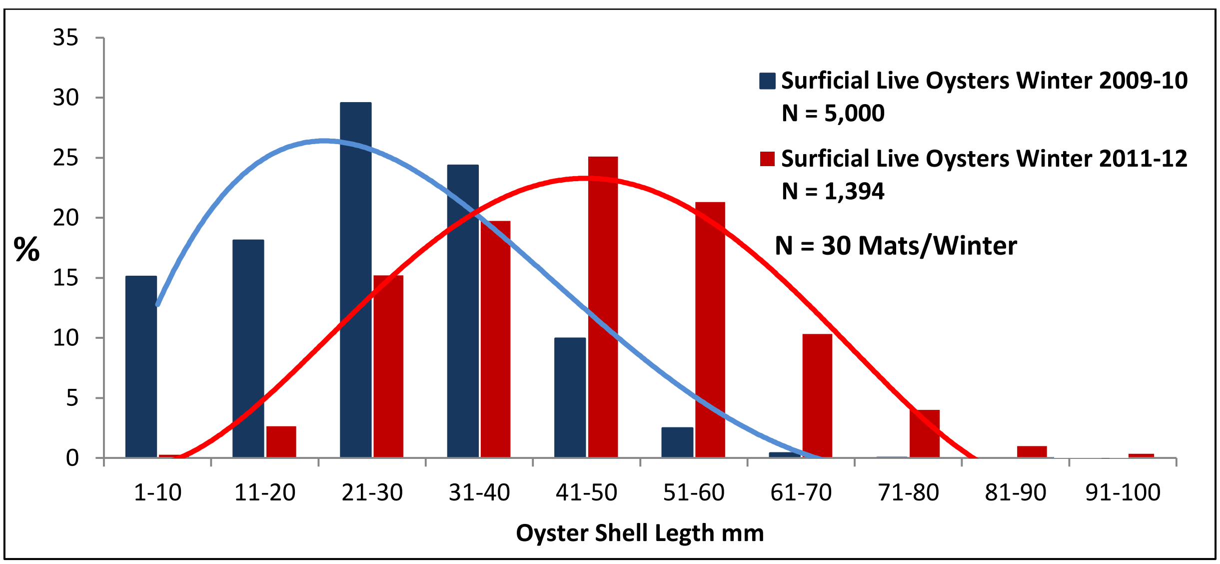

Figure 29. Oyster population length frequencies comparing Gabion Mat surficial populations between assessments winter 2009-10 and winter 2011-12.

Similar to the 2009-10 winter assessment, the most dominant associated organism on the Gabion Mats other than oysters was the hooked mussel, *Ischadium recurvum* (Figue 31). Hooked mussels compete for food and space and can be found in great numbers associated with oysters (Figure 32). Ninety-nine percent (99%) of all mussels identified on the Gabion Mats, as well as on the other two experimental structures, A-Jacks and ReefBlks were hooked mussels. The second most abundant mussel, but with a negligent presence at a little less than one percent (<1%), was the ribbed mussel *Gukensia demissus*. The ratio of hooked mussels to oysters increased from a ratio of 1.6:1 in the winter of 2009-10 to a ratio of 1.9:1 in the winter of 2011-12, a 19% increase overall. The only sites where the ratio decreased were the mats at Reach E (Figure 31). The mean mussel density for this treatment was 1,213/m^2.

Gabion Mats, as did the other two experimental structure types, produces self-generated shell rubble and hash as oyster populations colonize, grow and die. Wave activity and tides have the potential to deposit this rubble and grit along strand lines on the Gabion Mats (Figure 33A). Also, wave activity from storms deposits shell rubble and hash washed up from the bottom of the estuary (Figure 33B). This shell rubble and hash may have created some frictional and stability problems for oysters to create reef; although this potentially negative aspect has not been measured. A potential positive aspect of the shell rubble and hash is deposition in the adjacent marsh and creating habitat and structure and thereby helping with erosion control.

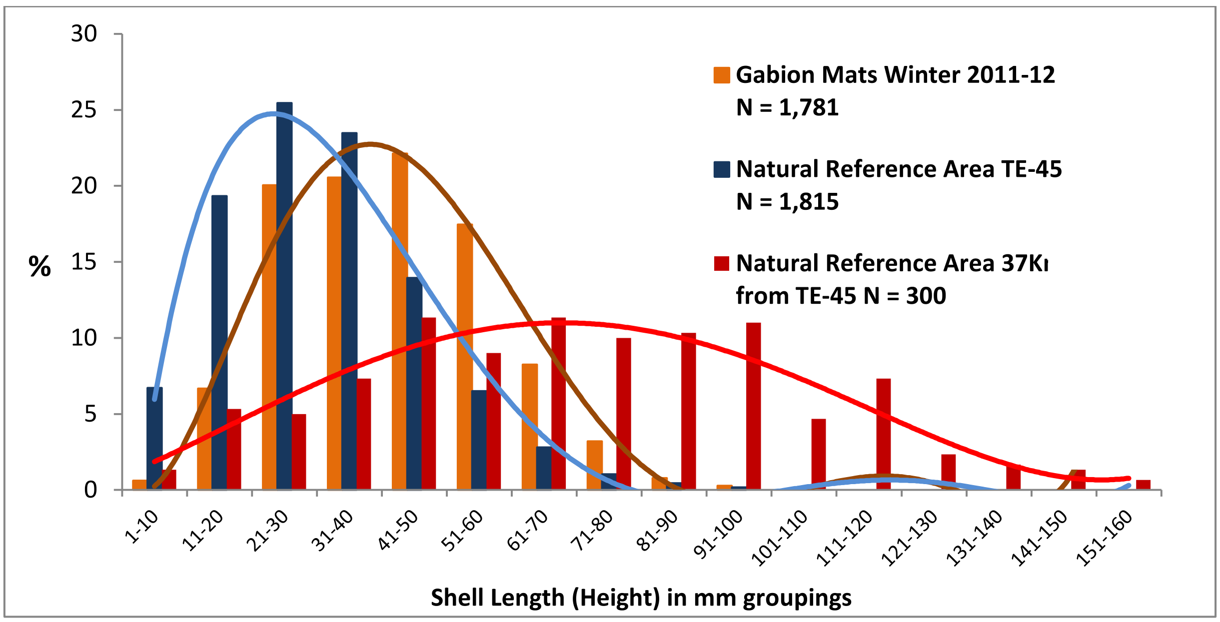

Figure 30. **Oyster population length frequencies comparing Gabion Mat population winter 2011-12 to natural intertidal reef populations. Gabion Mat data represents surficial and interior oysters.**

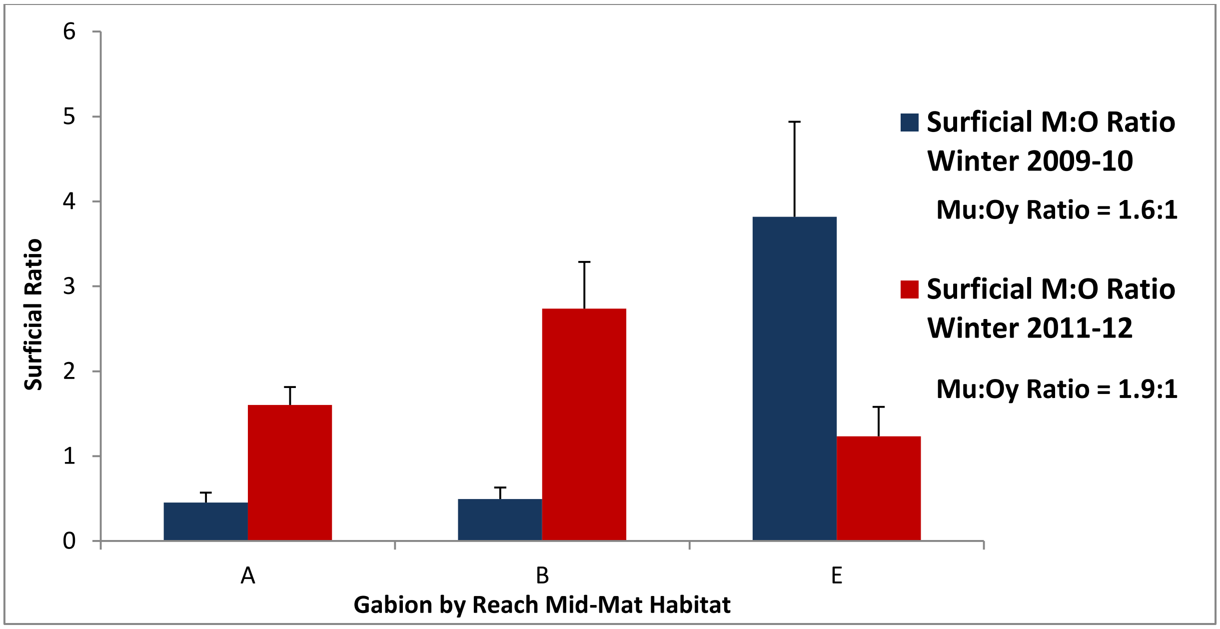

Figure 31. **Hooked mussels to oyster ratio on Gabion Mats comparing winter 2009-10 to winter 2011-12 assessments. Data is mid-mat sites only for both winters.**

Fig 32. **Photo of hooked mussels covering oysters on a Gabion Mat.**

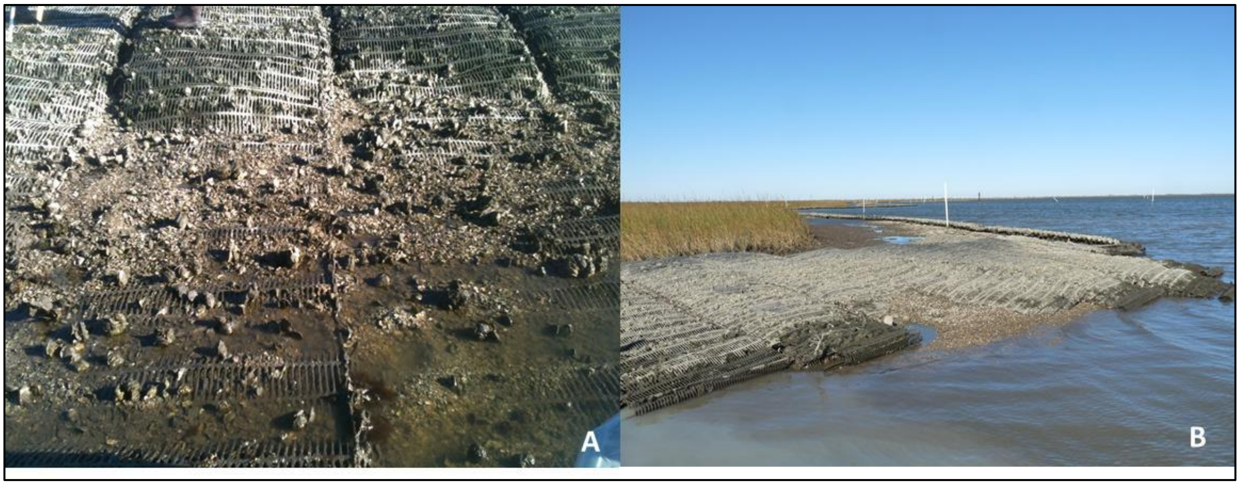

Figure 33. **Photo of shell rubble and hash from self-generated reef activities (A), and from washed up from estuary by storms and tides (B).**

A-Jacks

In the winter 2011-12 assessment of A-Jack structures oysters covered an overall average of 60%, as compared to 58% of Gabion Mats at the 3-4 m distance (Figure 34). Overall percent consolidated oyster reef on A-Jacks was at half the oyster coverage, 30%, as compared to Gabion Mats with 32% reef at the 3-4 m distance. Statistically, there was no significant difference by Reach for percent oyster coverage or % consolidated reef (Figure 34). Visually, the extent of oyster coverage and reef development can be seen in Figure 35.

Mean oyster densities on A-Jacks were very similar and not statistically different by Reach (Figure 36); overall density was 498/m^2 oysters. Caution must be exercised when comparing oyster meter square densities between structure types; each experimental structure has a unique surface and interior shape which influences how density samples are collected and therefore reported (refer back to methods section of this report). A-Jack oyster densities in winter 2011-12 are relatively good, as were Gabion Mat densities.

A-Jacks oyster length frequency data was similar for all three Reaches (Appendix D) and therefore were pooled and graphed together (Figure 37). Oyster modal lengths in winter 2011-12 as compared to winter 2009-10 were similar, but this is not considered to be detrimental to the progression for reef development. It is usual for smaller-sized oysters to dominate, as seen in the two intertidal reference sites (Figure 38). What is important to notice is that A-Jacks' oysters by winter 2011-12, 4-years post construction, have oysters as large as 150 mm. The larger oysters at A-Jacks far surpasses the sizes found at the nearby reference site near Reach E, and begins to approach numbers similar to the reference site in Grand Bayou du Large 37 Km away. A relatively good proportion of larger oysters suggest not only good survival but good shell growth, both important for reef development.

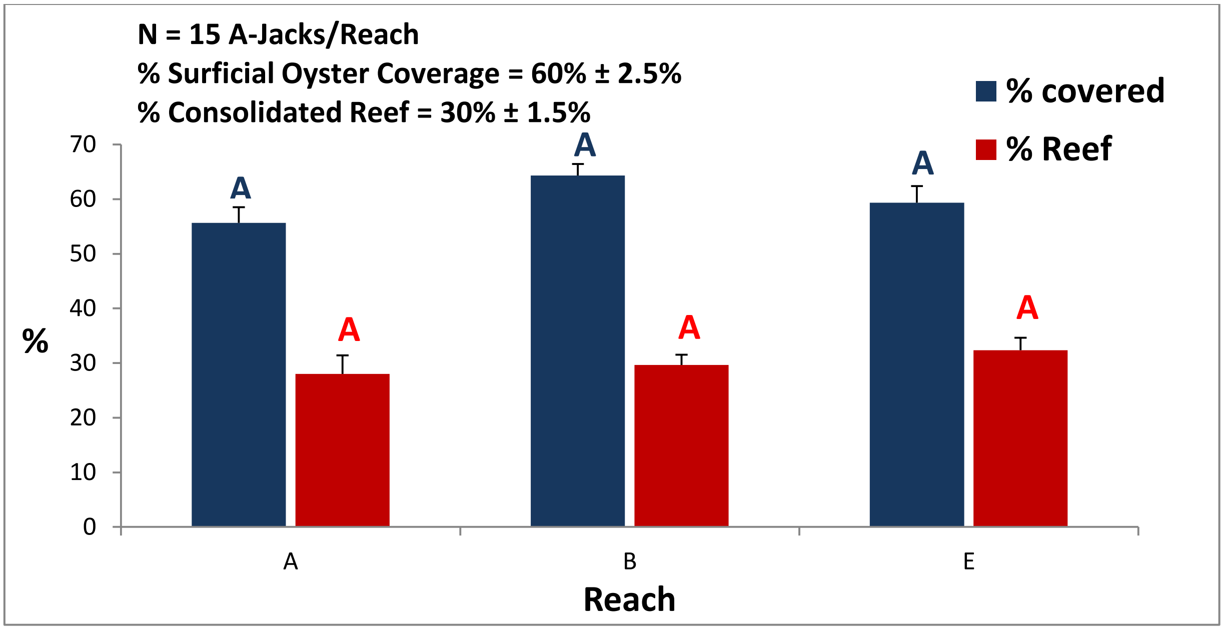

Figure 34. **Mean percent coverage (+1 S.E) by Reach of surficial oyster coverage and consolidated oyster reef found on A-Jacks in winter 2011-12. Identical colored letters above error bars indicate similarity and not significant differences at the P<.05 level or less.**

Figure 35. **Photo of A-Jacks showing surficial oyster coverage and oyster reef development as well as bare areas during winter 2011-12 assessment.**

A-Jacks' oyster population size distribution (Figure 37) was relatively better than that found on the Gabion Mats during the same winter 2011-12 assessments (Figure 30); this difference was anticipated. A-Jacks are solid concrete allowing for oyster settlement on the surfaces of the structures and thereby creating relatively good opportunities for food, flushing of waste metabolites by water currents, and sufficient dissolved oxygen. In contrast, Gabion Mats are limestone rocks stacked 0.3 m (1 ft) thick creating interior interstitial spaces that can potentially reduce water-borne food access, less flushing of mussels were present in large numbers on the A-Jacks similar to abundance found on Gabion Mats (Figure 39). There were differences in mussel-to-oyster ratios between Reaches in winter 2011, but all were relatively high (Figure 39). Overall mussel-oyster ratio in winter 2011-12 was 3.0:1, about 65% greater than the ratio found on A-Jacks in the winter of 2009-10.waste and more competition for dissolved oxygen; all influencing oyster growth (Figure 27B) and survival. The mean mussel density for this treatment was 1,583/m^2.

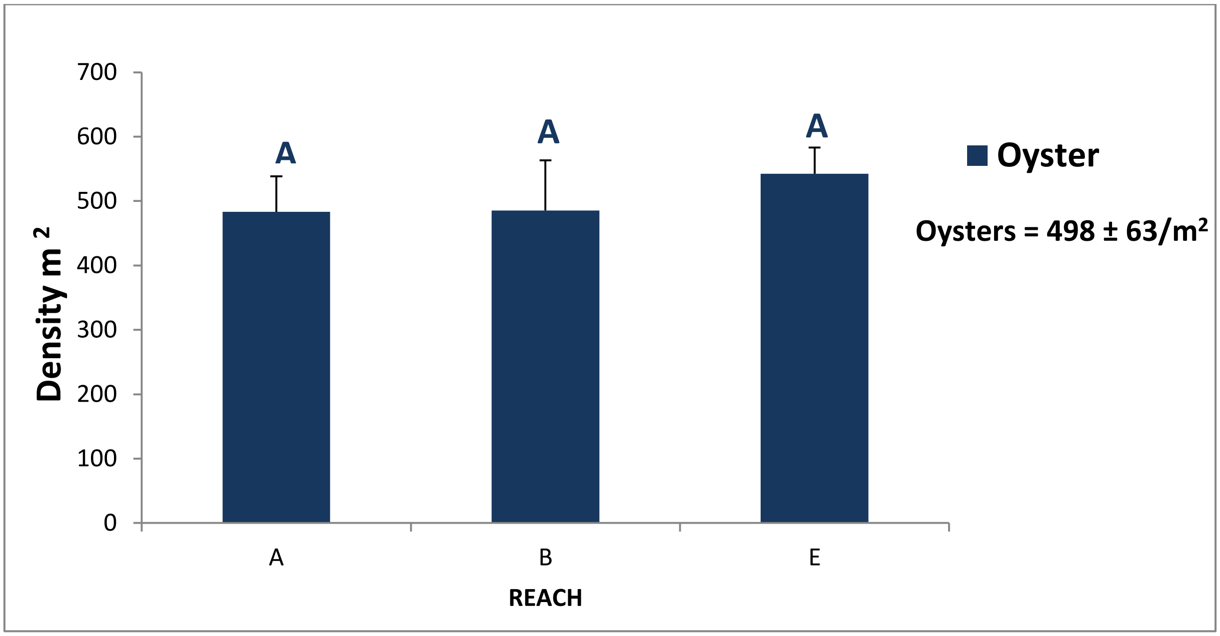

Figure 36. **Mean density on A-Jacks of oysters (+1 S.E.) by Reach for winter 2011-12. Identical letters above bars indicate similarity and not significant differences at the P<.05 level or less.**

A-Jacks, like Gabon Mats, produced self-generated oyster shell rubble and hash. Most was deposited on the backside (leeward) edge of the structures (Figure 40A). Added to the self-generated shell fragments were shell fragments from storm activity washing up onto the structures on windward as well as leeward sides. The shell fragments were mixed with small limestone rocks that were used with geotextile fabric as a base upon which the A-Jacks were placed the slow or impede subsidence (Figure 40B). The shell fragment-limestone complex did not appear to have any significant colonization of oysters, probably due to the instability of the material and it frictional activity as it moved about by storms and strong tides. One can see, however, a live intact oyster about 50 mm in length in Figure 40B that was displaced off of the A-Jacks structure probably by storm activity.

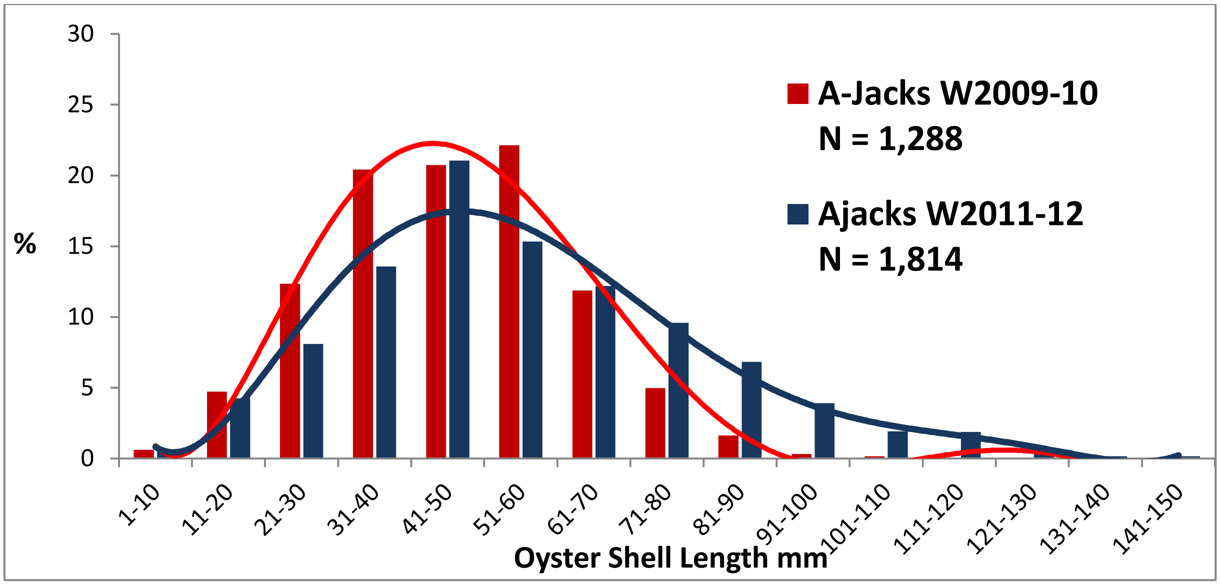

Figure 37. Oyster population length frequencies comparing A-Jacks populations between assessments winter 2009-10 and winter 2011-12. All three Reaches data combined.

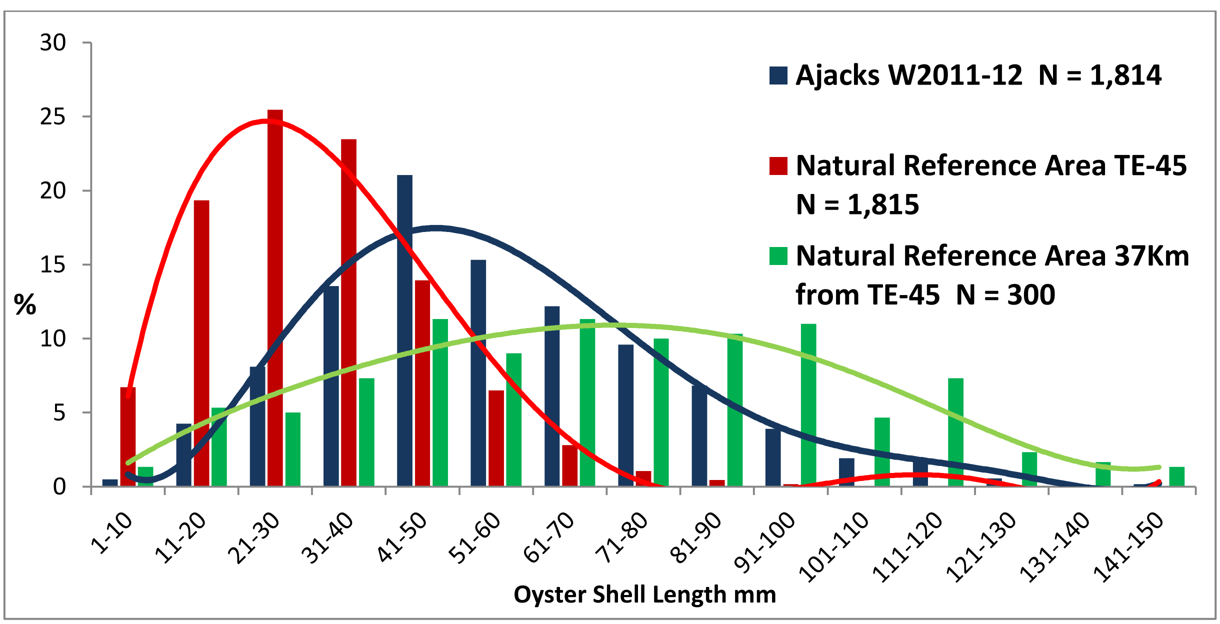

Figure 38. Oyster population length frequencies comparing A-Jacks population winter 2011-12 to natural intertidal reef populations.

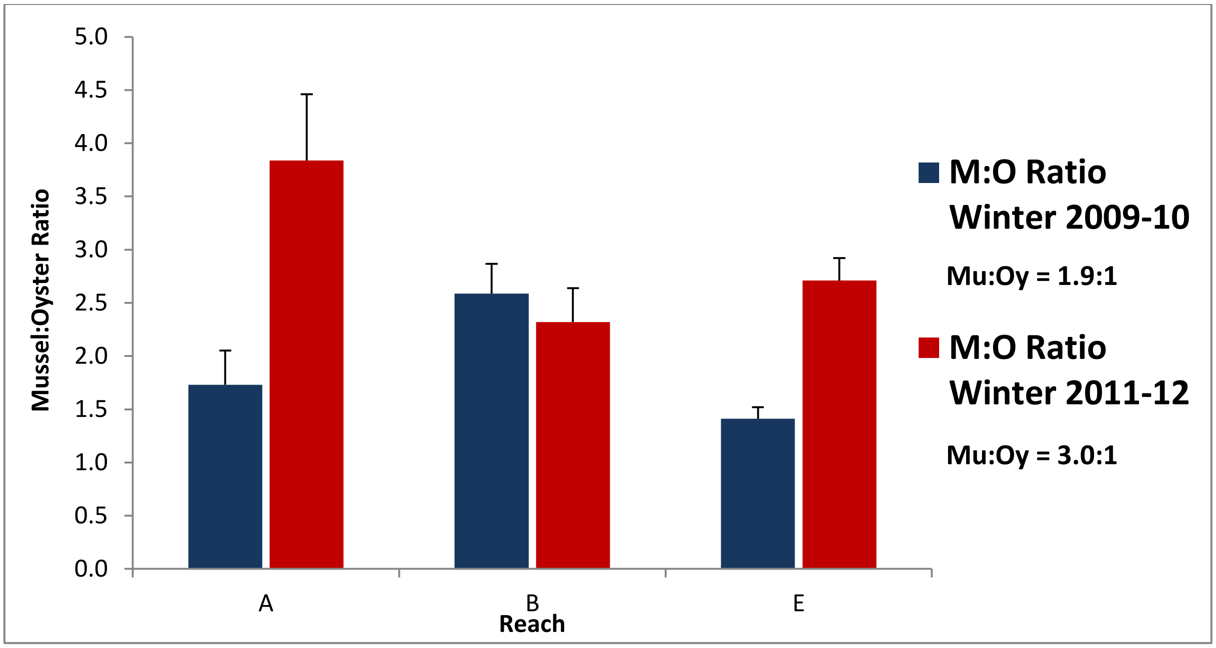

Figure 39. **Mean (+ 1 S.E.) of hooked mussels to oyster ratio on A-Jacks by Reach comparing winter 2009-10 to winter 2011-12 assessments.**

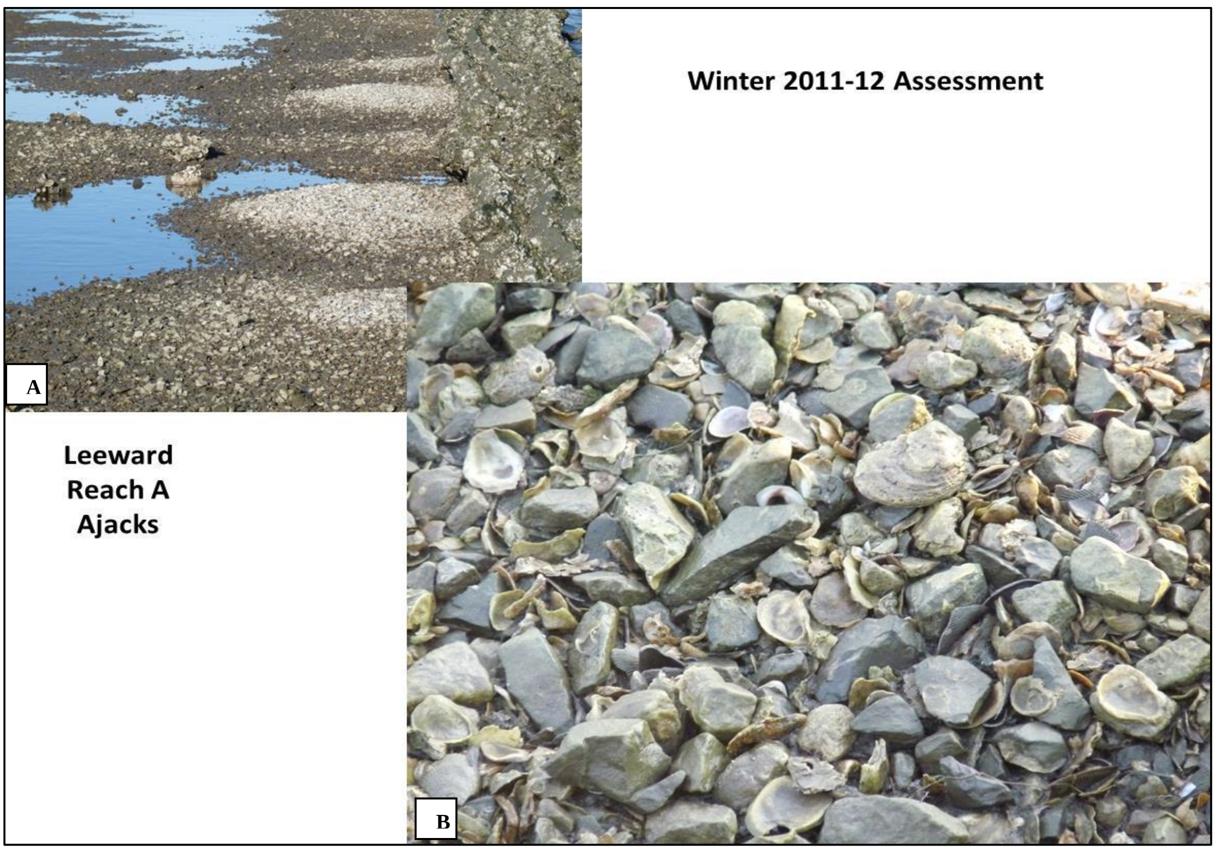

Figure 40. **Photo of shell rubble and hash from self-generated A-Jacks oyster activities and shell washed up from estuary by storms and tides.**

ReefBlks

The most conspicuous and dynamic aspect of the winter 2011-12 assessments for ReefBlks was the disappearance of oyster shells within the structures, especially evident at Reach E (Figure 41). Moreover, Reach E was not the only ReefBlk structures experiencing loss of oyster shell within its bags. Reaches A and B, to a lesser extent also experienced loss (Figure 42). Figure 42 shows the progression of shell loss through the years. In the winter of 2008-09 the shell is not considered a “loss”, but rather is probably due to settlement and packing of the oyster shell during transport from the staging and construction area to the Reaches and to a year post-construction exposure to storm and wave activities. However, the progressive percentage of loss in the winter 2011-12 and winter 2012-13 assessments are obviously not due to settlement and packing (Figure 42). To rule out the possibility of wave and storm influences to ReefBlks based on orientation, i.e., windward or leeward facing, the data on all ReefBlks per Reach were assessed using the T-Test statistical procedure. The results indicated that ReefBlk orientation was not a significant factor (Figure 43).

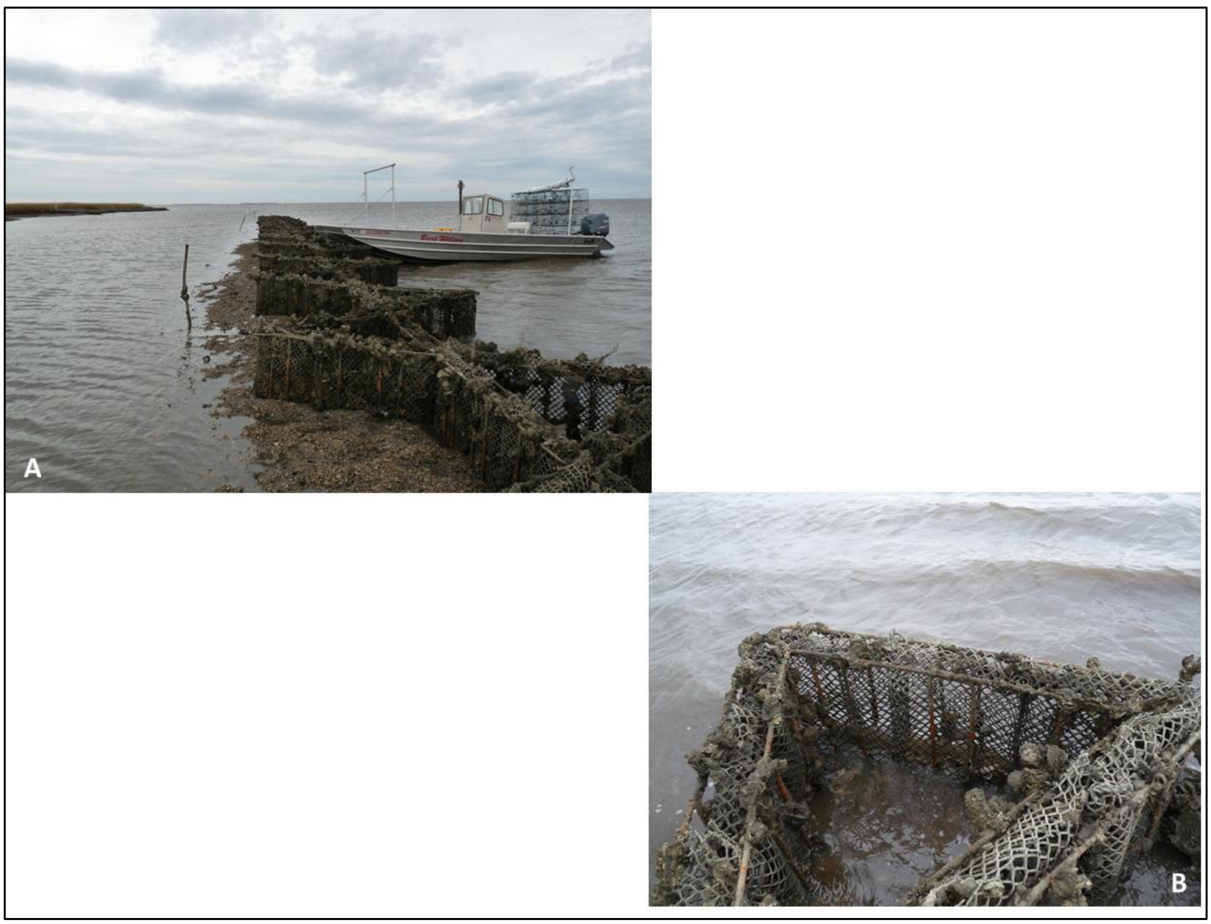

Figure 41. **Photos of ReefBlks at Reach E showing void (gap) spaces where shell once existed. Winter 2011-12 assessment four years post construction.**

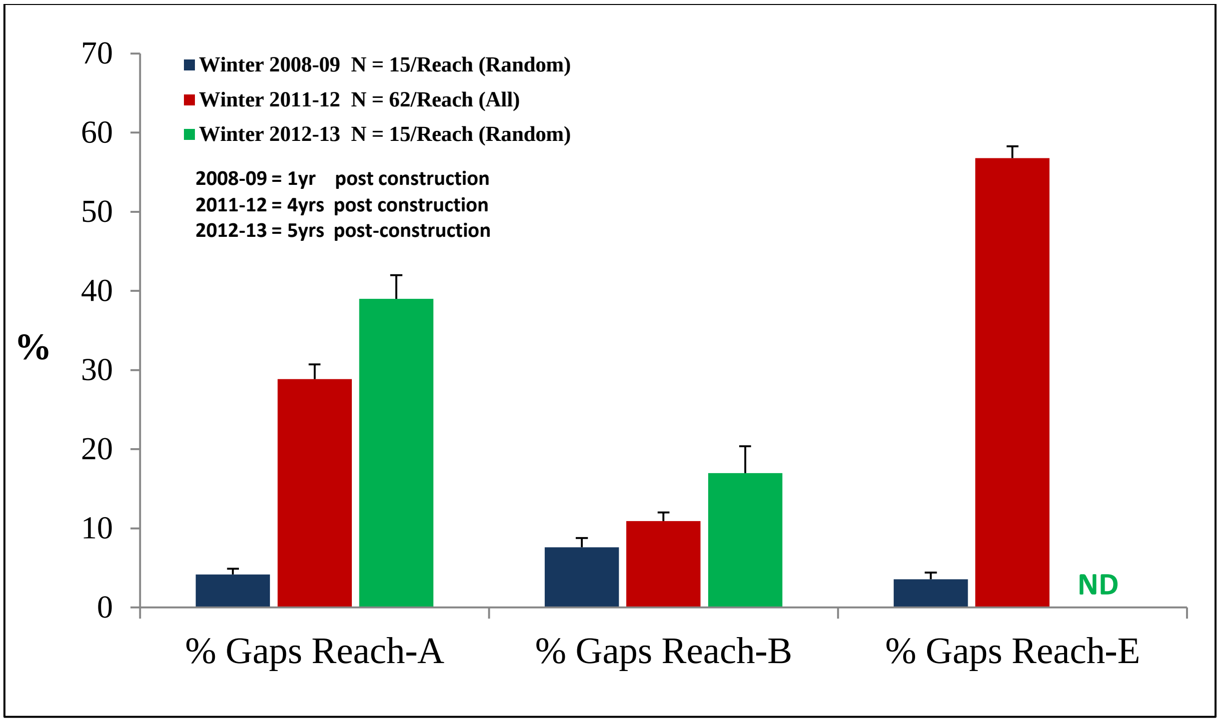

Figure 42. **Mean percent (+1S.E.) void (gap) spaces in ReefBlks by Reach and year.**

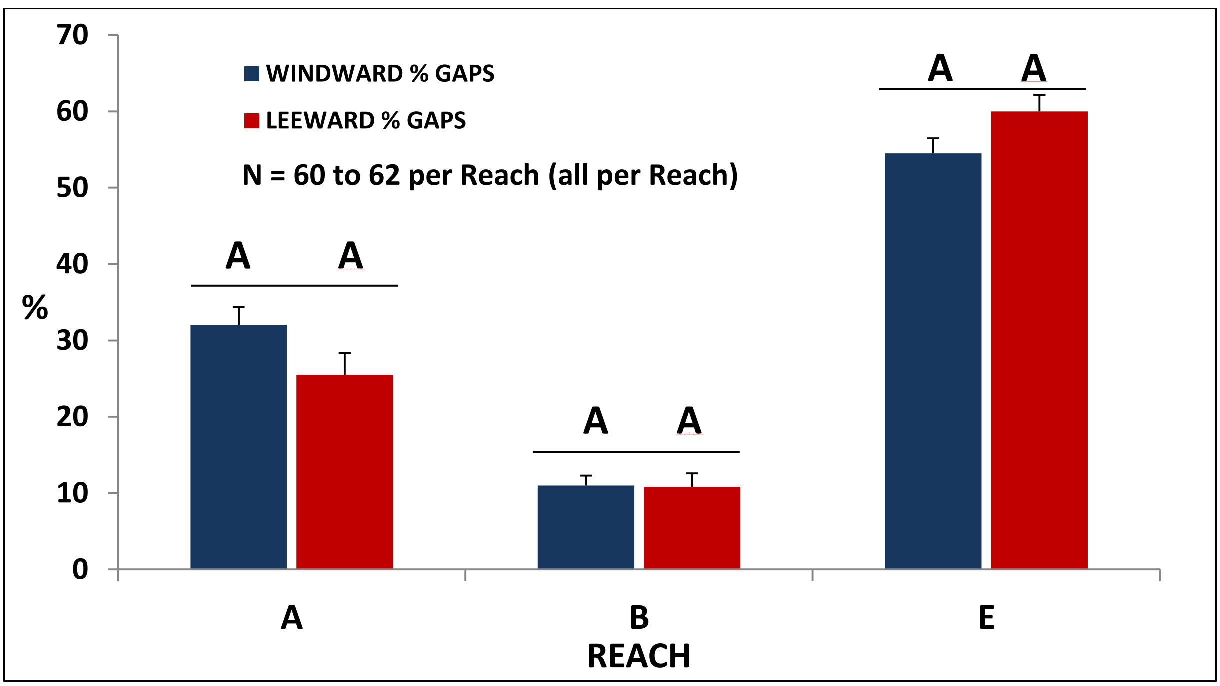

Figure 43. **Paired T-test comparisons by Reach of windward-facing to leeward-facing ReefBlks during the winter 2011-12 assessment. Horizontal bar indicates the statistical pairing and similar letters above each pairing indicates no significant differences (P < .05).**

Since orientation of ReefBlks is not considered an influence on oyster shell disappearance from the bags, what is causing the disappearance? The current hypothesis is a combination of physical and biological influences working in synergy. The influences are the extent of time underwater as influenced by tidal inundation duration (Figure 44A), the intensity of water energy, especially during storms (Figure 44B), the settlement and compaction of shell post-construction that produced a space and niche for crab invasion (Figure 44C), the colonization of organisms that use oyster shell has habitat, namely Polycheate mud worms, <u>Polydora websteri</u> (Figure 44D) and boring sponges, <u>Cliona</u> <u>celata</u> (Figure 44E), and thus erode the shell making it more susceptible to breakage. The final hypothesized piece to this synergy is the entrapment of juvenile small stone crabs, <u>Menippe</u> <u>adina</u>, (Figure 44F) in the bag's settlement space, subsequent molting (ecdysis) becoming too large to escape through the bag's mesh, and it's eventual feeding on all types of fauna, including oyster spat, that colonized the shells. As a stone crab feeds it uses its powerful claws which crush shell; subsequently, the crushed oyster shell is washed out of the bag.

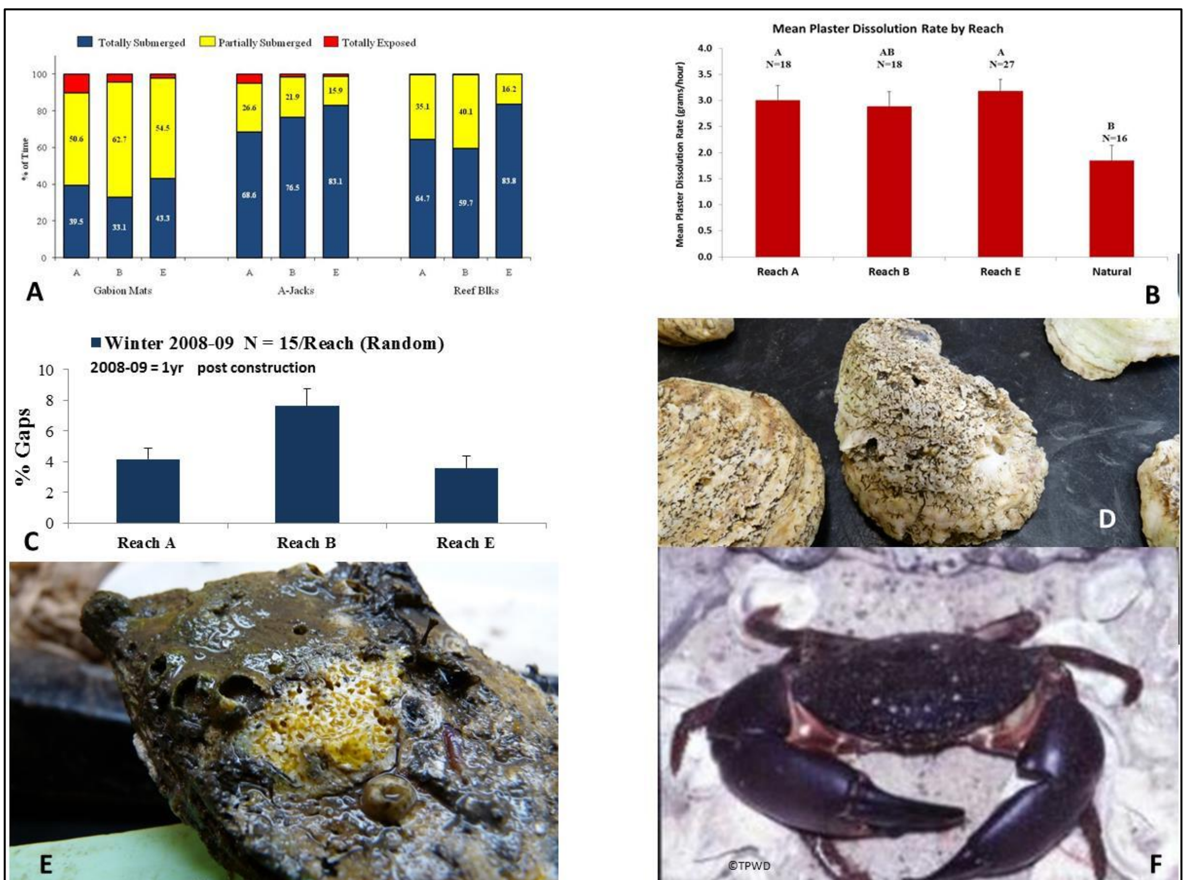

Figure 44. **The Synergy of factors hypothesized for causing oyster shell disappearance in ReefBlk bags. See text narrative for explanation of interactions.**

Louisiana has a very distinctive microtidal environment with diurnal tidal ranges that vary on average from 30-60 cm (11-24 inches) during spring tides and 10-20 cm (4-8 inches) during neap tides, unless influenced by storms and wind (Leonard and Luther 1995). Such small tide ranges restrict placement of objects along a shoreline in the intertidal zone with very little room for error or later settlement. For example, Figure 44A represents percent of time ReefBlks were underwater during the 2009 and 2010 period, 64-84%, with Reach E having the highest inundation; experimental structures' settlement, i.e., subsidence, is continuing across all Reaches and would suggest that percent of time completely inundated is also increasing (refer back to Table 2).

The salinity regime at Reaches A and B has a 5-year average of 15‰, and at Reach E 17‰. Both salinity regimes are within the prime habitat zone considered conducive to both intertidal and subtidal oyster reef development (Melancon et al 2008), but is located on the upper end of the range. Salinities that consistently average slightly higher than TE-45 would be considered unproductive for subtidal natural reef development because of the abundance of predators and shell-boring fauna that are also present at relatively high salinity (Cake 1983). For example, the boring sponge, *Cliona celata*, occurs more often when salinities are higher than 10-15 ‰ but suffers significant mortalities when consistently below 10‰ (Hopkins 1962). Also, the mud worm *Polydora websteri* has shown sublethal stress when subjected to salinity less than 10‰ but thrives at a salinity of 20 ‰ (Brown 2012). The TE-45 habitat is also prime habitat for juvenile stone crabs.

Brown and Bert (1993) found that juvenile stone crabs, *Menippe adina*, molted the highest proportion, 83% of the time, when water temperature was 25°C and 20‰, and had a 78% molting rate at 30°C and 15‰. Juvenile stone crabs occur almost exclusively on shell bottom in areas where other sources of hard substrate rare or scattered (Minello 1999; Lowrey and Paynter 2002). Megalopae (larvae) of stone crabs key in on the chemical cues of oysters and associated biofilms for settlement (Krimsky and Epifanio 2008). Cake (1983) considered the stone crab to be one of the most destructive predators on northern Gulf on oysters. For stone crabs to be the cause of an empty bag, then stone crab "shell predation" must be greater than the combined resources of bagged half-shell volume, density of oyster spat recruitment to the bagged shell, and live oyster shell deposition and growth after recruitment and survival.

Assessment of oyster populations on ReefBlks during winter 2011-12 focused on Reaches A and B since Reach E is considered failing with over 50% shell loss. A successful ReefBlk with no shell bags with gaps (void spaces) is shown in Figure 45. Also note the accumulation of oyster shell fragments and hash on the geotextile/limestone mat (Figure 45), which, similar to Gabon Mats and A-Jacks, contributes to additional habitat and can be washed into the marsh to further potentially slow shoreline erosion. Unique to the ReefBlks are the triangle inner areas (Figure 46) which also accumulates shell fragments and hash providing additional habitat for species.

ReefBlk percent surficial oyster coverage on bagged oyster shell and percent consolidated reef development were significantly different (P<.05) in densities between Reaches (Figure 47). ReefBlk percent surficial coverage of oysters ranged from 42% for Reach A to 65% for Reach B. Correspondingly, consolidated oyster reef was less with Reach A having 21% and Reach B having 28%. Reaches A and B together had 54% surficial oyster coverage and 25% consolidated reef coverage

Figure 45. **Photo of Reach B ReefBlks at low tide during the winter 2011-12 assessment. showing successful colonization. Also notice the shell and limestone on the bottom of the windward side . A-Jacks used to tie-in the flank of the project are seen in the background.**

(Figure 47). It must be noted that the percent coverage and consolidated reef data are based on documenting only those regions within ReefBlk sides that still had bagged oyster shell present.

ReefBlk oyster densities were taken only from the middle bag of the unit's three sides. If a unit's side did not have shell to near the top of the horizontal rebar (Figure 45), i.e, not having gaps (void spaces), it was not used in the analysis for density. Oyster densities between Reaches A and B were not significantly different (P <.05) and had an aggregate density of 2,294 live oysters per square meter, far exceeding densities found on Gabion Mats and A-Jacks (Figure 48). ReefBlks with relatively significant tidal inundation (Figure 44A) and high vertical relief can attract oysters and other fauna in great numbers, for example hooked mussels.

Hooked mussel were also in greatest densities when comparing all three experimental structure types, but showed much greater variability than did oyster densities s on the ReefBlks (Figure 49). There were significant differences in mussel concentrations with Reach A averaging $10{,}797/m^2 \pm 1.981$, and Reach B averaging $13{,}704/m^2 \pm 2{,}251$. Overall, when Reaches A and B are combined, mussel densities averaged $12{,}250/m^2 \pm 1{,}497$.

Figure 46. Photo showing oyster shell and mussel shell deposition with the ReefBlk triangle during the winter 2011-12 assessment.

Live oyster populations within Reaches A and B were similar in length frequency distributions (Appendix D13). When Reaches A and B length data is combined (Figure 50), the modal length range is 31-40 mm, a little larger than the TE-45 natural intertidal oyster reef reference site, but less than the natural intertidal reef 37 Km away. The large number of small oyster reflects the many found within the interior interstitial spaces of the shell bags; this is similar to the interior habitat that is provided by the Gabion Mats' limestone. Such small oysters will probably never develop into fused reef structure.

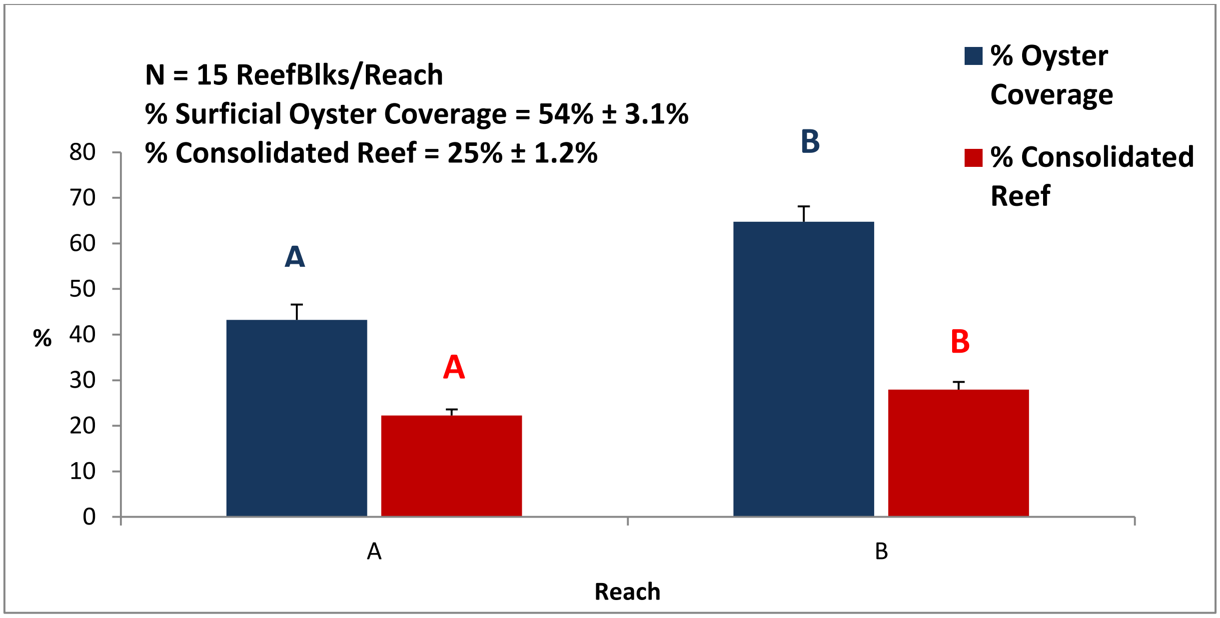

Figure 47. **Mean (+1 S.E.) of percent oyster coverage and percent consolidated reef on ReefBlks during the winter 2011-12 assessment. Different colored letters above each pairing indicates significant differences (P < .05).**

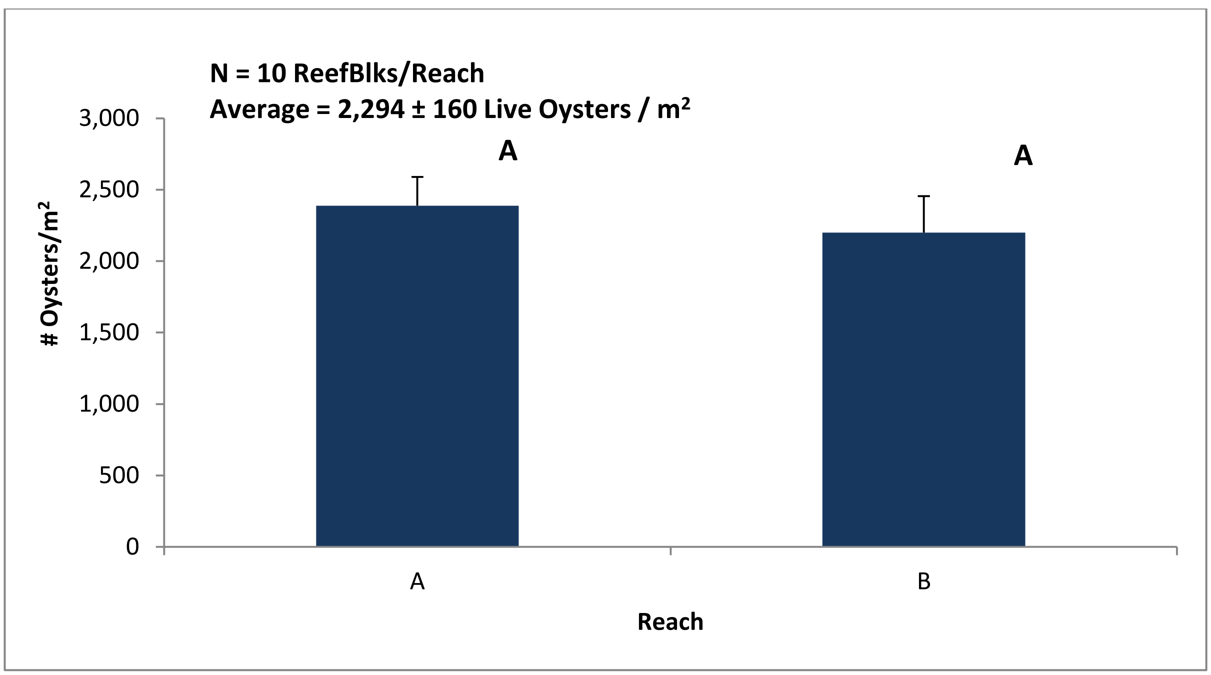

Figure 48. **Mean (+1 S.E) oyster density by Reach for ReefBlks during winter 2011-12 assessment. Similar letters above each pairing indicates no significant differences (P < .05).**

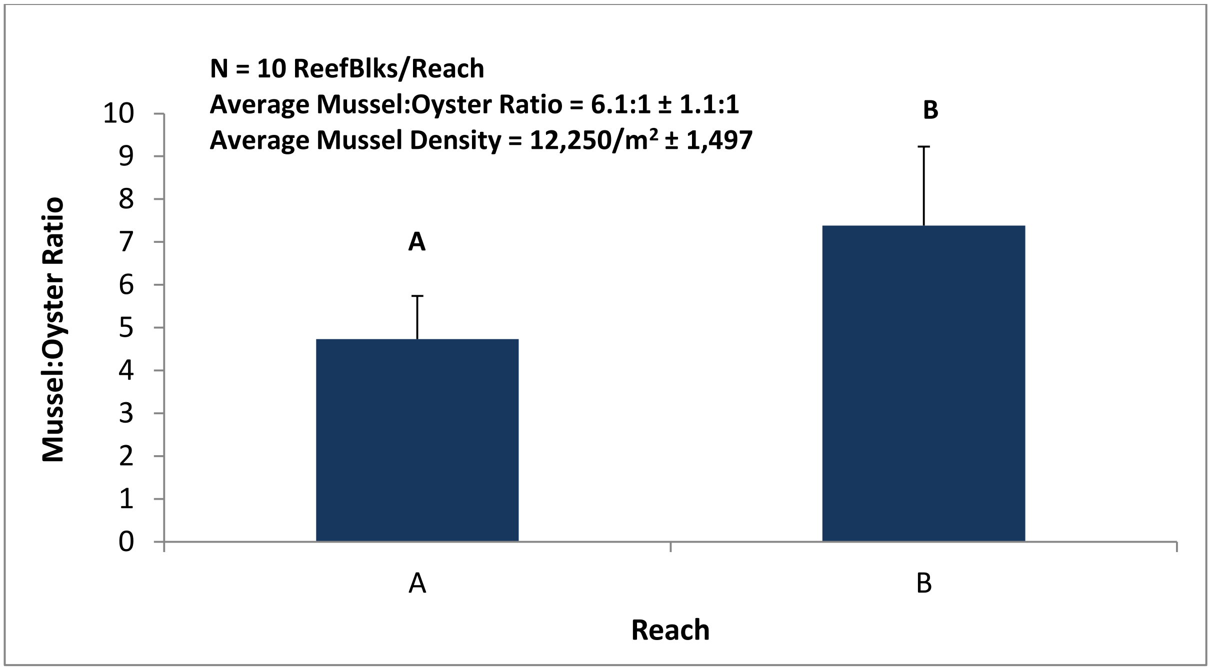

Figure 49. Mean (+1S.E) oyster density by Reach for ReefBlks during winter 2011-12 assessment. Different letters above each pairing indicates significant differences (P < .05).

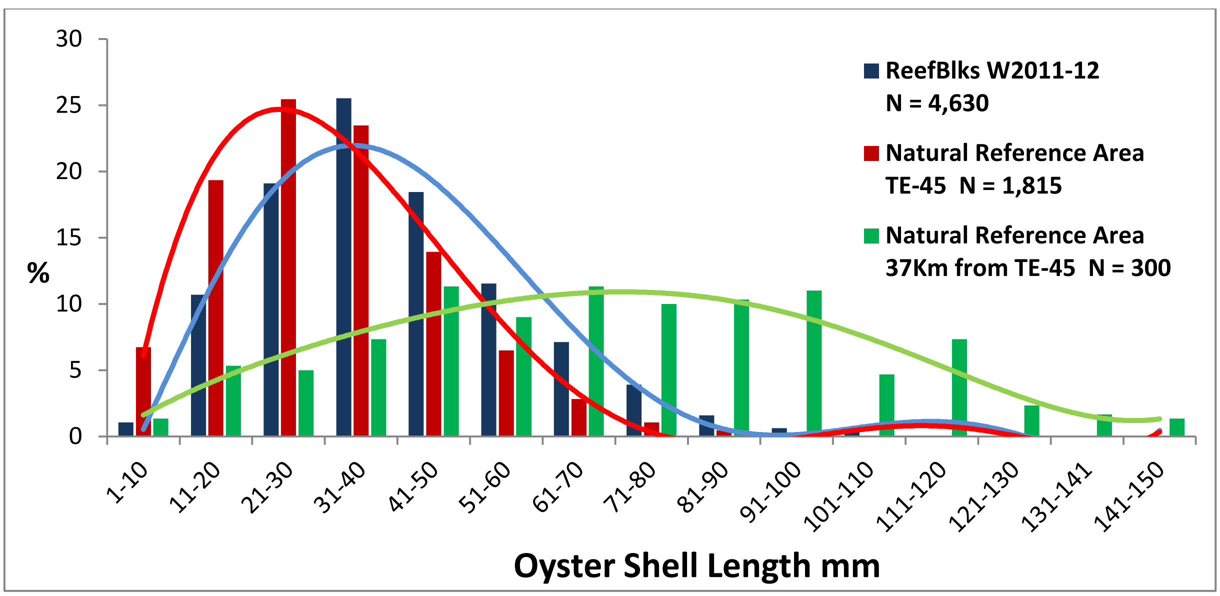

Figure 50. Live oyster length frequencies for cumulative populations at Reaches A and B during the winter 2011-12 assessment and compared to natural intertidal reefs.

Oyster Populations on Experimental Structures Summary

Table 3 summarizes the oyster and mussel population data collected for the TE-45 project during the winter of 2011-2012. All data in the table are grouped by treatment to evaluate the functioning of each structure type after four years of reef development. Each structure type had similar percentages of surficial oyster coverage and percent consolidated reef. This data can be graphically viewed in Figures 25 (Gabion Mats), 34 (A-Jacks), and 47 (ReefBlks). The A-Jack treatment had the highest percentage of "sack oysters" (> 75 mm) (Figures 37 and 38) followed by the ReefBlk (Figure 50) and the Gabion Mat (Figures 29 and 30) treatments. The ReefBlks had considerably larger densities of oysters (Figure 48) per square meter due to its vertical structure. Although lower, the densities of Gabion Mats (Figure 26) and A-Jacks (Figure 36) were respectable and beneficial to reef expansion. The Reefblks (Figure 49) also had a considerably larger mussel to oyster ratio than the Gabion Mat (Figure 31) or A-Jack (Figure 39) structures. However, the ReefBlks have lost a sizable portion of their oyster shell causing the void spaces in the ReefBlk mesh bags to expand. The creation of these void spaces has substantially reduced the reef building potential of the ReefBlk structures. While the shell loss was most pronounced at Reach E, Reach A and B also showed declines in their oyster shell substrates (Figures 41, 42, and 43). The progressive loss of the shell substrate does not bode well for the continued development of oyster reef on the ReefBlk structures while the prognosis for reef enhancement on the Gabion Mat and A-Jack treatments is more likely.

Table 3 **The winter of 2011-2012 (4 years post-construction) oyster population metrics by treatment.**

Treatment	Oysters/m^2	Hooked Mussels/m^2	% Oyster Coverage on Structures	% Oyster Pop >75mm (3in.)	% Consolidated Oyster Reef on Structures	Potential for Continued Oyster Reef Development
Gabion Mats[(1)]	960 ± 158	1,213 ± 143	58% ± 1.3	2.4 %	32% ± 3.0	Good
A-Jacks	498 ± 63	1,583 ± 192	60% ± 2.5	19.8 %	30% ± 1.5	Good
ReefBlks[(2)]	2,294 ± 160	12,250 ± 1,497	54% ± 3.1	7.0 %	25% ± 1.2	Poor

(1) Only mid-mat areas were sampled in winter 2011-12 which may bias the percentage of oysters actually on the mat that are greater than 75mm in shell length; low-mat areas that are more regularly covered with water at high tides may increase the percentage (this will be documented in future work).

(2) ReefBlk data were generated using only those structural units that had bagged oyster shell remaining. Units with empty or missing shells were avoided.

Cost-effectiveness

The cost-effectiveness of the Terrebonne Bay Shore Protection Demonstration (TE-45) structures is outlined in the paragraphs below. Construction costs and structure functioning were utilized to assess the feasibility of the treatments.

The ReefBlk structures were the most economical treatment constructed at the TE-45 Reaches followed by the A-Jack and Gabion Mat structures (Table 4). The costs of the Gabion Mat structure [$1,758/m ($536/ft)] were noticeably more expensive than the A-Jack [$1,510/m ($460/ft)] and ReefBlk [$1,310/m ($399/ft)] treatments. It is mildly surprising that the A-Jack and ReefBlk treatments were less costly because these treatments required foundation and anchoring support while the Gabion Mat treatment did not. However, the Gabion Mats were filled with stone inflating the structure cost.

The Gabion Mat treatment has been the most effective structure in reducing shoreline erosion rates to date. Furthermore, this treatment was significantly ($P < 0.05$) superior to the ReefBlk and A-Jack treatments in lowering erosion rates at the TE-45 Reaches. Essentially, no erosion occurred behind the Gabion Mat treatment while the shorelines behind ReefBlk and A-Jack treatments eroded at comparable rates (Table 4). Therefore, the Gabion Mats functioned at a higher level than the other treatments in reducing the erosion rates.

Table 4. Structure cost-effectiveness variables and rankings at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

Structure	***Structure Cost* $/m ($/ft)**	***Shoreline Change 2010-2012* (m/yr)**	***Oyster Coverage*[1] *(%)***	***Consolidated Oyster Reef (%)***	***Structure Volume Change* (m3)**	***Structure Settlement* (m)**	***Rank***
Gabion Mat	$1,758 ($536)	-0.1	58%	30%	3.8	-0.07	*1*
A-Jack	$1,510 ($460)	-1.05	60%	30%	-13.3	-0.06	*2*
ReefBlk	$1,310 ($399)	-1.11	54%	25%	-4.8	-0.08	*3*

(1) % oyster coverage on ReefBlks are for only those ReefBlks that still have sufficient shell in bags within structures; Reach E is excluded.

The Gabion Mat treatment was the only structure to experience a mean volume gain behind (leeward position) the structures. At all three Reaches the Gabion Mats showed minimal sedimentation. The ReefBlk at Reach B was the only other structure to display aggradation in the leeward position. However, the mean sedimentation rate behind the ReefBlk structures exhibited a volume loss. The A-Jack treatment had the largest mean volume loss (Table 4). Therefore, the Gabion Mat treatment was more proficient than the other treatments in aggrading the shoreline.

The A-Jack, Gabion Mat, and ReefBlk treatments settled at similar rates. The A-Jack treatment recorded the lowest settlement rate. The Gabion Mat treatment had the second lowest settlement rate and the ReefBlk had the highest (Table 4). The Gabion

Mat treatment had low variability in structure settlement while the ReefBlk structures had considerably higher variation from the mean. Although the A-Jack structures had the lowest settlement rate, they were likely the lightest structures installed. Structures at Reach E had higher settlement rates due to poorer soil bearing values (Eustis 2002).

The variables percent oyster coverage and percent consolidated reef are two of the most important to document for biological assessment (Table 4). But from purely an oyster recruitment perspective, i.e., live oyster densities, ReefBlks possessed on average more than twice the number of oysters (Table 3). But each experimental structure has a unique shape, and density per unit area should not be used as a stand-alone metric for success or failure comparisons and evaluations. Additionally, the ReefBlks have lost a considerable amount of their oyster shell, thereby rendering them as failures. Specifically, 89% of the individual ReefBlk units at Reach E have lost 50% or more of their oyster shell, while 8% of individual Reach A units have lost 50% or more shell, then followed by Reach B with no units having 50% or greater shell loss. But Reach A is showing 57% of its ReefBlks with 25-49% shell loss, and Reach B showing 12% of its units showing 25-49% shell loss. The ReefBlk shell losses have significantly reduced the development of oyster reef habitat on this structure. Moreover, these shell losses have progressively increased over the last five years (Figure 42). In contrast to ReefBlks, Gabion Mats and A-Jacks experimental units remain intact and continue to enhance oyster recruitment.

The cost-effective ranking of the TE-45 treatments are as follows - Gabion Mats (1), A-Jacks (2), and ReefBlks (3) (Table 4). The Gabion Mat treatment ranks as the most cost-effective TE-45 structure. Although this treatment was the most expensive, this structure functioned extremely well at slowing shoreline erosion and recruiting oysters. Moreover, this treatment was the only treatment to aggrade the shorelines behind all three Reaches. While the A-Jack and ReefBlk treatments reduced shoreline erosion rates, these rates are increasing over time. In addition, these treatments recorded mean volume losses behind the structures. The ReefBlks also experienced considerable oyster shell loss affecting the functioning of this treatment. Therefore, it is plausible to infer that the Gabion Mat treatment is currently the most feasible because this structure significantly reduced shoreline erosion and enhanced oyster production.

CRMS Supplemental

Land/Water Classification CRMS0341 and CRMS0355

The Land/Water classification of CRMS0341 and CRMS0355 showed that the 1.0 km^2 (0.4 mi^2) square portions of these sites were experiencing minor subaerial land loss from 2005 to 2008 and illustrate that these sites are predominantly water. The land/water maps for CRMS0341 in 2005, CRMS0341 in 2008, CRMS0355 in 2005, and CRMS0355 in 2008 are provided in appendix G. The percentage of subaerial land inside the CRMS0341 site were 22% in 2005 and 19% in 2008 while the CRMS0355 percentages were 6% in 2005 and 6% in 2008 (Figure 51). These percentages correspond to land to open water ratios of 0.28:1.0 (CRMS0341 in 2005), 0.23:1.0

(CRMS0341 in 2008), 0.07:1.0 (CRMS0355 in 2005), and 0.06:1.0 (CRMS0355 in 2008). CRMS0341 subaerial land habitat declined by 4 ha (9 acres) or 1 ha/yr (3 acres/yr) and the CRMS0355 habitat declined by 1 ha (2 acres) or 0.4 ha/yr (1 acre/yr) during this interval. The CRMS0341 site displayed erosion along its shorelines. CRMS0355 showed creek expansions and shoreline erosion. As a result, the marshes adjoining the Terrebonne Bay Shore Protection Demonstration (TE-45) project area exhibited effects (Appendix G) from the increased intensity and frequency of tropical storms in the recent past (Figure 16) (Morton and Barras 2010; Stone et al. 1997) and cold fronts (Watzke 2004).

Vegetation CRMS0341 and CRMS0355

The CRMS0341 and CRMS0355 vegetation data confirms the classification of the Terrebonne Bay Shore Protection Demonstration (TE-45) project area as saline marsh habitat. The dominant species found was *Spartina alterniflora* Loisel. (smooth cordgrass). *Iva frutescens* L. (Jesuit's bark) and *Batis maritima* L. (turtleweed) were

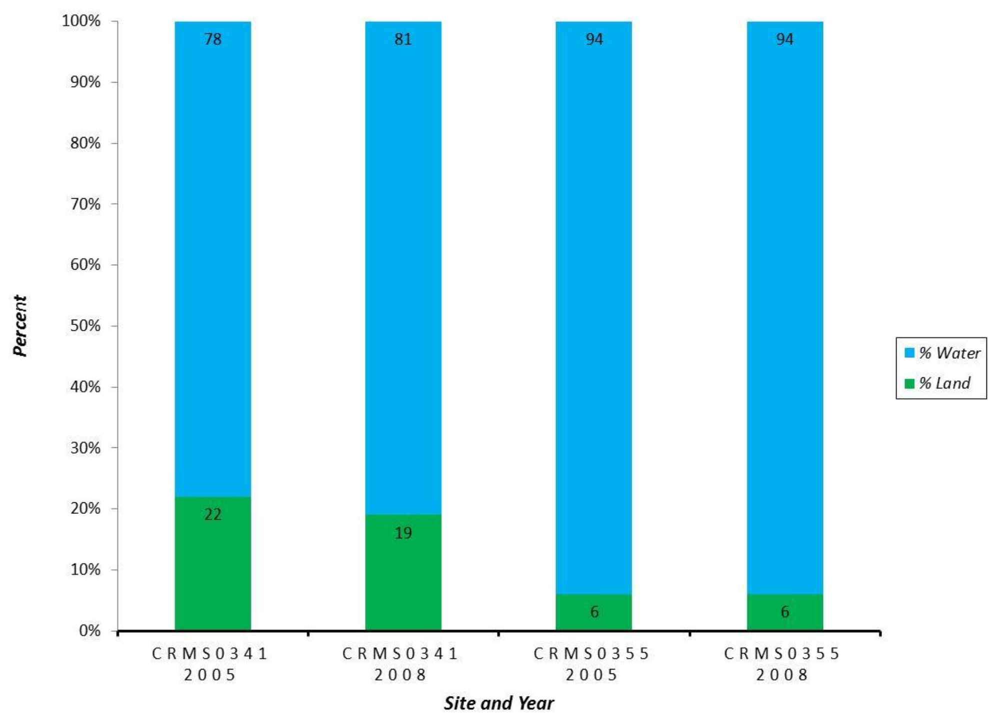

Figure 51. **Percentage of land and water inside the CRMS reference areas in 2005 and 2008.**

also consistently abundant at CRMS0355 over time (Figures 52 and 53). *S. alterniflora* is a common inhabitant and indicator species for salt marsh environments (Chabreck and Condrey 1979). Although the vegetation community at the CRMS0341 site was monotypic (*S. alterniflora)*, the CRMS0355 vegetation community displayed selected diversity. The slight cover disparities between sampling events are probably due to seasonal variations in species growth. Some *Spartina* species have been shown to have seasonal standing crops (Kirby and Grosselink 1976). As a result, their cover values are also cyclic and vary by season. The relatively stable FQI and mean cover values measured at the CRMS0341 (mean = 66) and CRMS0355 (mean = 61) (Figure 52 and 53) signify that these sites are structurally saline marsh habitats. Note that the site FQI scores for CRMS0341 were generally higher than the CRMS0355 scores although the vegetative cover was higher at CRMS0355. This is a result of the large coefficient of conservatism (CC) score assigned to *S. alterniflora* (10) while other species had lower scores (Figure 52 and 53). The site FQI scores were comparable to the Terrebonne Basin (Figure 54) and higher than the coastwide averages (Figure 55). In closing, the CRMS vegetation data support the classification of the TE-45 project area as saline marsh habitats.

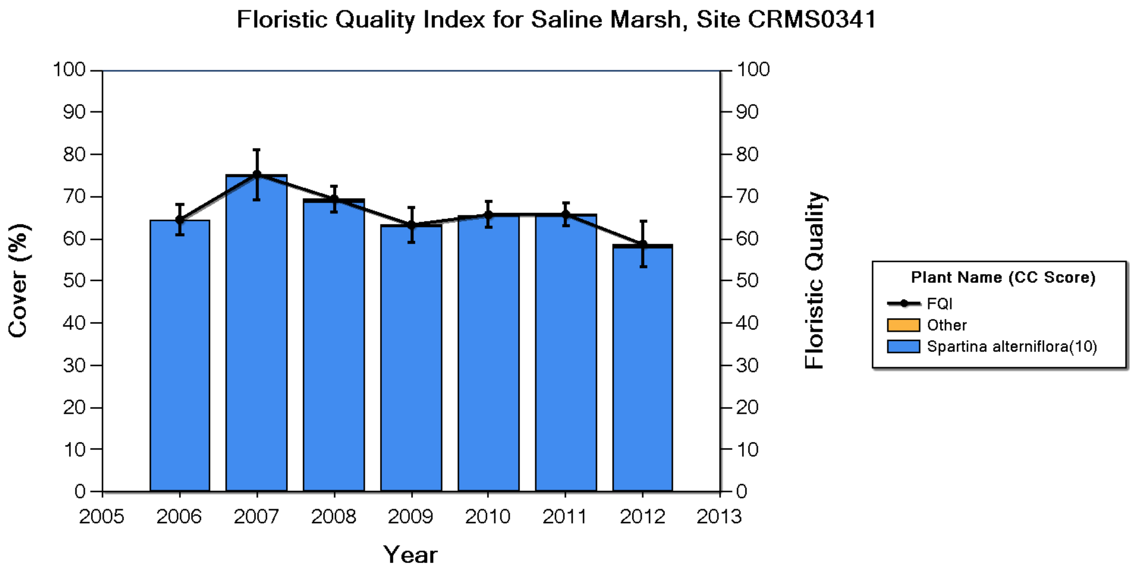

Figure 52. **Mean percent cover and floristic quality index (FQI) for vegetation species populating the CRMS0341 site in 2006, 2007, 2008, 2009, 2010, 2011, and 2012.**

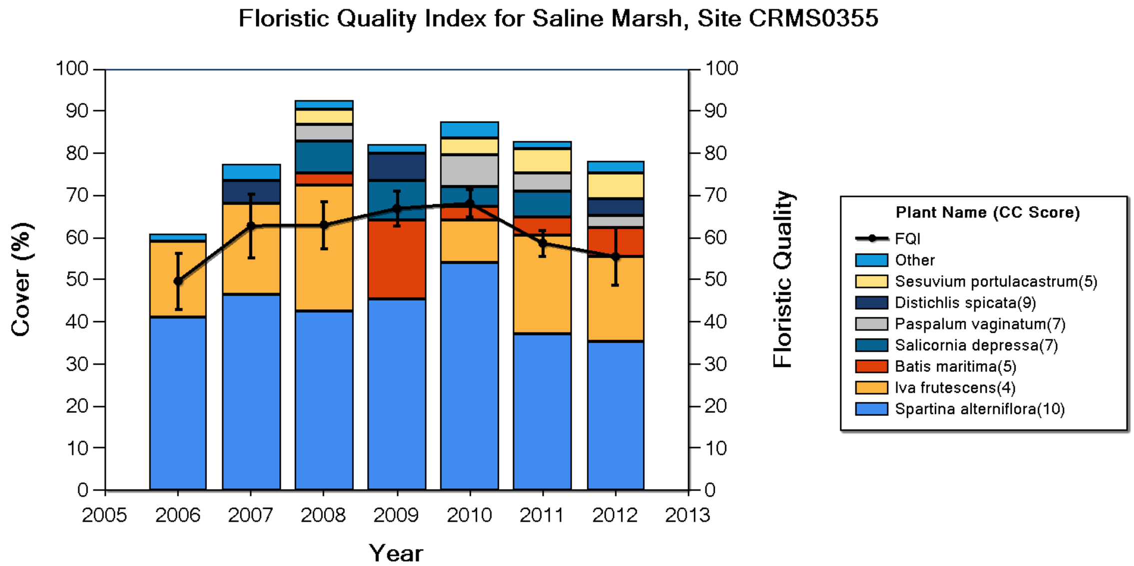

Figure 53. Mean percent cover and floristic quality index (FQI) for vegetation species populating the CRMS0355 site in 2006, 2007, 2008, 2009, 2010, 2011, and 2012.

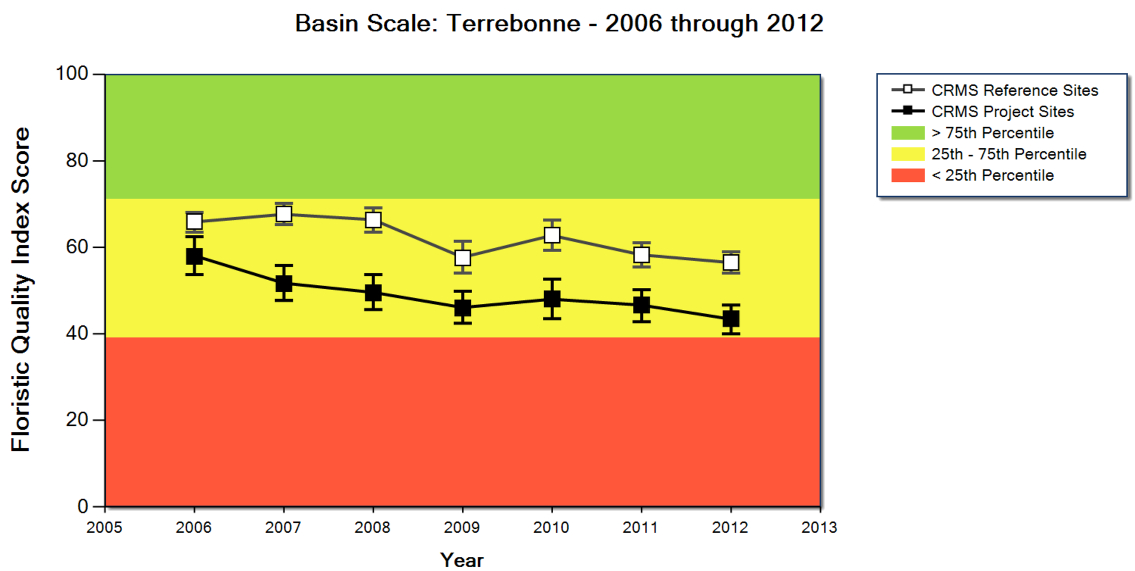

Figure 54. Floristic quality index (FQI) scores for all CRMS sites within the Terrebonne Basin [project (n=25) and reference (n=43)] over time. Note that the FQI scores for the CRMS0341 and CRMS0355 sites are similar to the averages of the reference sites within the basin.

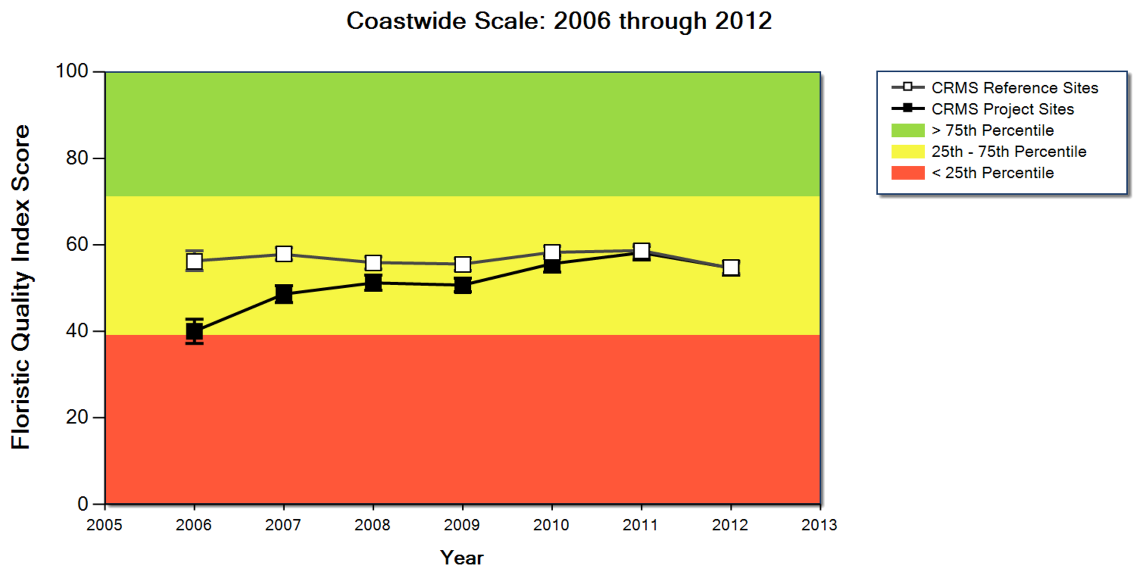

Figure 55. **Floristic quality index (FQI) scores for all CRMS sites in coastal Louisiana [project (n=143) and reference (n=241)] over time. Note that the FQI scores for the CRMS0341 and CRMS0355 sites and the Terrebonne Basin are slightly higher than the averages of the reference sites along the coast.**

V. Conclusions

a. Project Effectiveness

The results of the Terrebonne Bay Shore Protection Demonstration (TE-45) project reveal that all three of the project goals were attained to date. The first goal to reduce shoreline erosion while minimizing scouring to the bay bottom adjacent to each shoreline protection treatment was realized because the shorelines behind all structures have incurred reduced post-construction shoreline erosion rates. Moreover, all the post-construction shoreline change rates behind the structures were significantly different from their corresponding pre-construction rates. While some scouring did occur windward of the Gabion Mat structures at Reach E, the adjacent Reach E reference are also experienced scouring signifying that the structure is not the cause of the scouring.

The second goal to quantify and compare the ability of each of the shoreline protection treatments to reduce erosion and enhance oyster production was achieved. The Gabion Mat, ReefBlk, and A-Jack structures have reduced the erosion rates along their shorelines and outperformed the reference areas. Though the ReefBlk and A-Jack structures have produced variable erosion rates, shoreline transgressions behind these treatments were temporally similar. The Gabion Mat treatment is maintaining its shorelines and seems to show the greatest promise as a shoreline protection structure. As a result, the Gabion Mat is clearly the most effective shoreline protection structure at the TE-45 Reaches to date. Moreover, this structure is significantly so.

All the structures showed the ability to enhance oyster production in the TE-45 project area. The Gabion Mat, A-Jack, and ReefBlk structures all had notable surficial oyster coverages in the areas sampled. These structures also created a limited amount consolidated reef in naturally selected areas. The A-Jack structure produced a considerably larger number of "sack oysters" than the other structures. Therefore, the oyster populations on the A-Jack structure were maturating at a higher rate. The ReefBlks had substantially larger densities of oysters per square meter due to its vertical structure. Although lower, the densities of Gabion Mats and A-Jacks were respectable and beneficial to reef expansion. However, the ReefBlks have lost a sizable portion of their oyster shell causing the void spaces in the ReefBlk mesh bags to expand. The creation of these void spaces has greatly reduced the reef building potential of the ReefBlk structures. The progressive loss of the shell substrate does not bode well for the continued development of oyster reef on the ReefBlk structures while the prognosis for reef enhancement on the Gabion Mat and A-Jack treatments is more likely.

The third goal to quantify and compare the cost-effectiveness of each shoreline protection treatment in reducing shoreline erosion and enhancing oyster production was also realized. The ReefBlk structures were the most economical treatment constructed while the Gabion Mat and A-Jack treatments were noticeably more expensive. The Gabion Mat treatment has been the most effective structure in reducing shoreline erosion rates to date. Furthermore, this treatment was significantly superior to the ReefBlk and A-Jack treatments in lowering erosion rates at the TE-45 Reaches. The shorelines behind ReefBlk and A-Jack treatments eroded at comparable rates. From purely an oyster recruitment perspective, i.e., live oyster densities, ReefBlks possessed on average more than twice the number of oysters. But each experimental structure has a unique shape, and density per unit area should not be used as a stand-alone metric for success or failure comparisons and evaluations. Additionally, the ReefBlks have lost a considerable amount of their oyster shell, thereby rendering them as failures. The ReefBlk shell losses have significantly reduced the development of oyster reef habitat on this structure. Moreover, these shell losses have progressively increased over the last five years. In contrast to ReefBlks, Gabion Mats and A-Jacks experimental units remain intact and continue to enhance oyster recruitment. Therefore, the cost-effective ranking of the TE-45 treatments are as follows - Gabion Mats (1), A-Jacks (2), and ReefBlks (3).

b. Recommended Improvements

The only structural modifications to the constructed treatments were the settlement of the structures and the loss of oyster shell from the ReefBlks. From our observations, it appears some settlement of the structures has occurred. This is confirmed by an elevation survey conducted in 2011 as shown in Table 2. All of the structures have settled since construction, with the most extreme area being Reach E. In particular, the Reach E A-Jack and ReefBlk structures experienced considerable settlement. No remedial activities are being recommended to correct structure settlement and oyster shell loss. By comparing photographs of previous inspections, the area of water behind the Gabion Mats on the southern end of Reach E appears to be increasing. The Gabion Mats in this area are not adjacent to the shoreline and cannot function as designed since flanking erosion is occurring and has been progressing behind this structure due to wind, wave, and tidal forcing over time. There are no provisions in the O&M Plan to reconnect the end of the Gabion Mats with the shoreline. The damage to the two warning signs appears to be due to high winds or extreme weather. Since there are no funds to replace the signs and the signs are still visible, there are no recommendations for maintenance at this time.

c. Lessons Learned

The shoreline erosion rate behind each treatment type has been reduced when compared to the reference area and pre-construction shorelines. It is still not determined if oyster reef can develop is such a manner as to take over the role of erosion control as the treatments deteriorate. Hooked mussels may be impeding some oyster reef development.

Estuaries are highly variable and therefore require an adequate sampling regime that addresses the scale of the research question that is asked (Livingston 1987). Coupling an estuary's inherent nature for heterogeneity with the inherent clustering nature of oysters generates a significant challenge to adequately develop a sampling regime. The sampling regime must accurately portray how each structure type is performing in reef development. Therefore, the methods of assessment must be multi-layered, where each layer of sampling strategy adds further insight for final interpretation. The sampling elements and protocols developed to date will initially satisfy that need, but must remain flexible enough to change, as long as analytical integrity is retained.

Elevation Summary

- All shoreline Reaches recorded volume losses during both pre- and post-construction intervals.
- The Reach A and E reference areas had substantial volume reductions for areas of less than one acre because of erosion along their shorelines.
- The Reach E reference area and the Reach E Gabion Mats experienced shoreface scouring.
- The TE-45 structures and reference areas sustained post-construction sedimentation deficits primarily in the windward position.
- The Reach E structures were established at a slightly lower vertical position than the Reach A and B structures.
- The Reach E structures incurred greater settlement due to lower soil bearing values than the other Reaches.
- Currently, the Reach E ReefBlk and A-Jack structures have the lowest vertical profile.

Shoreline Change Summary

- The pre-construction TE-45 shorelines transgressed at high and variable rates.
- All the structures and all the Reaches experienced reductions in shoreline erosion rates during the post-construction assessments.
- To date the Gabion Mat treatment is clearly the most effective shoreline protection structure at the TE-45 Reaches.
- The post-construction shoreline transgressions behind the ReefBlk and A-Jack treatments were temporally similar.
- The post-construction reference area Reaches have continued to erode at differential rates.
- Additional temporal data is needed to determine if the low erosion rates behind these structures are sustainable.

Hydrology Summary

- Seasonal tidal amplitudes were within normal limits observed in coastal Louisiana, except during times of tropical storms, hurricanes and cold fronts.
- Based on daily tidal amplitudes during the study period, the on-shore Gabion Mats exhibit the greatest percentage of time totally exposed at low tide, followed by the on-shore/off-shore A-Jacks that were placed at the marsh edge, and then the off-shore ReefBlks with the greatest amount time submerged.
- All three structure types at Reach E exhibited more time submerged than at Reach A and Reach B, which were comparable to one another.

Oyster Spat Availability Summary

- Variability in oyster recruitment density by tidal height, year, month and Reach was evident, but this is typical and intrinsic in this type of data and did not vary more than expected.
- Oyster spat recruitment available to the structures Reach-wide was favorable and considered to be more than sufficient for all years, except perhaps in 2010 when there was a spring spat failure.

Oyster Populations Length Frequency Summary

- All three experimental structure (treatment) types exhibit a relatively good oyster population size distribution indicating good recruitment and survival.
- Interior oysters, especially at Gabion Mats and ReefBlks, exhibited a much smaller size than the surficial oysters. This is probably due to greater competition for interstitial space and reduced water flow bringing less food and a greater challenge to flush waste.

Oyster Density Summary

- Gabion Mats and A-Jacks continue to function with oysters distributed as expected.
- Gabion Mats and A-Jacks have relatively good densities of oysters.
- ReefBlks, where oysters continue to exist, has the greatest density of the three experimental types; over twice that of the other two experimental structure types.
- Consolidated reef on all the structures is the typical veneer-type development with living oysters more concentrated on the surface and where larger-sized oysters usually concentrate.
- ReefBlks are failing. Reach E has lost most of its bagged oyster shell that was initially deployed; the bags are empty. Reach A and Reach B ReefBlks are still functioning to recruit oysters, but there has also been a progression of lost bagged shell and gaps (voids) continue to rise.

Oyster Coverage and Consolidated Reef Summay

- Oyster Coverage and the amount of consolidated reef across structures are considered two of the most important variables to measure for success or failure of oyster populations establishments.
- Consolidated oyster reef are a veneer development on structures, which is also typical of natural reefs. This is more evident on Gabion Mats and ReefBlks since both structure types have depth with rock or oyster shell.
- Gabion Mats and A-Jacks have the greatest percent oyster coverage on their structures, respectively 58 ± 1.3% and 60 ± 2.5%. Although ReefBlks were not far behind in exhibiting 54 ± 3.1% coverage, only Reaches A and B were assessed because of ReefBlks failure at Reach E. Additionally, any ReefBlks at Reaches A

and B that exhibited large gap (void) spaces were also not included in the assessments.

- Gabion Mats and A-Jacks have the greatest consolidated reef coverage on their structures, respectively 32 ± 3.0% and 30 ± 1.5%. ReefBlks lagged behind at 25% ± 1.2% consolidated oyster reef. Similar to as stated in the above bullet, assessments of ReefBlks at Reach E did not occur and some ReefBlks and Reaches A and B were excluded.

VI. References

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Appendix A
(TE-45 Structure Designs)

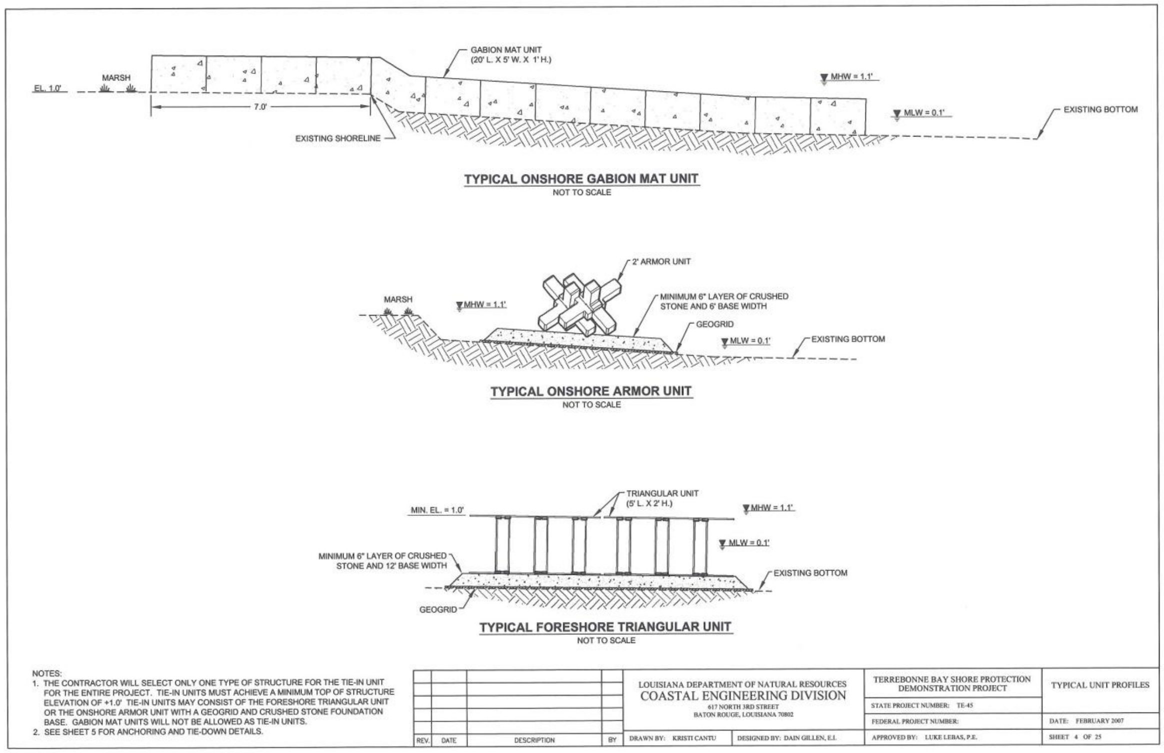


Figure A-1. **Typical cross sections showing the Terrebonne Bay Shore Protection Demonstration (TE-45) project's shoreline protection structures.**

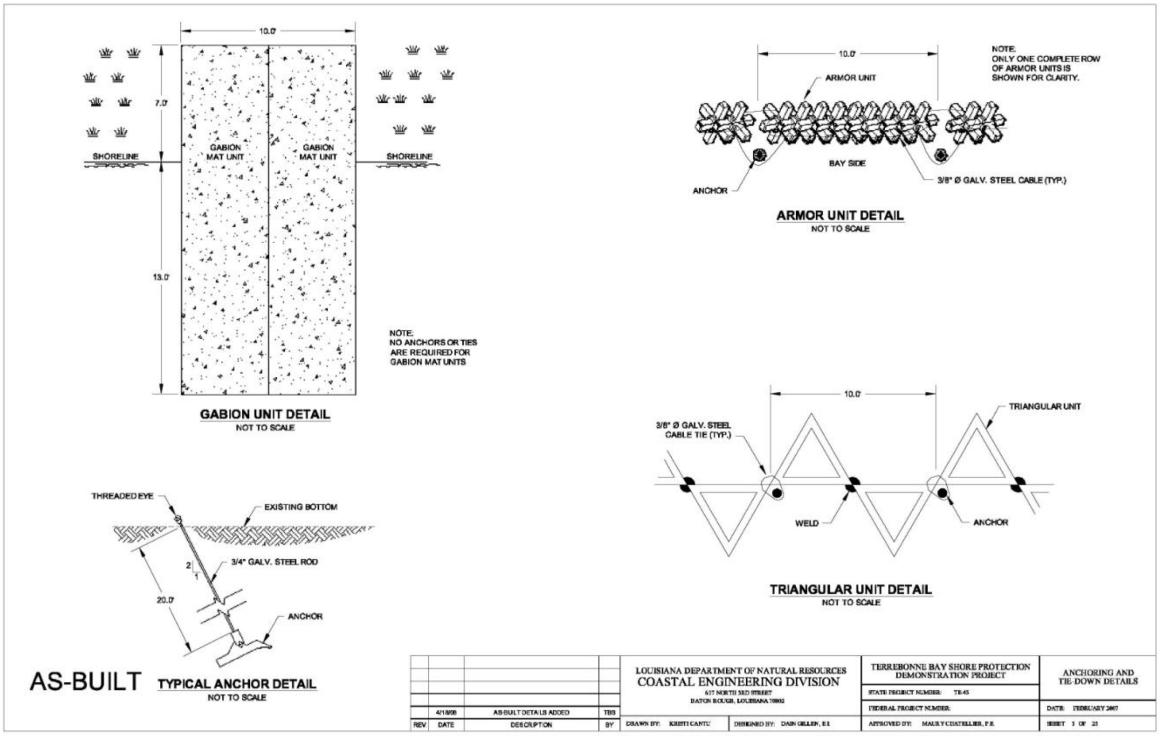


Figure A-2. **Aerial view depicting the typical layout and anchoring details for the Terrebonne Bay Shore Protection Demonstration (TE-45) project's Gabion Mat, A-Jack, and ReefBlk structures.**

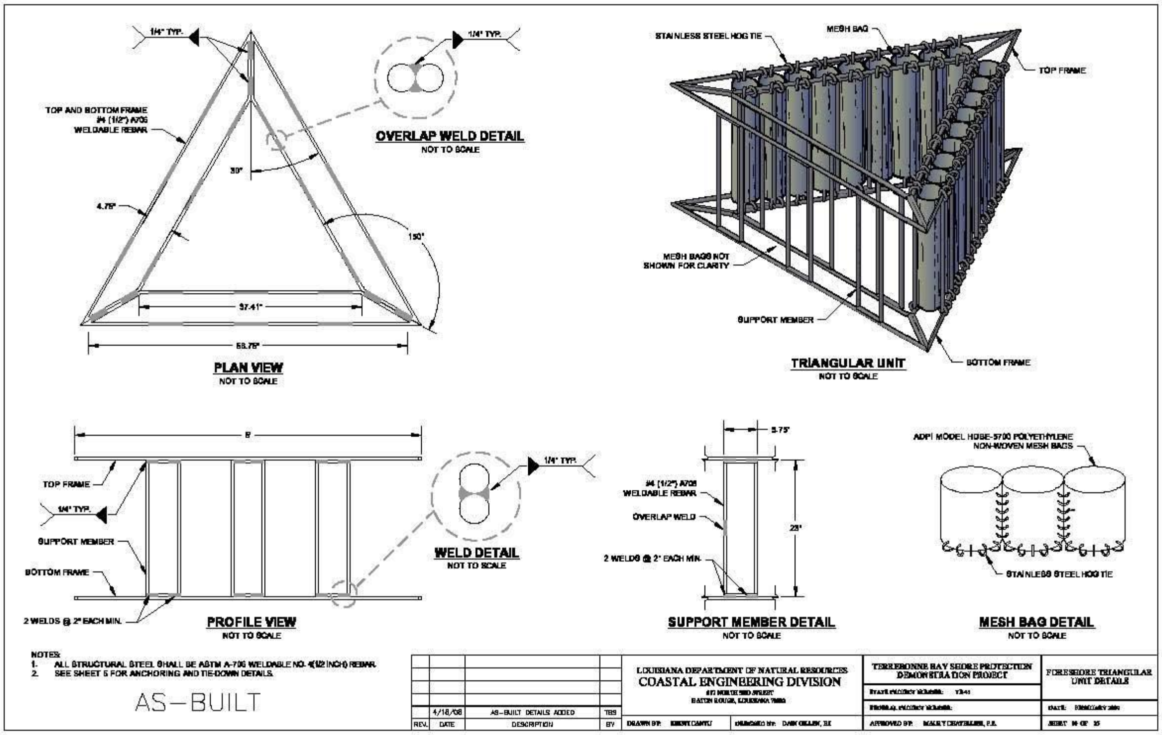


Figure A-3. **Design drawings showing the Terrebonne Bay Shore Protection Demonstration (TE-45) project's ReefBlk structure.**

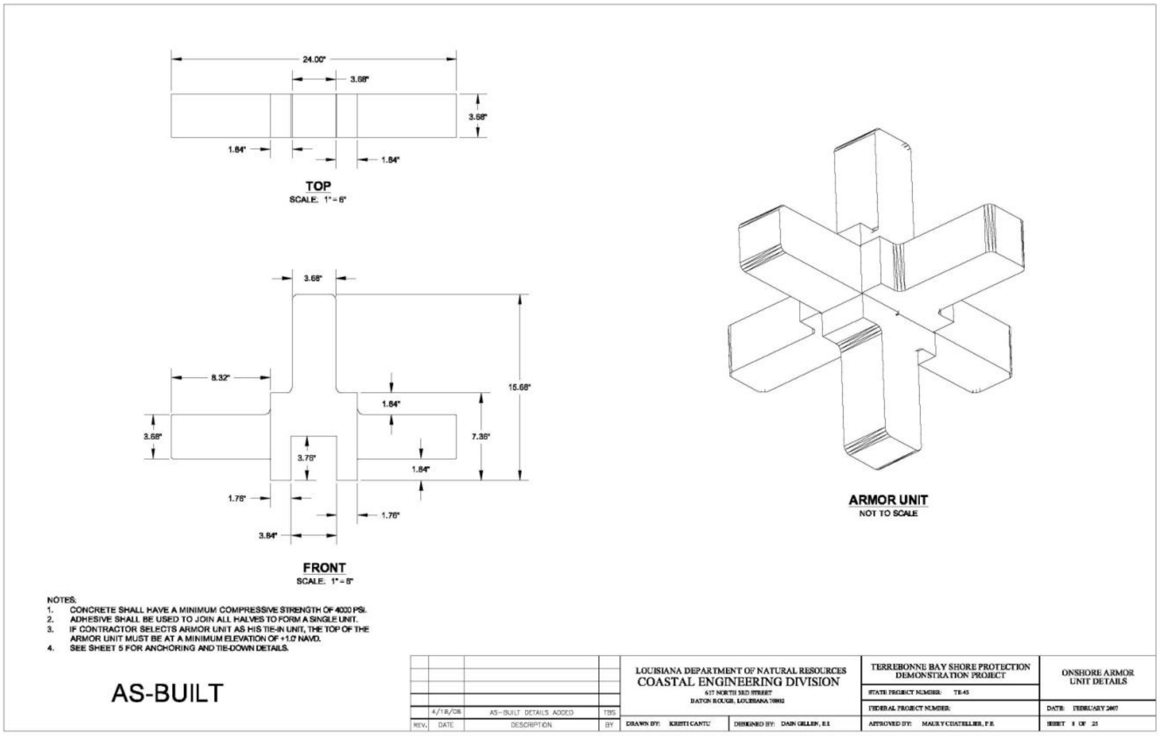


Figure A-4. **Design drawings showing the Terrebonne Bay Shore Protection Demonstration (TE-45) project's A-Jack structure.**

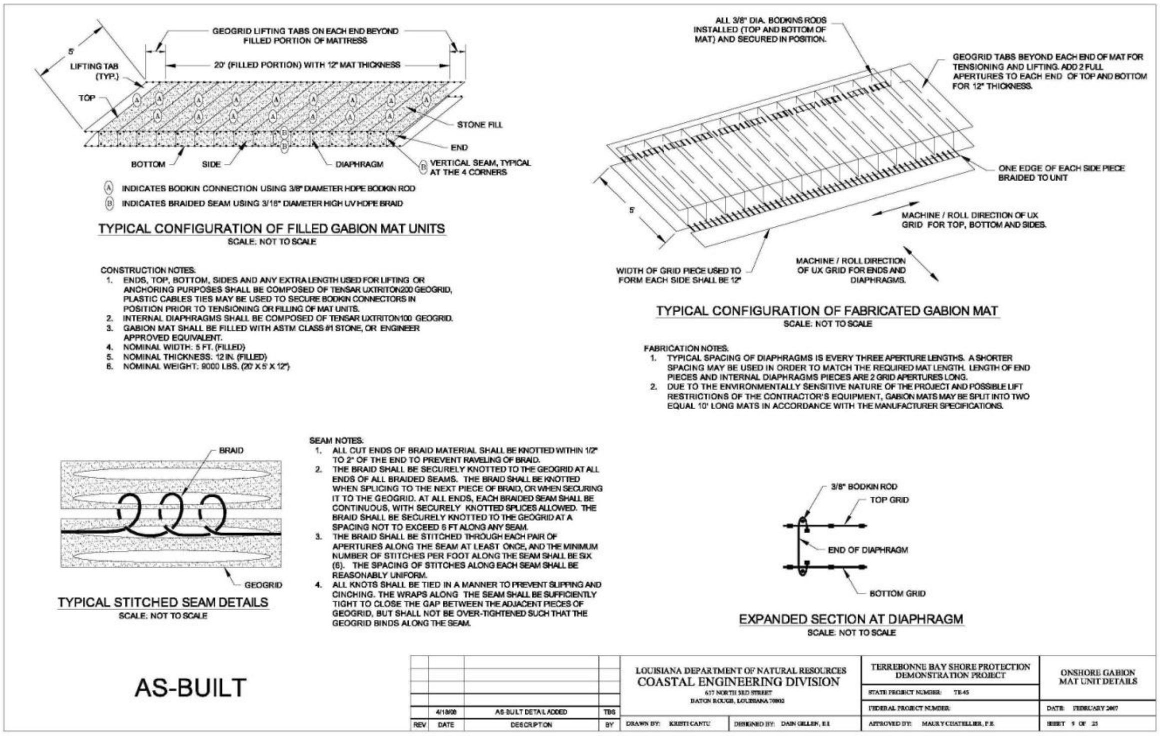


Figure A-5. **Design drawings showing the Terrebonne Bay Shore Protection Demonstration (TE-45) project's Gabion Mat structure.**

Appendix B
(Inspection Photographs)

Photo 1: Gabion Mats located on the southern end of Reach A looking north

Photo 2: Gabion Mats located on the southern end of Reach A looking north

Photo 3: View of Reach A A-Jacks looking west

Photo 4: View of Reach A ReefBlks looking west

Photo 5: Gabion Mats located on the southern end of Reach B looking north

Photo 6: Transition between Gabion Mats and A-Jacks on Reach B

Photo 7: Transition of A-Jacks and ReefBlks on Reach B

Photo 8: Close up view of ReefBlks on Reach B

Photo 9: Transition of ReefBlks to the shoreline tie-in on north side of Reach B

Photo 10: View of shoreline tie-in on north side of Reach B

Photo 11: View of Gabion Mats on the south end of Reach E looking south

Photo 12: View of Gabion Mats on the south end of Reach E looking north

Photo 13: View of Gabion Mats low area and transition to ReefBlks on Reach E looking north

Photo 14: View of Gabion Mats low area on Reach E looking east

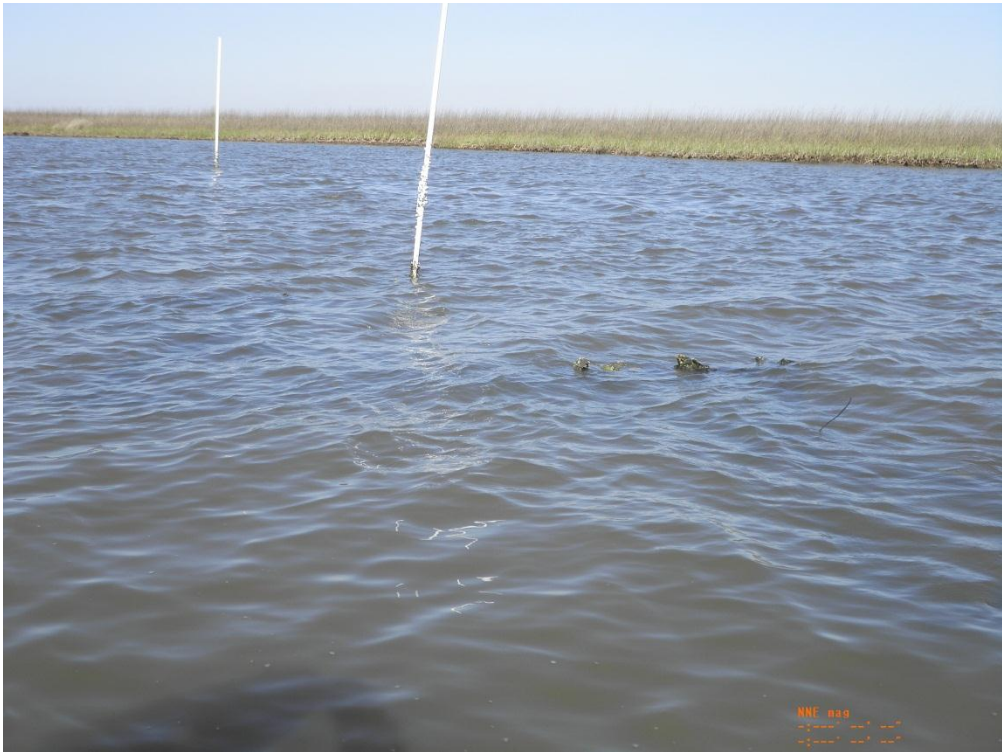


Photo 15: Transition from Gabion Mats to ReefBlks on Reach E submerged

Photo 16: View of submerged ReefBlks on Reach E

Photo 17: View of submerged A-Jacks on Reach E

Photo 18: View of Damaged warning sign along Reach E

Appendix C
(Three Year Budget Projection)

Terrebonne Bay Shore Protection Demonstration / TE45 / PPL10

Three-Year Operations & Maintenance Budgets 07/01/2013 - 06/30/2016

Project Manager	O & M Manager	Federal Sponsor	Prepared By
	Dearmond	USFWS	Ledet

	2013/2014	2014/2015	2015/2016
Maintenance Inspection	$ 6,365.00	$ 6,569.00	$ 6,779.00
Structure Operation	$ -	$ -	$ -
Administration	$ -		$ -
USACE Administration	$ -	$ -	$ -
Maintenance/Rehabilitation			

13/14 Description:

E&D	$ -		
Construction	$ -		
Construction Oversight	$ -		
Sub Total - Maint. And Rehab.	$ -		

14/15 Description

E&D			
Construction			
Construction Oversight			
	Sub Total - Maint. And Rehab.	$ -	

15/16 Description:

E&D			$ -
Construction			$ -
Construction Oversight			$ -
		Sub Total - Maint. And Rehab.	$ -

	2013/2014	2014/2015	2015/2016
Total O&M Budgets	**$ 6,365.00**	**$ 6,569.00**	**$ 6,779.00**

O&M Budget (3 yr Total)	**$ 19,713.00**
Unexpended O&M Funds	**$ 45,905.65**
Remaining O&M Budget (Projected)	**$ 26,192.65**

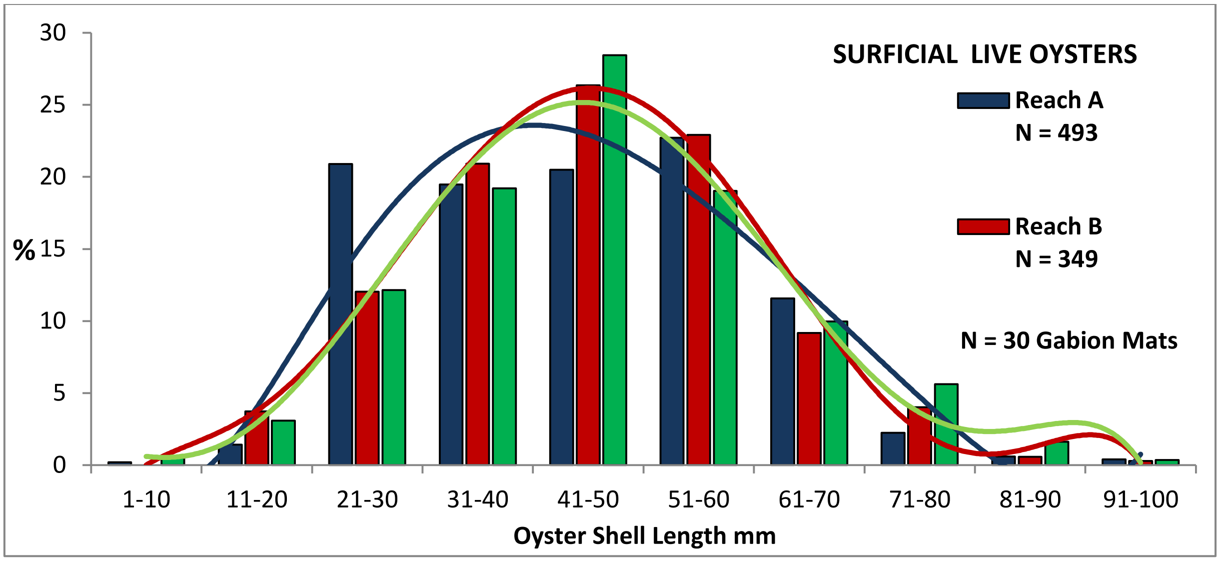
Appendix D
(TE-45 Oyster Statistics)

Appendix D1

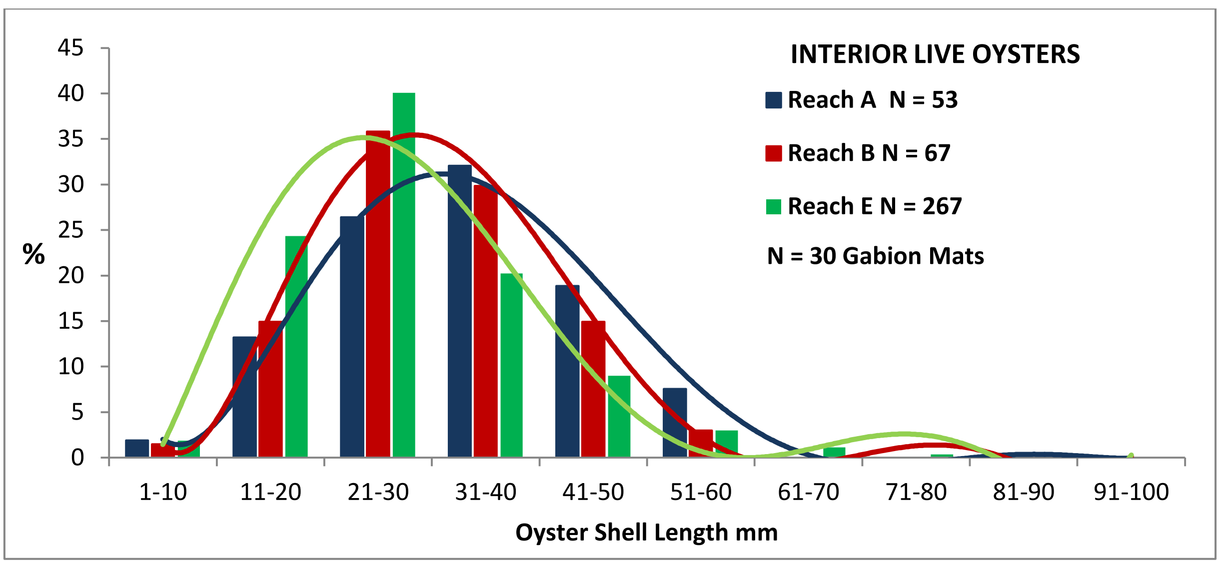
One Way Analysis of Variance					
Data source: Data 1 in Spat 2008-12.SNB					
Dependent Variable: Oyster spat/cm^2 for the five year period 2008-2012					
Normality Test:	Failed	(P < 0.050)			
Test execution ended by user request, ANOVA on Ranks begun					
Kruskal-Wallis One Way Analysis of Variance on Ranks					
Data source: Data 1 in Spat 2008-12.SNB					
Group	N	Missing	Median	25%	75%
A	230	0	0	0	0.0267
B	209	0	0	0	0.0222
E	267	0	0.0178	0	0.128
H = 45.532 with 2 degrees of freedom. (P = <0.001)					
The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = <0.001)					
To isolate the group or groups that differ from the others use a multiple comparison procedure.					
All Pairwise Multiple Comparison Procedures (Dunn's Method) :					
Comparison	Diff of Ranks	Q	P<0.05		
E vs B	111.365	5.912	Yes		
E vs A	89.869	4.898	Yes		
A vs B	21.496	1.103	No		
Note: The multiple comparisons on ranks do not include an adjustment for ties.					

Appendix D2

One Way Analysis of Variance							
Data source: Data 1 in Gabion Density.SNB							
Dependent Variable: Gabion Live Oysters/m^2 during winter 2011-12 Assessment							
Normality Test:	Passed	(P = 0.277)					
Equal Variance Test:	Passed	(P = 0.182)					
Group Name	N	Missing	Mean	Std Dev	SEM		
A	10	0	899.2	369.104	116.721		
B	10	0	667.2	403.579	127.623		
E	10	0	1312	725.569	229.445		
Source of Variation	DF	SS	MS	F	P		
Between Groups	2	2133316	1066658	3.876	0.033		
Residual	27	7430067	275187.7				
Total	29	9563383					
The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.033).							
Power of performed test with alpha = 0.050: 0.508							
The power of the performed test (0.508) is below the desired power of 0.800.							
Less than desired power indicates you are more likely to not detect a difference when one actually exists. Be cautious in over-interpreting the lack of difference found here.							
All Pairwise Multiple Comparison Procedures (Tukey Test):							
Comparisons for factor: Reach							
Comparison	Diff of Means	p	q	P	P<0.050		
E vs. B	644.8	3	3.887	0.028	Yes		
E vs. A	412.8	3	2.488	0.202	No		
A vs. B	232	3	1.399	0.59	No		



Appendix D3. **Gabion Mats surficial live oysters length frequencies by Reach for winter 2011-12 assessment.**



AppendixD4. **Gabion Mats interior live oysters length frequencies by Reach for winter 2011-12 assessment.**

Appendix D5

One Way Analysis of Variance					
Data source: Data 1 in AJacks Cover.SNB					
Dependent Variable: % Consolidated Reef Ajacks Winter 2011-12					
Normality Test:	Passed	(P = 0.291)			
Equal Variance Test:	Failed	(P < 0.050)			
Test execution ended by user request, ANOVA on Ranks begun					
Kruskal-Wallis One Way Analysis of Variance on Ranks					
Data source: Data 1 in AJacks Cover.SNB					
Group	N	Missing	Median	25%	75%
A	15	0	30	16.25	38.75
B	15	0	30	25	35
E	15	0	30	25	40
H = 1.248 with 2 degrees of freedom. (P = 0.536)					
The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant					

Appendix D6

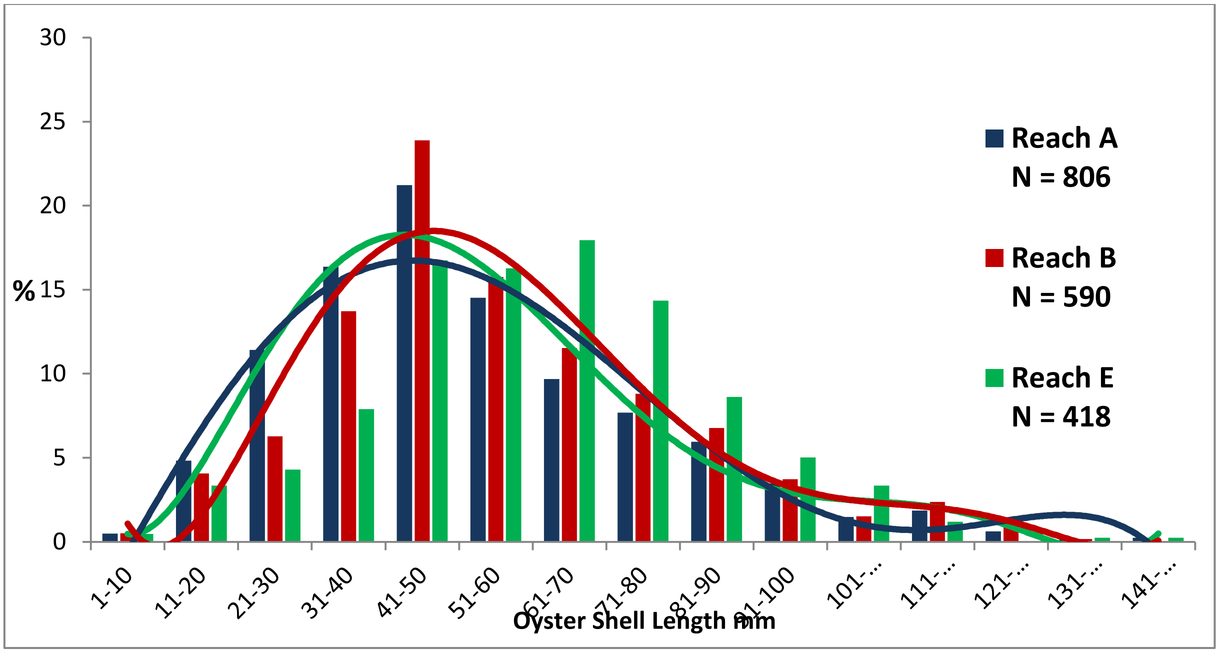
One Way Analysis of Variance						
Data source: Data 1 in AJacks Cover.SNB						
Dependent Variable: % oyster cover Ajacks winter 2011-12						
Normality Test:	Passed	(P = 0.246)				
Equal Variance Test:	Passed	(P = 0.405)				
Group Name	N	Missing	Mean	Std Dev	SEM	
A	15	0	55.667	11.159	2.881	
B	15	0	64.333	8.209	2.119	
E	15	0	59.333	11.932	3.081	
Source of Variation	DF	SS	MS	F	P	
Between Groups	2	567.778	283.889	2.548	0.09	
Residual	42	4680	111.429			
Total	44	5247.778				
The differences in the mean values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.090).						

Appendix D7

One Way Analysis of Variance							
Data source: Data 1 in AJacks Density.SNB							
Dependent Variable: AJacks Live Oysters/m^2 Winter 2011-12							
Normality Test:	Passed	(P = 0.227)					
Equal Variance Test:	Passed	(P = 0.442)					
Group Name	N	Missing	Mean	Std Dev	SEM		
A	14	0	483.429	206.163	55.099		
B	15	0	485.333	302.774	78.176		
E	9	0	542.222	122.231	40.744		
Source of Variation	DF	SS	MS	F	P		
Between Groups	2	22979.26	11489.63	0.206	0.815		
Residual	35	1955476	55870.75				
Total	37	1978456					
The differences in the mean values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.815).							

Appendix D8

One Way Analysis of Variance						
Data source: Data 1 in AJacks Density.SNB						
Dependent Variable: AJacks Live Mussels/m^2 Winter 2011-12						
Normality Test:	Passed	(P = 0.658)				
Equal Variance Test:	Passed	(P = 0.161)				
Group Name	N	Missing	Mean	Std Dev	SEM	
A	14	0	1569.143	706.331	188.775	
B	15	0	948.267	447.529	115.551	
E	9	0	1459.556	424.662	141.554	
Source of Variation	DF	SS	MS	F	P	
Between Groups	2	3098861	1549430	5.053	0.012	
Residual	35	10732395	306639.9			
Total	37	13831256				
The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.012).						
All Pairwise Multiple Comparison Procedures (Tukey Test):						
Comparisons for factor: Reach						
Comparison	Diff of Means	p	q	P	P<0.050	
A vs. B	620.876	3	4.267	0.013	Yes	
A vs. E	109.587	3	0.655	0.889	No	
E vs. B	511.289	3	3.097	0.087	No	



Appendix D9. A-Jacks length frequency data by Reach during winter 2011-12 assessment.

Appendix D10

Two Way Analysis of Variance							
Data source: Data 1 in Notebook 1							
General Linear Model							
Dependent Variable: % Gap Winter 2011-12 for ReefBlks							
Normality Test:	Failed	(P < 0.050)					
Equal Variance Test:	Failed	(P < 0.050)					
Source of Variation	DF	SS	MS	F	P		
Reach	2	67299.26	33649.63	245.058	<0.001		
Direction	1	58.76	58.76	0.428	0.514		
Reach x Direction	2	1292.662	646.331	4.707	0.01		
Residual	179	24579.01	137.313				
Total	184	93205.95	506.554				
The difference in the mean values among the different levels of Reach is greater than would be expected by chance after allowing for effects of differences in Direction. There is a statistically significant difference (P = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.							
The difference in the mean values among the different levels of Direction is not great enough to exclude the							

Appendix D10. Continued.

possibility that the difference is just due to random sampling variability after allowing for the effects of differences in Reach. There is not a statistically significant difference (P = 0.514).

The effect of different levels of Reach depends on what level of Direction is present. There is a statistically significant interaction between Reach and Direction. (P = 0.010)

Power of performed test with alpha = 0.0500: for Reach : 1.000							
Power of performed test with alpha = 0.0500: for Direction : 0.0500							
Power of performed test with alpha = 0.0500: for Reach x Direction : 0.674							
Least square means for Reach :							
Group	Mean	SEM					
A	28.871	1.488					
B	10.89	1.501					
E	57.258	1.488					
Least square means for Direction :							
Group	Mean	SEM					
leeward	31.776	1.222					
windward	32.903	1.215					
Least square means for Reach x Direction :							
Group	Mean	SEM					
A x leeward	25.161	2.105					
A x windward	32.581	2.105					
B x leeward	10.167	2.139					
B x windward	11.613	2.105					
E x leeward	60	2.105					
E x windward	54.516	2.105					
All Pairwise Multiple Comparison Procedures (Tukey Test):							
Comparisons for factor: Reach							
Comparison	Diff of Means	p	q	P	P<0.050		
E vs. B	46.368	3	31.028	<0.001	Yes		
E vs. A	28.387	3	19.075	<0.001	Yes		
A vs. B	17.981	3	12.033	<0.001	Yes		

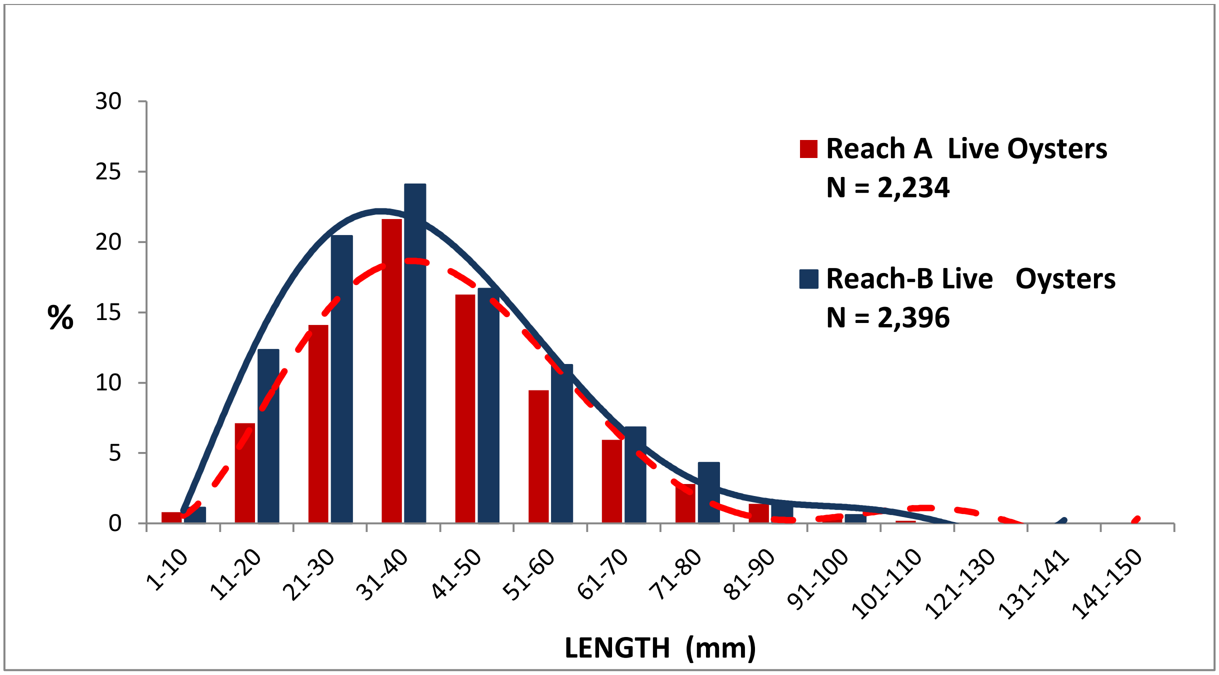
Appendix D10. Continued.							
Comparison Direction	Diff of Means	p	q	P	P<0.050		
windward vs. leeward	1.127	2	0.925	0.513	No		
Comparisons for factor: Direction within A							
Comparison	Diff of Means	p	q	P	P<0.05		
windward vs. leeward	7.419	2	3.525	0.013	Yes		
Comparisons for factor: Direction within B							
Comparison	Diff of Means	p	q	P	P<0.05		
windward vs. leeward	1.446	2	0.682	0.63	No		
Comparisons for factor: Direction within E							
Comparison	Diff of Means	p	q	P	P<0.05		
leeward vs. windward	5.484	2	2.606	0.065	No		
Comparisons for factor: Reach within leeward							
Comparison	Diff of Means	p	q	P	P<0.05		
E vs. B	49.833	3	23.483	<0.001	Yes		
E vs. A	34.839	3	16.553	<0.001	Yes		
A vs. B	14.995	3	7.066	<0.001	Yes		
Comparisons for factor: Reach within windward							
Comparison	Diff of Means	p	q	P	P<0.05		
E vs. B	42.903	3	20.385	<0.001	Yes		
E vs. A	21.935	3	10.423	<0.001	Yes		
A vs. B	20.968	3	9.963	<0.001	Yes		

Appendix D11

One Way Analysis of Variance						
Data source: Data 1 in Notebook 1						
Dependent Variable: % Consolidated Reef ReefBlks Winter 2011-12						
Normality Test:	Passed	(P = 0.083)				
Equal Variance Test:	Passed	(P = 0.440)				
Group Name	N	Missing	Mean	Std Dev	SEM	
A	30	15	22.25	5.137	1.326	
B	30	15	27.917	6.642	1.715	
Source of Variation	DF	SS	MS	F	P	
Between Groups	1	240.833	240.833	6.832	0.014	
Residual	28	987.083	35.253			
Total	29	1227.917				
The differences in the mean values among the treatment groups are greater						
than would be expected by chance; there is a statistically significant difference (P = 0.014).						
Power of performed test with alpha = 0.050: 0.646						
All Pairwise Multiple Comparison Procedures (Tukey Test):						
Comparisons for factor: Reach						
Comparison	Diff of Means	p	q	P	P<0.050	
B vs. A	5.667	2	3.696	0.014	Yes	

Appendix D12

One Way Analysis of Variance						
Data source: Data 1 in Notebook 1						
Dependent Variable: % cover ReefBlks Winter 2011-12						
Normality Test:	Passed	(P = 0.239)				
Equal Variance Test:	Passed	(P = 0.967)				
Group Name	N	Missing	Mean	Std Dev	SEM	
A	30	15	43.25	12.902	3.331	
B	30	15	64.75	13.137	3.392	
Source of Variation	DF	SS	MS	F	P	
Between Groups	1	3466.875	3466.875	20.45	<0.001	
Residual	28	4746.875	169.531			
Total	29	8213.75				
The differences in the mean values among the treatment groups are greater than						
would be expected by chance; there is a statistically significant difference (P = <0.001).						
Power of performed test with alpha = 0.050: 0.995						
All Pairwise Multiple Comparison Procedures (Tukey Test):						
Comparisons for factor: Reach						
Comparison	Diff of Means	p	q	P	P<0.050	
B vs. A	21.5	2	6.395	<0.001	Yes	



Appendix D13 **Live oyster populations' length frequencies by Reach for ReefBlks in winter 2011-12 assessment.**

Appendix D14

One Way Analysis of Variance						
Data source: Data 1 in ReefBlk Density.SNB						
Dependent Variable: # Oysters/m^2 ReefBlks 2011-12 Assessment						
Normality Test:	Passed	(P = 0.556)				
Equal Variance Test:	Passed	(P = 0.539)				
Group Name	N	Missing	Mean	Std Dev	SEM	
A	10	0	2387.5	637.259	201.519	
B	10	0	2200	807.087	255.223	
Source of Variation	DF	SS	MS	F	P	
Between Groups	1	175781.3	175781.3	0.332	0.571	
Residual	18	9517396	528744.2			
Total	19	9693177				
The differences in the mean values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.571).						

Appendix D15

One Way Analysis of Variance					
Data source: Data 1 in ReefBlk Density.SNB					
Dependent Variable: # Mussels / m^2 ReefBlks Winter 2011-12 Assessment					
Normality Test:	Passed	(P = 0.273)			
Equal Variance Test:	Passed	(P = 0.755)			
Group Name	N	Missing	Mean	Std Dev	SEM
A	10	0	10796.67	6264.385	1980.972
B	10	0	13704.17	7119.352	2251.337
Source of Variation	DF	SS	MS	F	P
Between Groups	1	42267781	42267781	0.94	0.345
Residual	18	8.09E+08	44963846		
Total	19	8.52E+08			
The differences in the mean values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.345).					

Appendix D16

One Way Analysis of Variance							
Data source: Data 1 in ReefBlk Density.SNB							
Dependent Variable: Mussel:Oyster Ratio ReefBlks Winter 2011-12 Assessment							
Normality Test:	Failed	(P < 0.050)					
Test execution ended by user request, ANOVA on Ranks begun							
Kruskal-Wallis One Way Analysis of Variance on Ranks							
Data source: Data 1 in ReefBlk Density.SNB							
Group	N	Missing	Median	25%	75%		
A	10	0	4.017	2.888	6.369		
B	10	0	5.752	4.462	7.753		
H = 1.651 with 1 degrees of freedom. (P = 0.199)							
The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.199)							

Appendix E
(Elevation Grid Models)

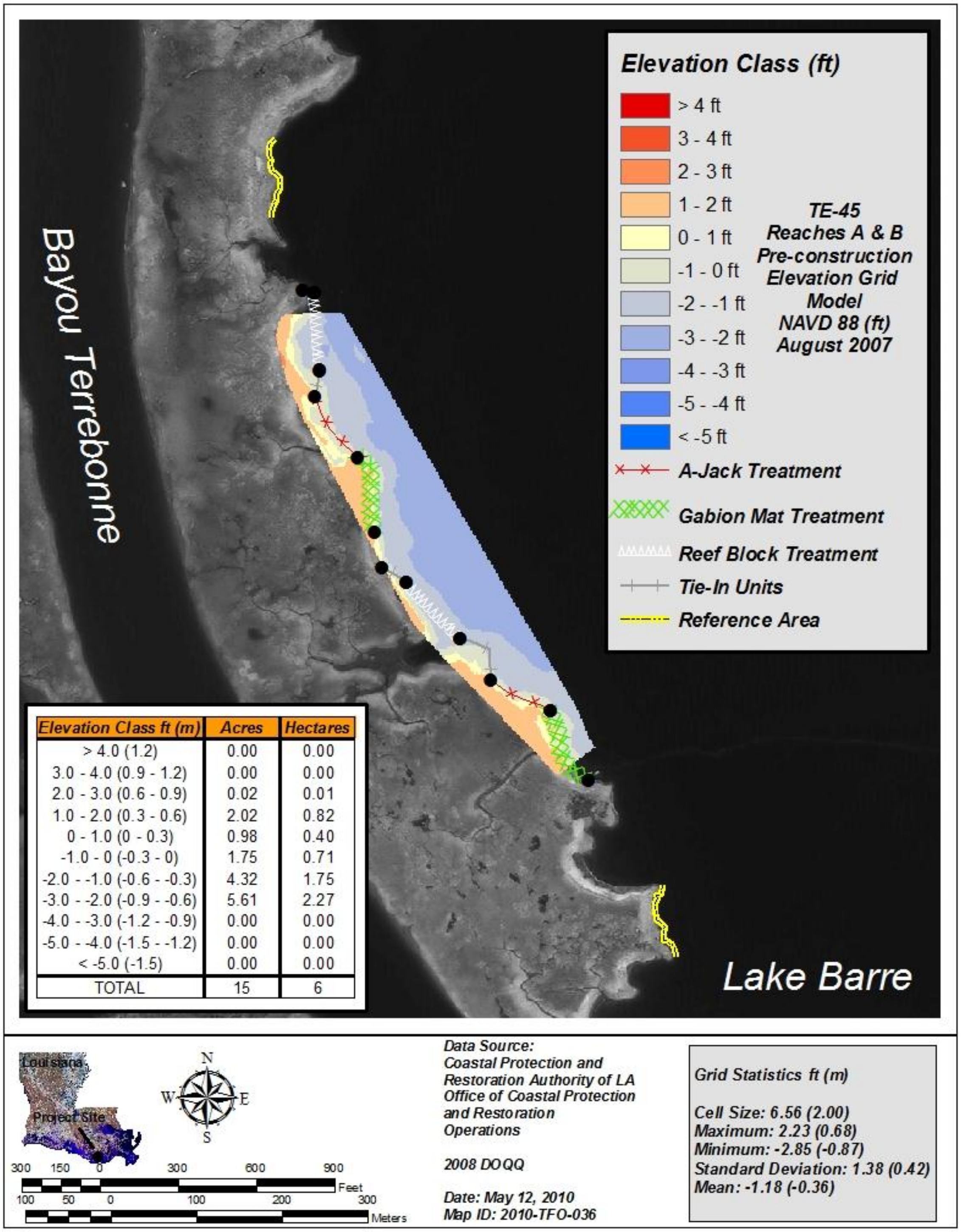


Figure E-1. Pre-construction (Aug 2007) elevation grid model for Reaches A and B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

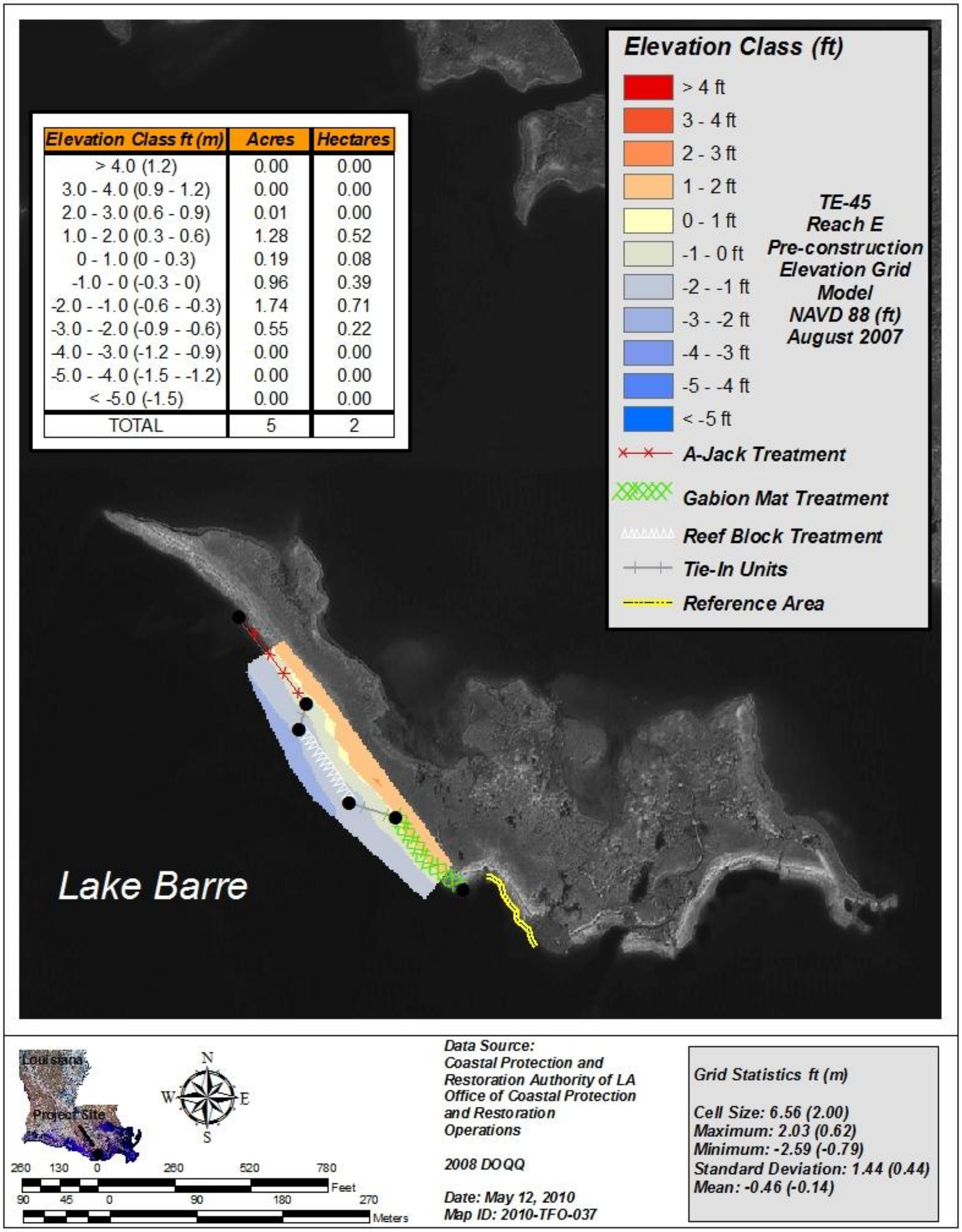


Figure E-2. **Pre-construction (Aug 2007) elevation grid model for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

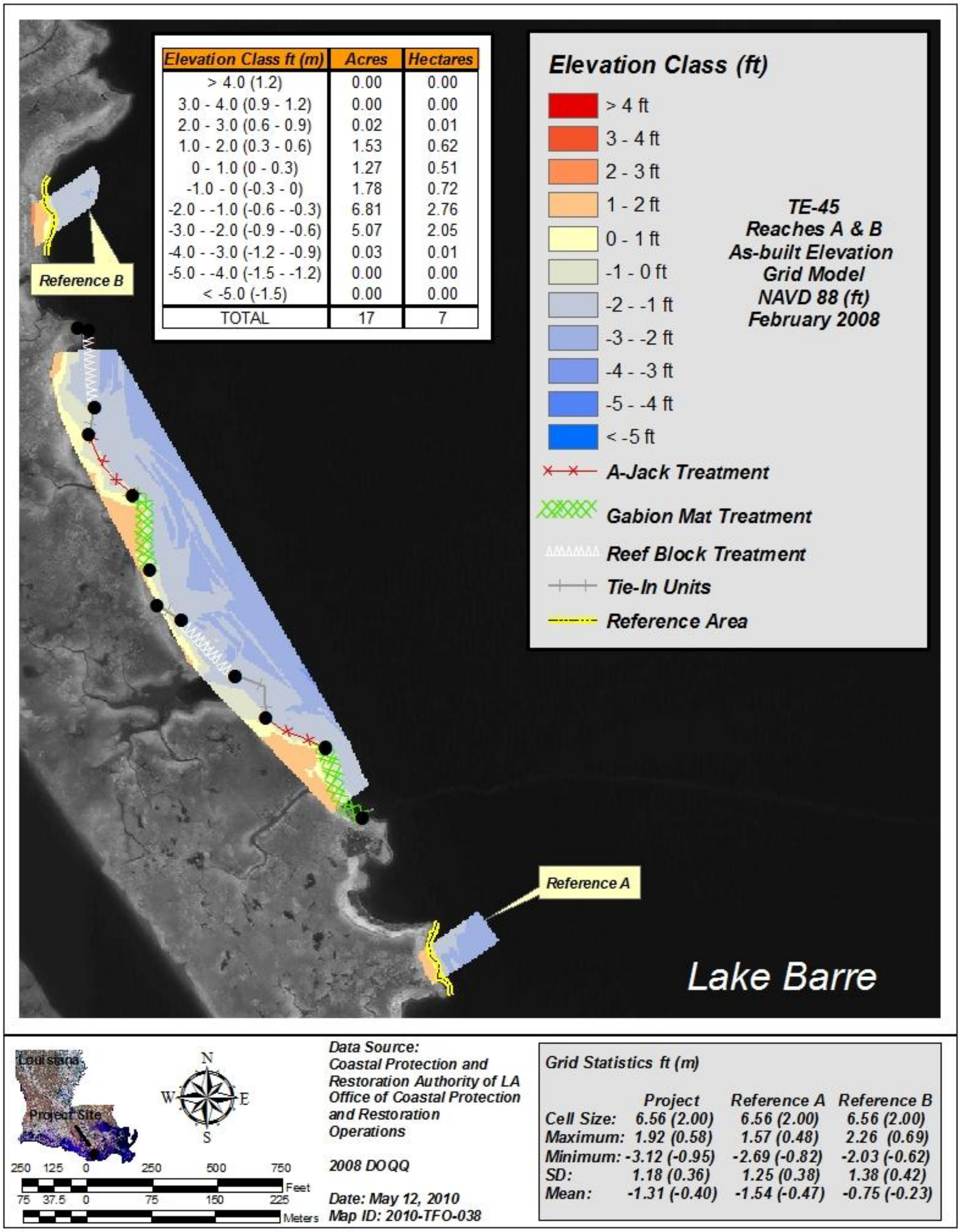


Figure E-3. **As-built (Feb 2008) elevation grid model for Reaches A and B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

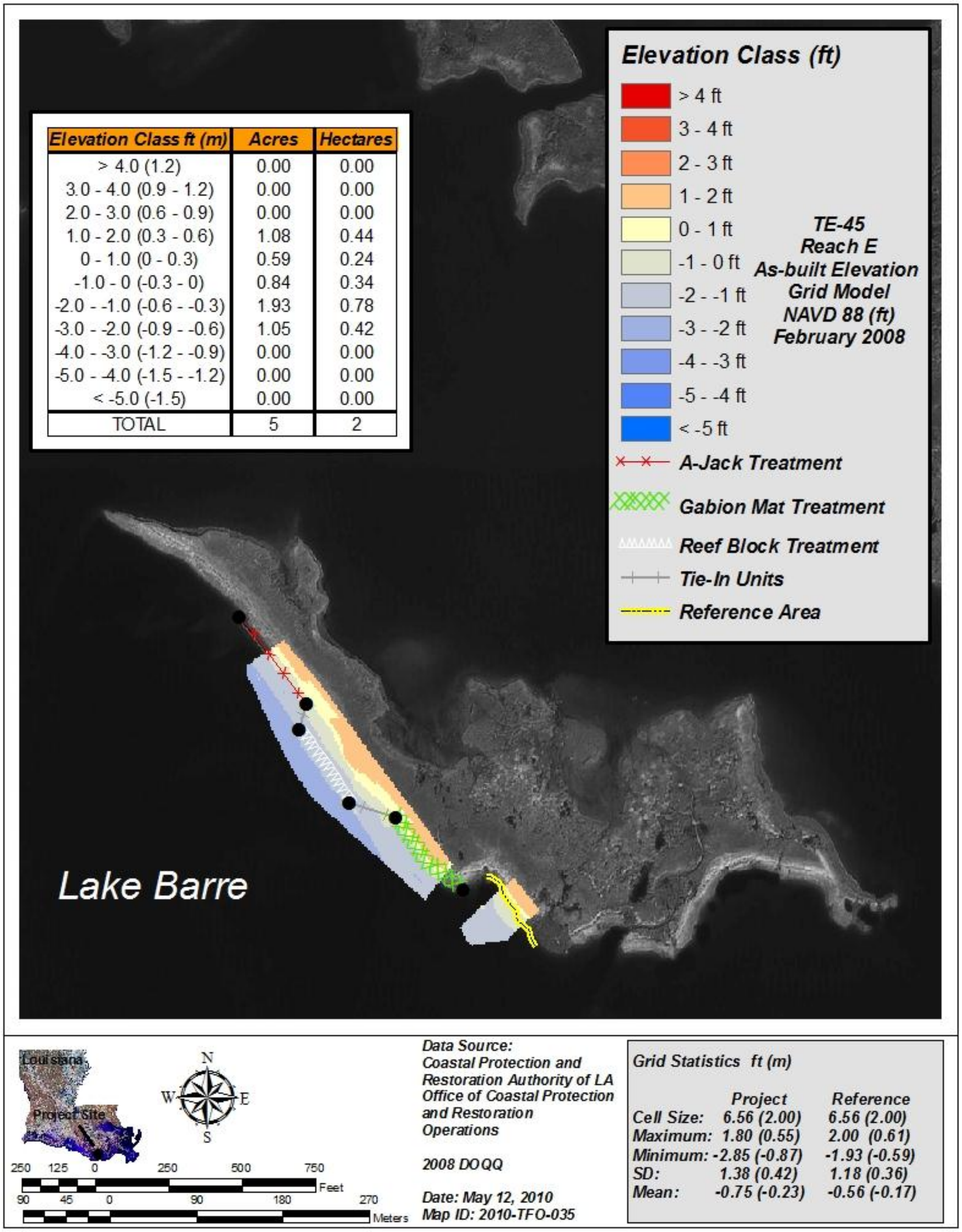


Figure E-4. **As-built (Feb 2008) elevation grid model for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

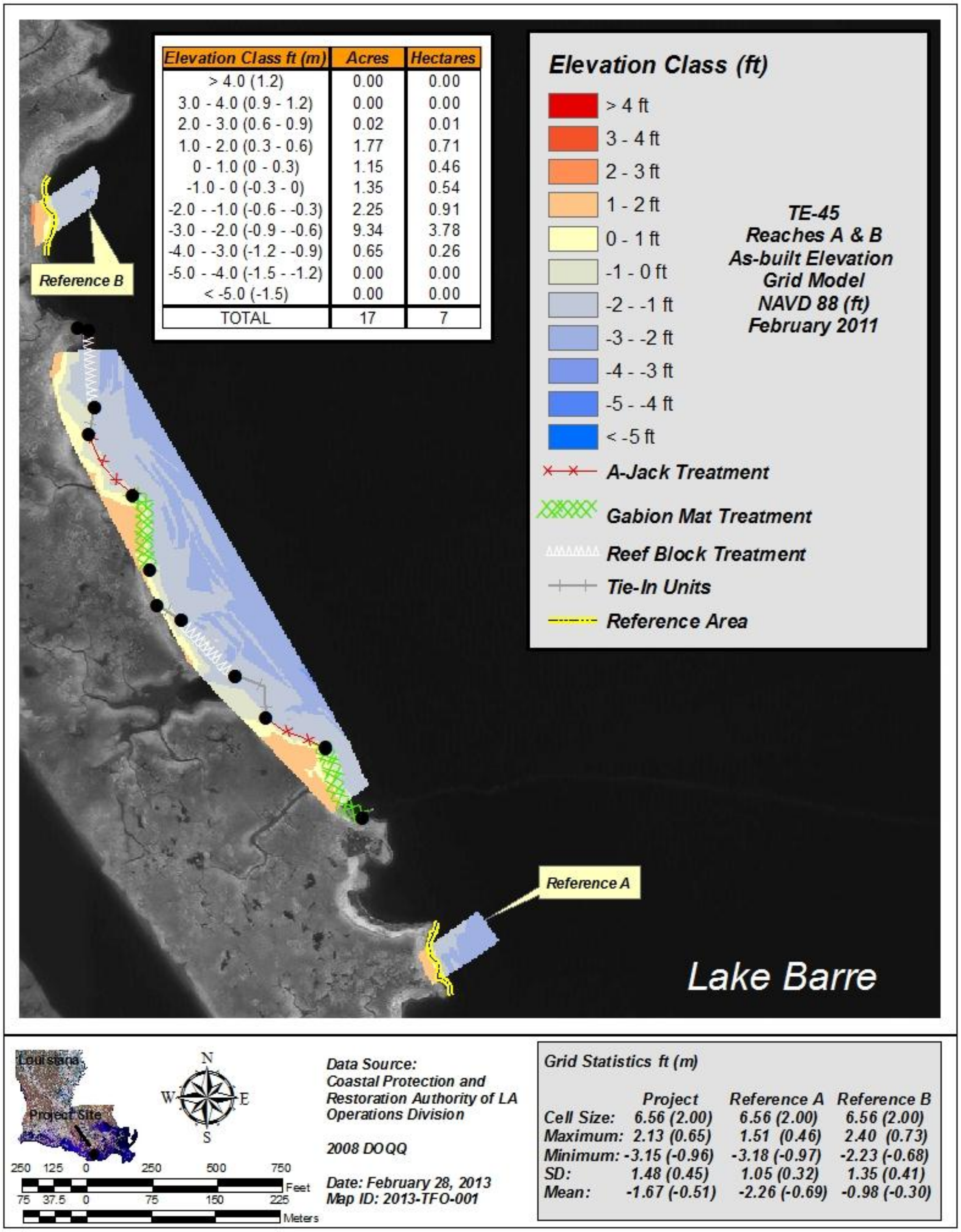


Figure E-5. Post-construction (Feb 2011) elevation grid model for Reaches A and B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

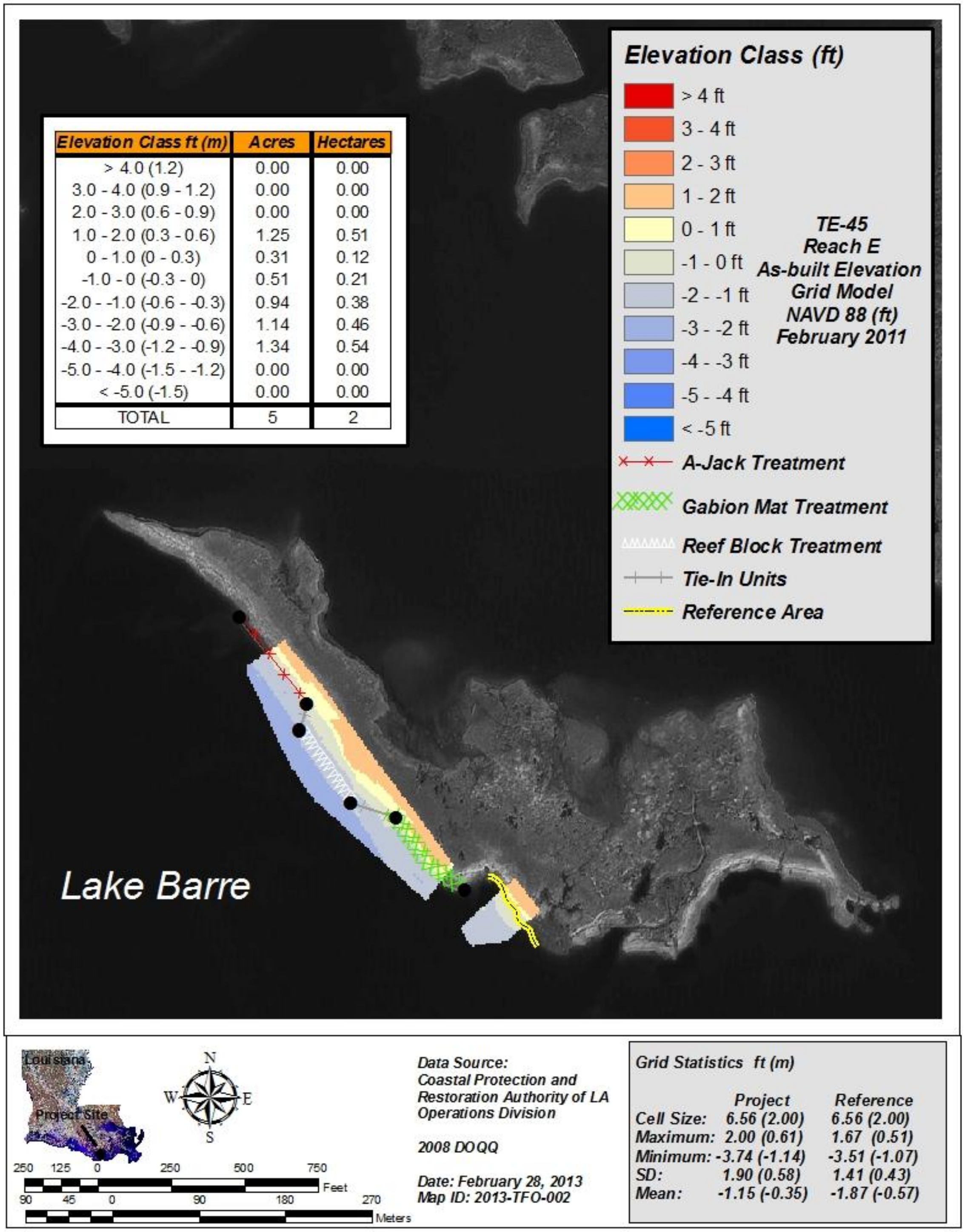


Figure E-6. Post-construction (Feb 2011) elevation grid model for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

Appendix F
(Shoreline Change Graphics)

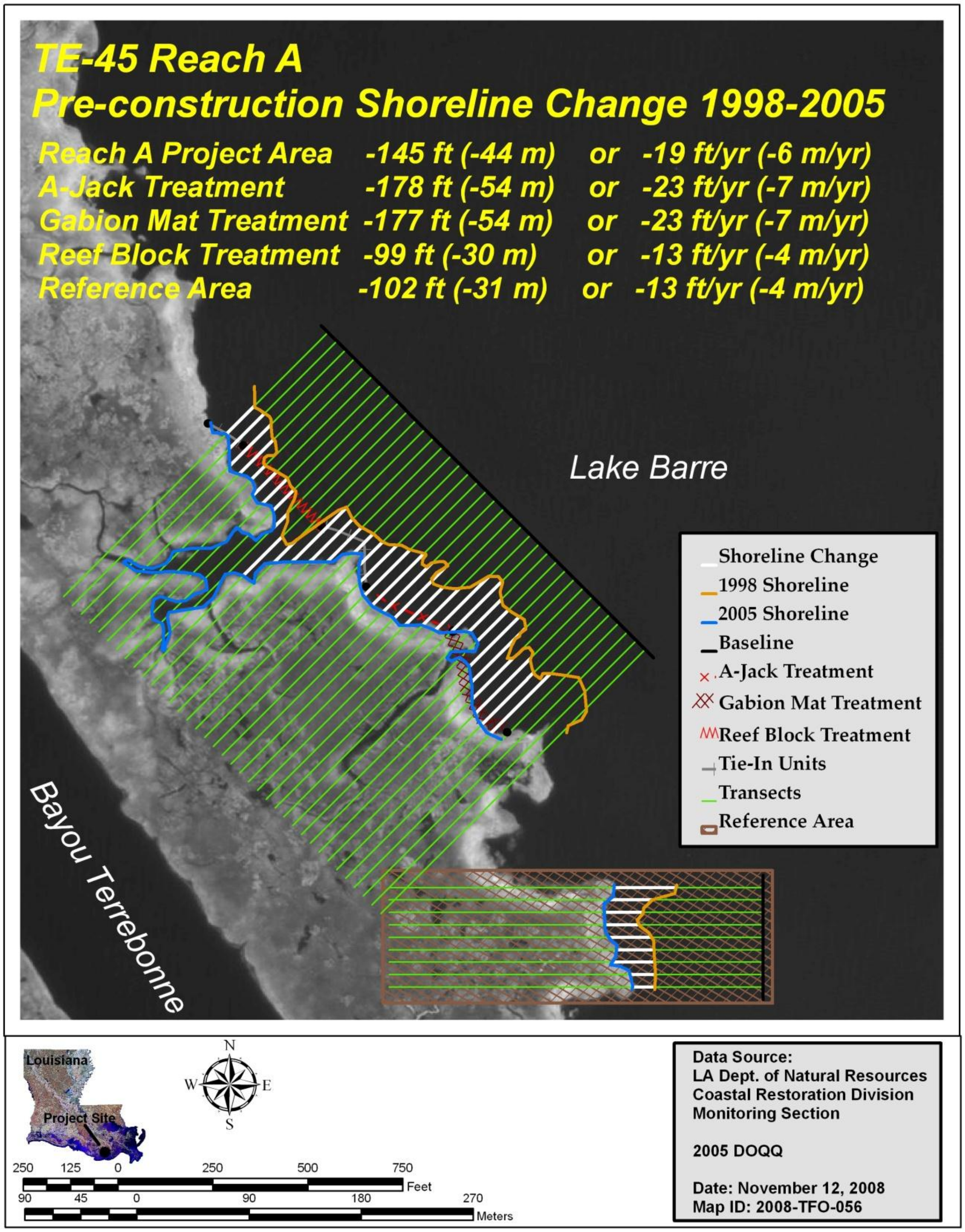


Figure F-1. **Pre-construction (1998-2005) shoreline change for Reach A at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

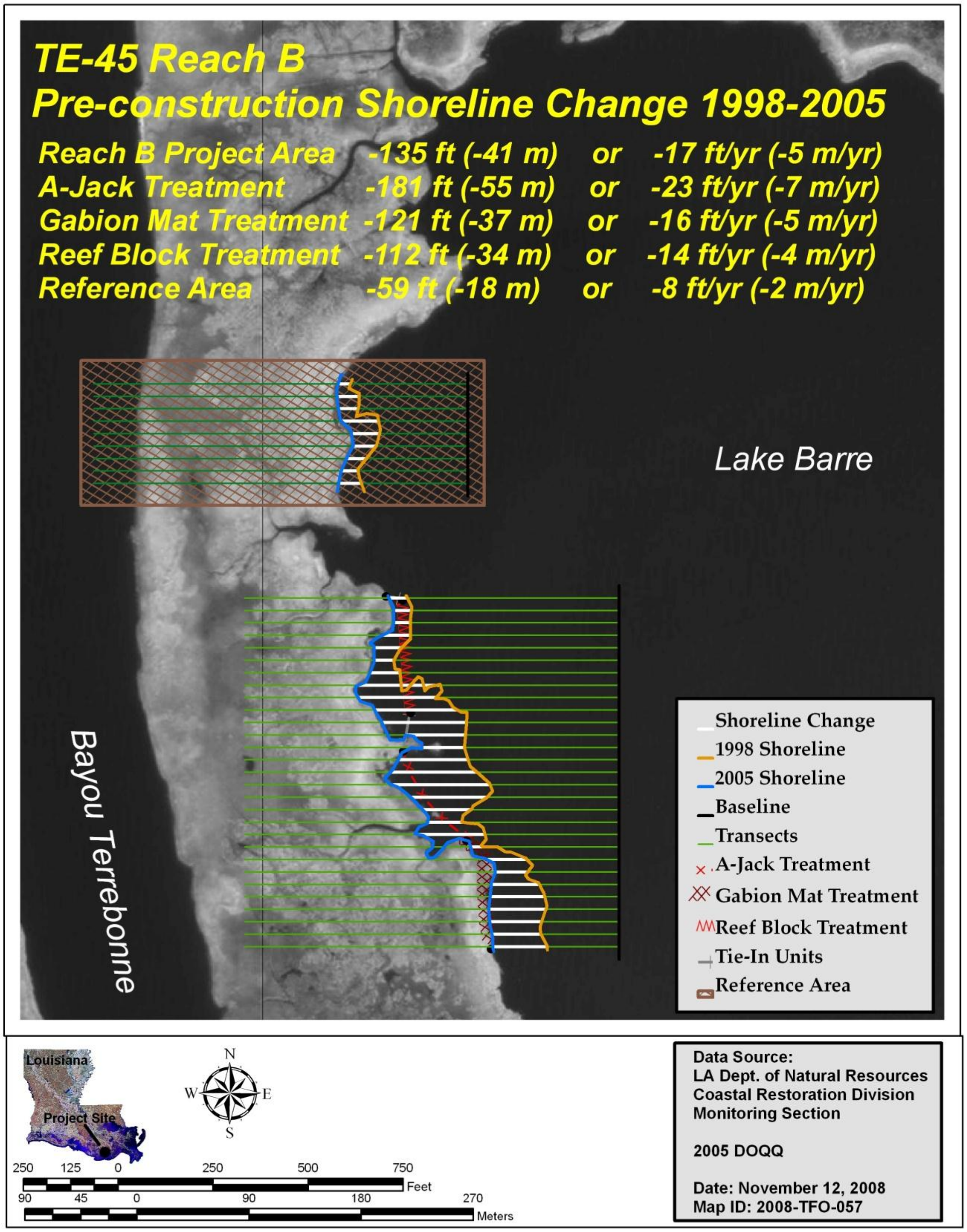


Figure F-2. **Pre-construction (1998-2005) shoreline change for Reach B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

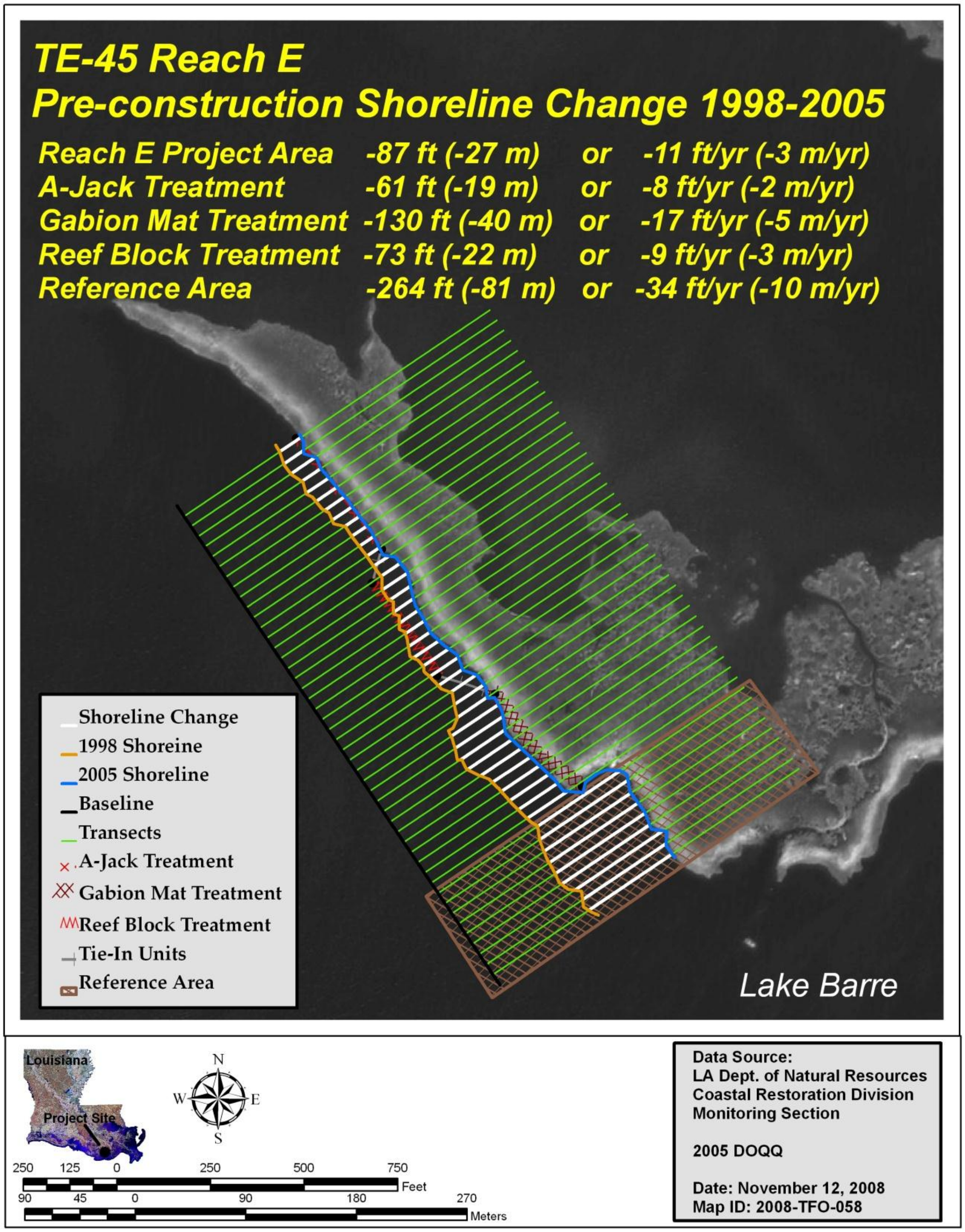


Figure F-3. **Pre-construction (1998-2005) shoreline change for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

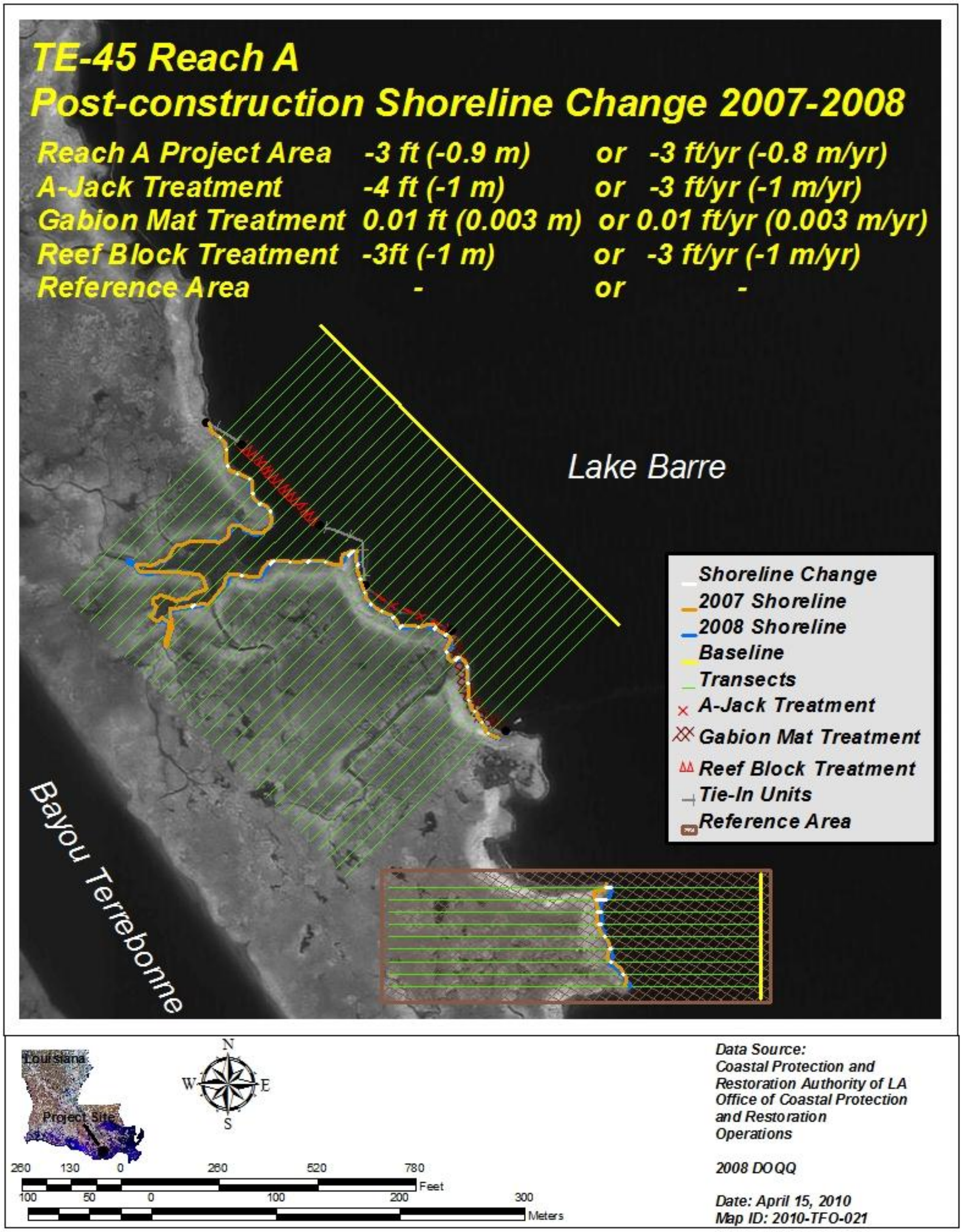


Figure F-4. **Post-construction (2007-2008) shoreline change for Reach A at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

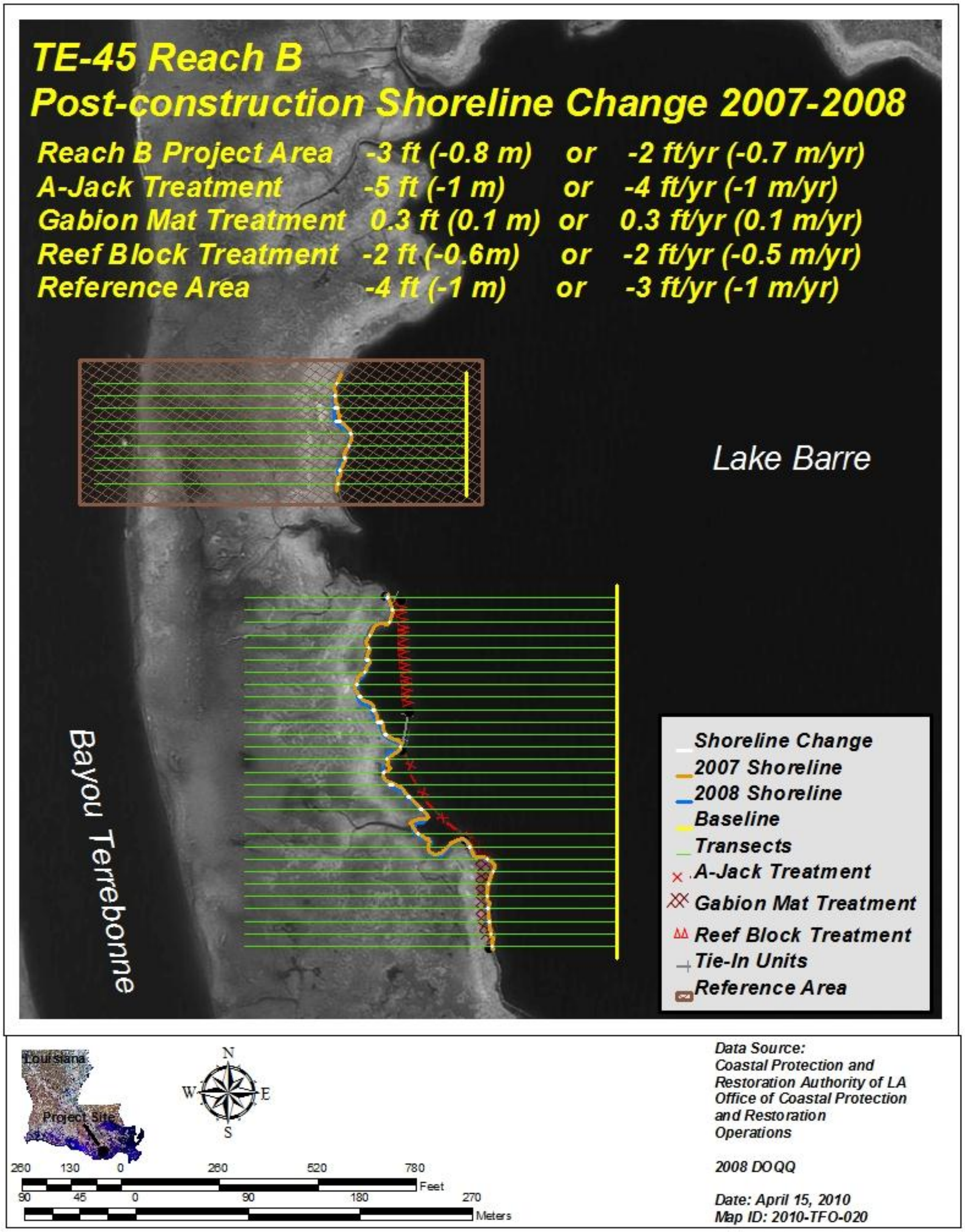


Figure F-5. Post-construction (2007-2008) shoreline change for Reach B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

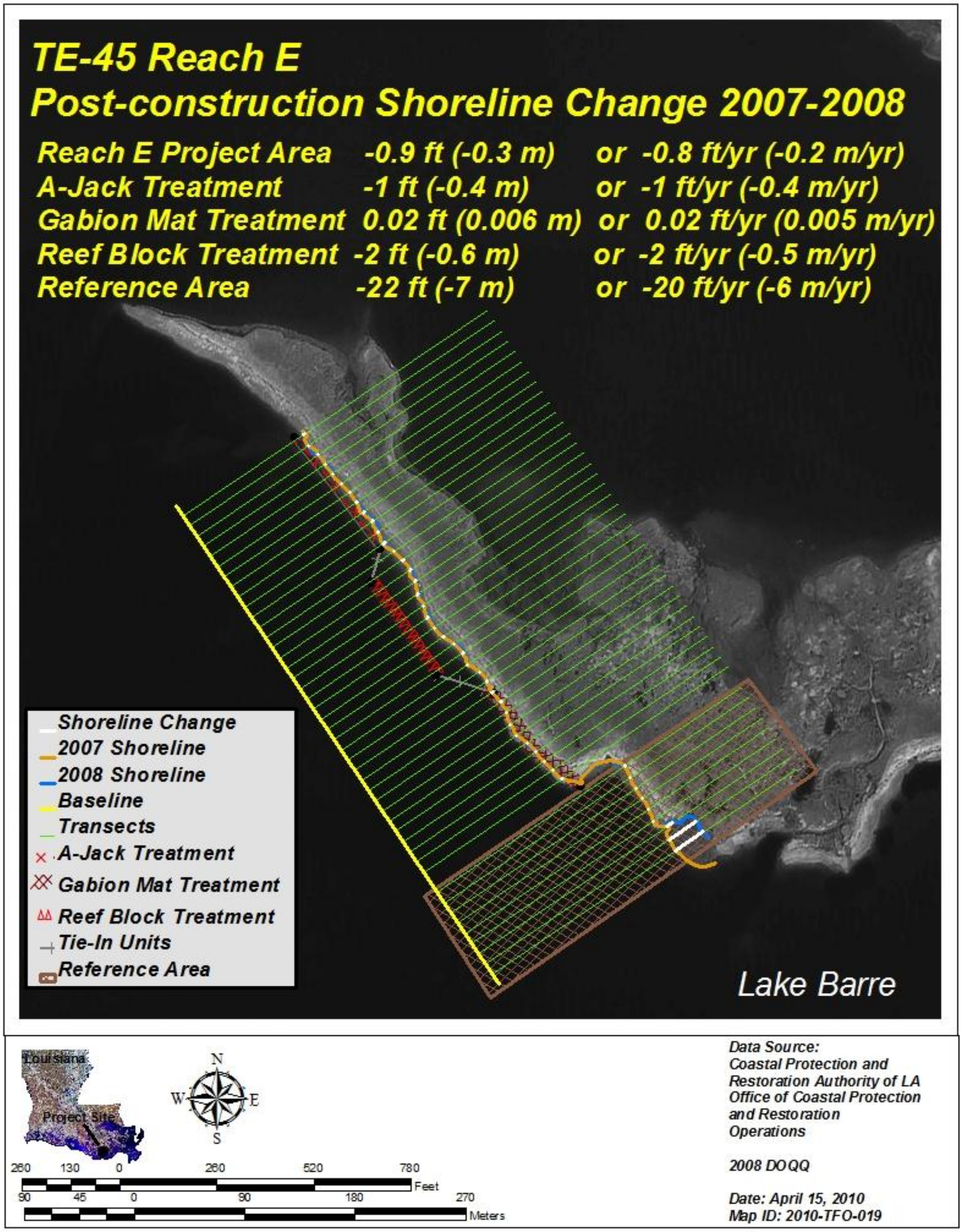


Figure F-6. **Post-construction (2007-2008) shoreline change for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

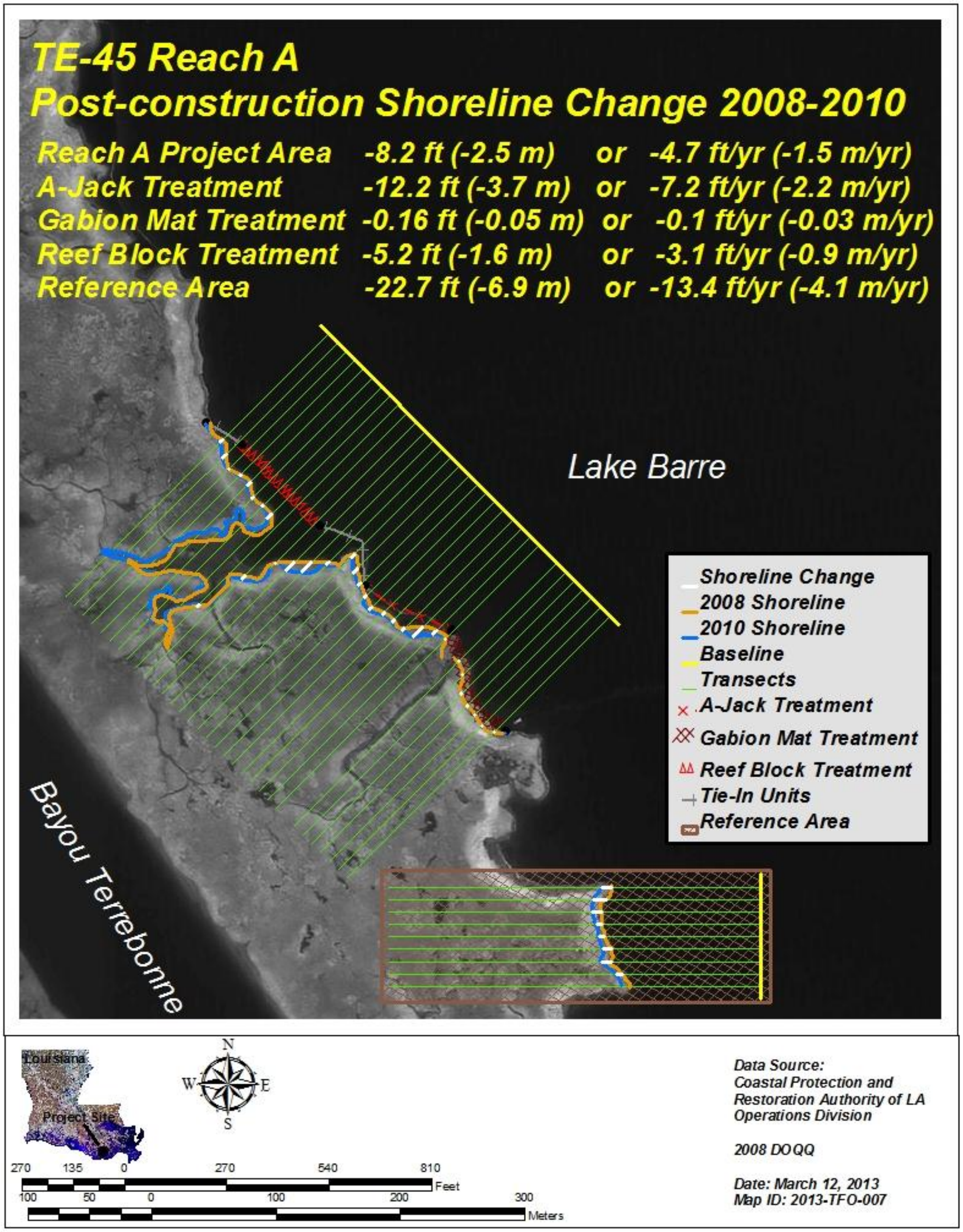


Figure F-7. Post-construction (2008-2010) shoreline change for Reach A at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

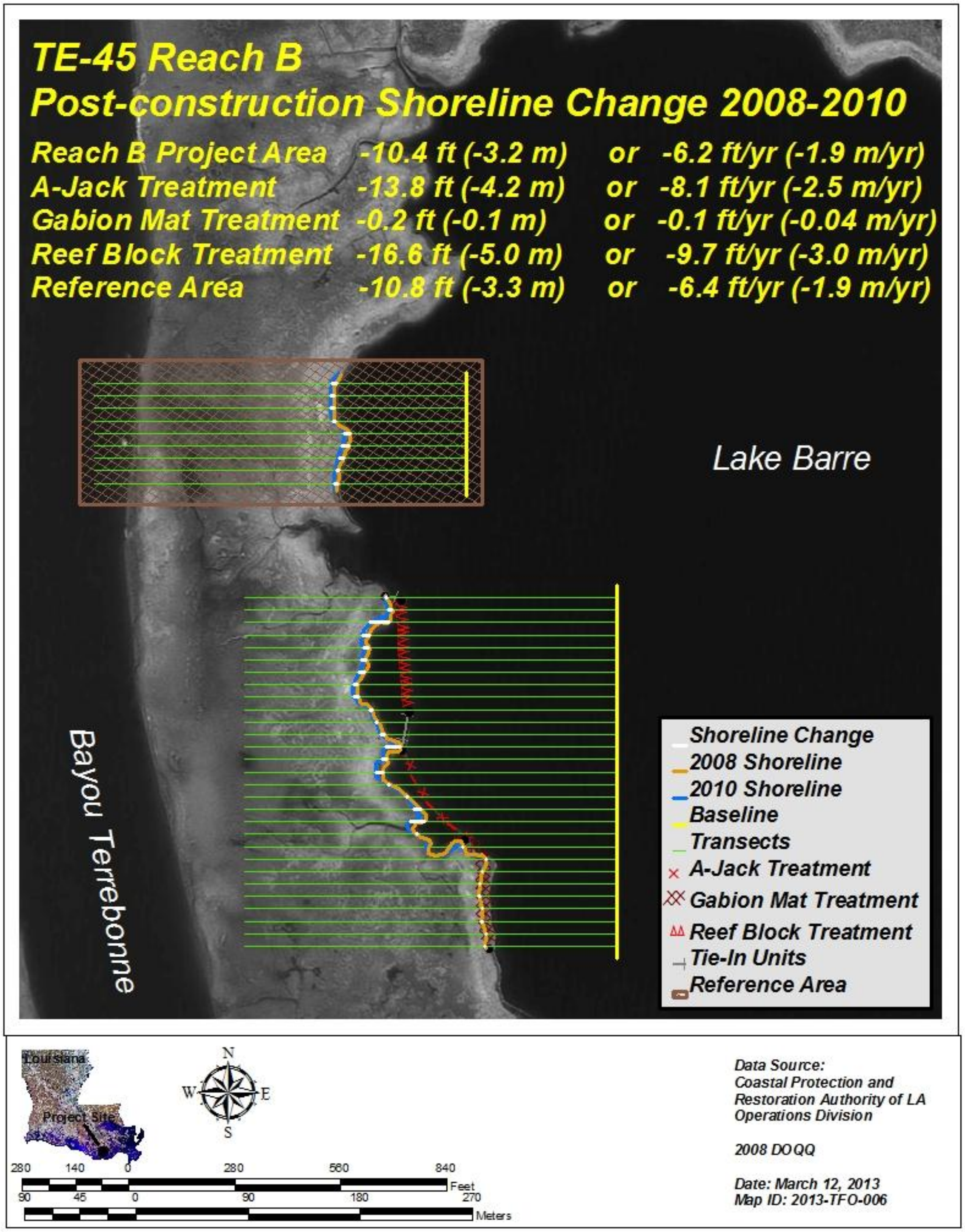


Figure F-8. **Post-construction (2008-2010) shoreline change for Reach B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

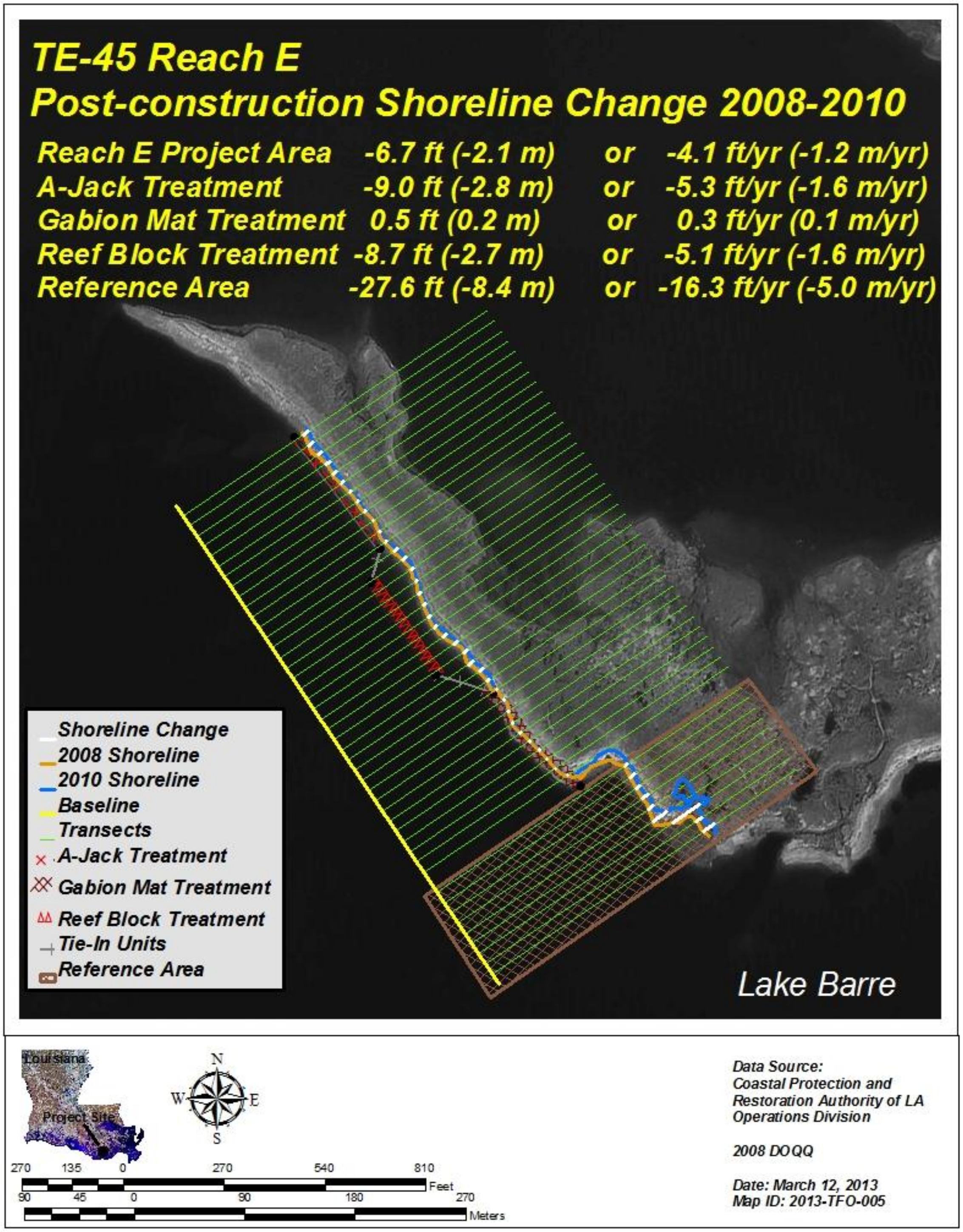


Figure F-9. **Post-construction (2008-2010) shoreline change for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

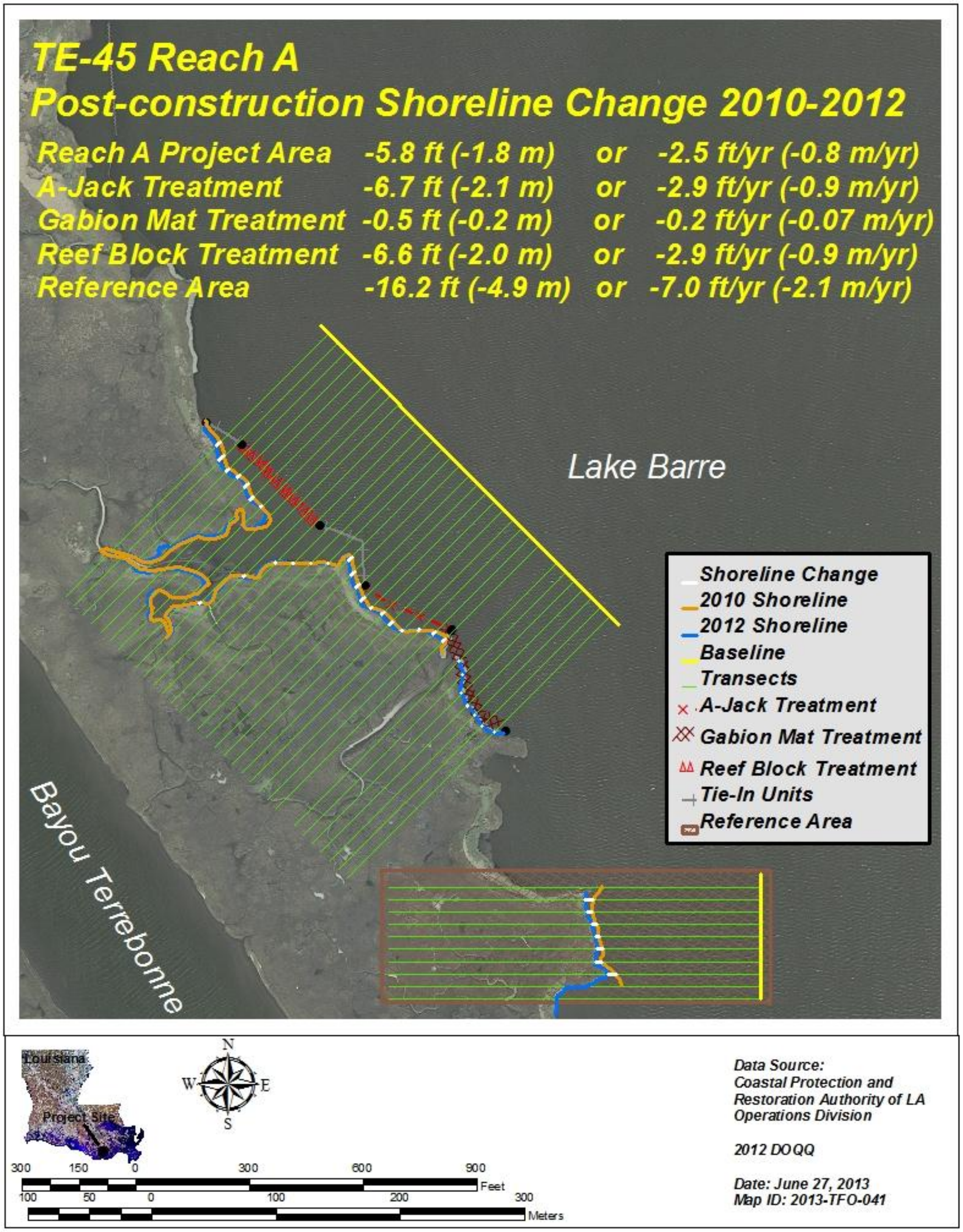


Figure F-10. Post-construction (2010-2012) shoreline change for Reach A at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

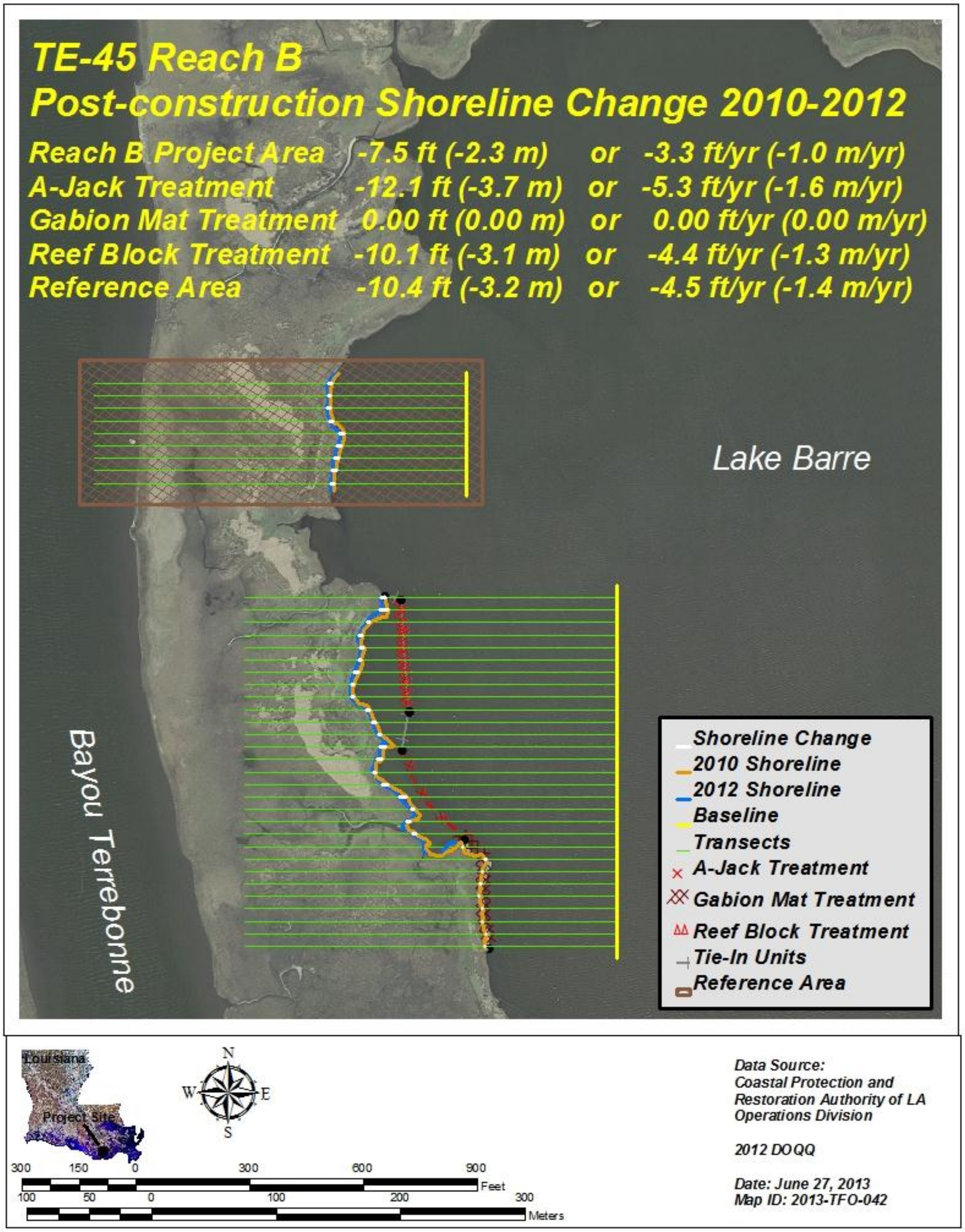


Figure F-11. Post-construction (2010-2012) shoreline change for Reach B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

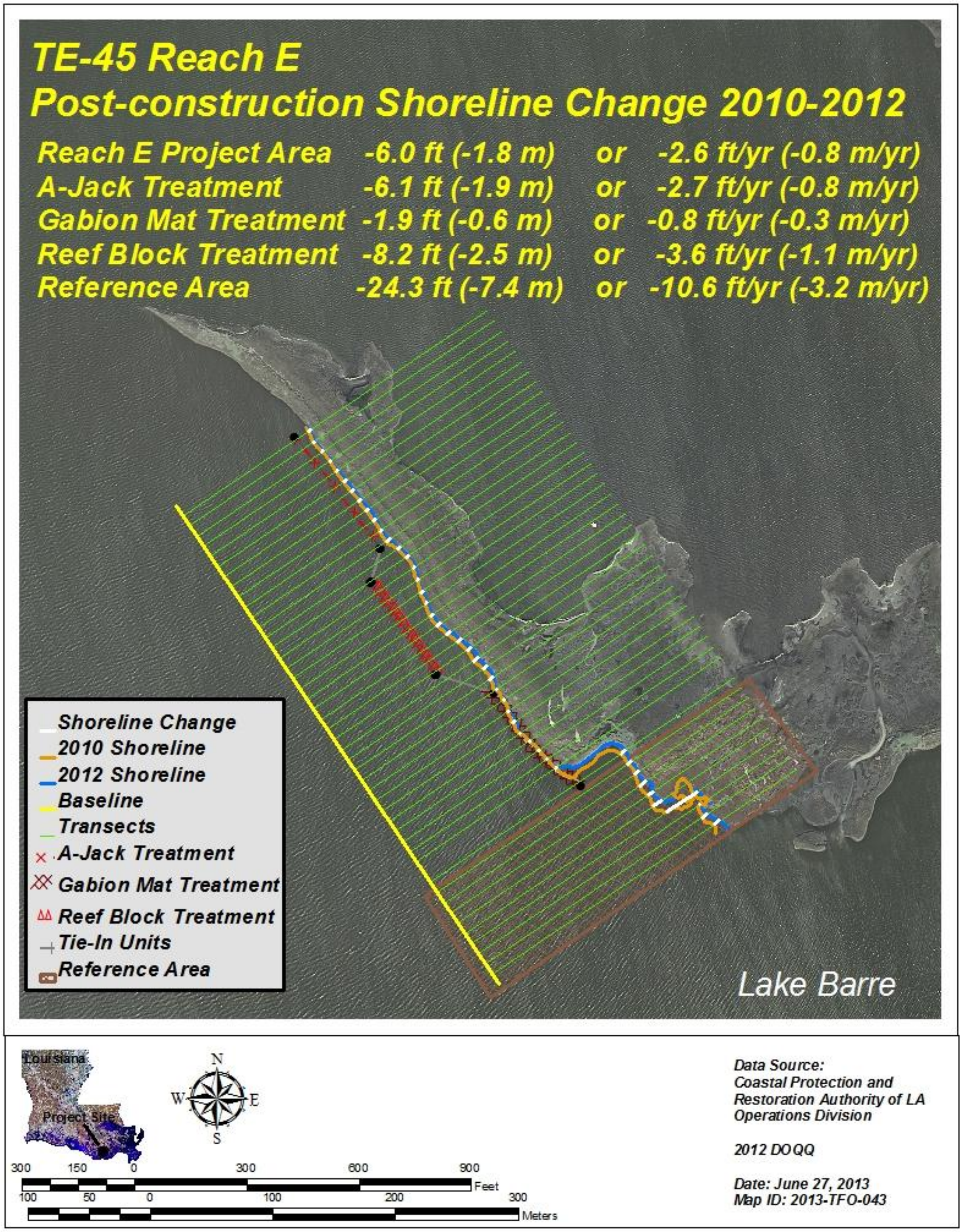


Figure F-12. Post-construction (2010-2012) shoreline change for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

Appendix G
(CRMS Land/Water Maps)

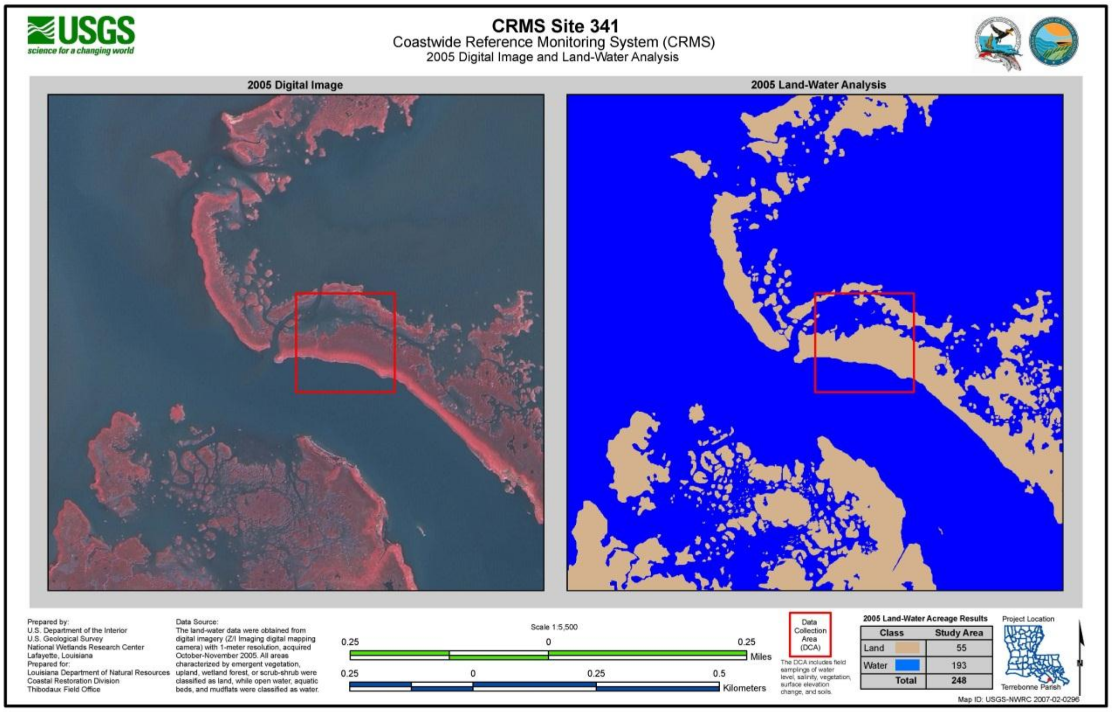


Figure G-1. 2005 land/water classification of the CRMS0341 1 km square.

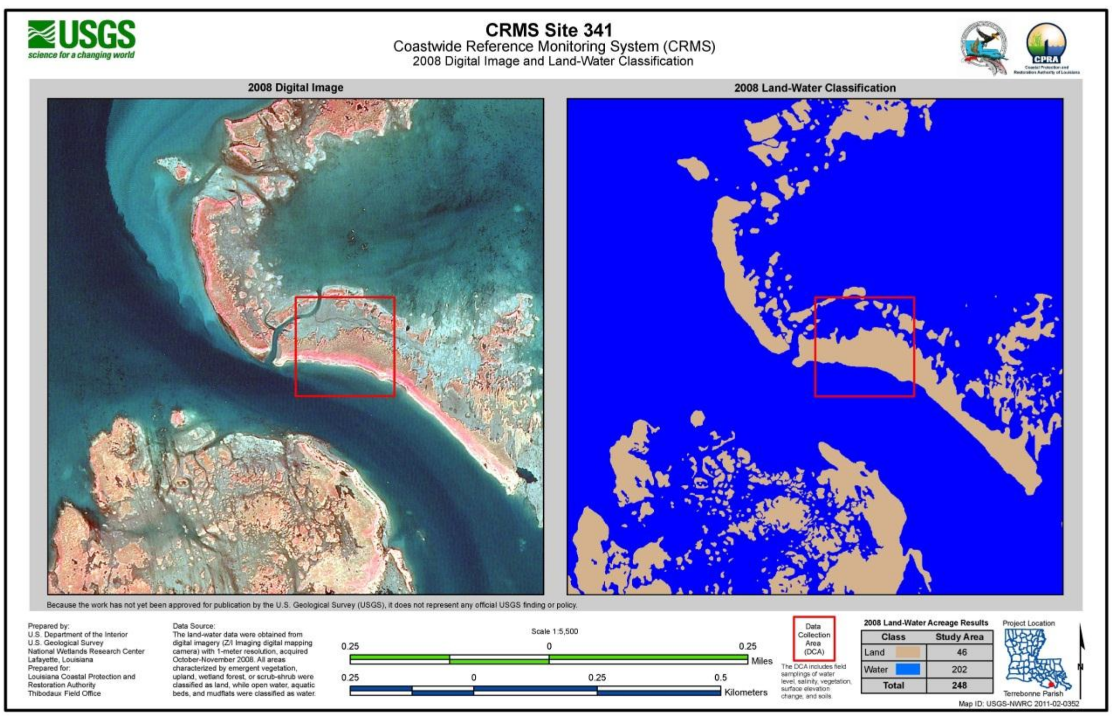


Figure G-2. 2008 land/water classification of the CRMS0341 1 km square.

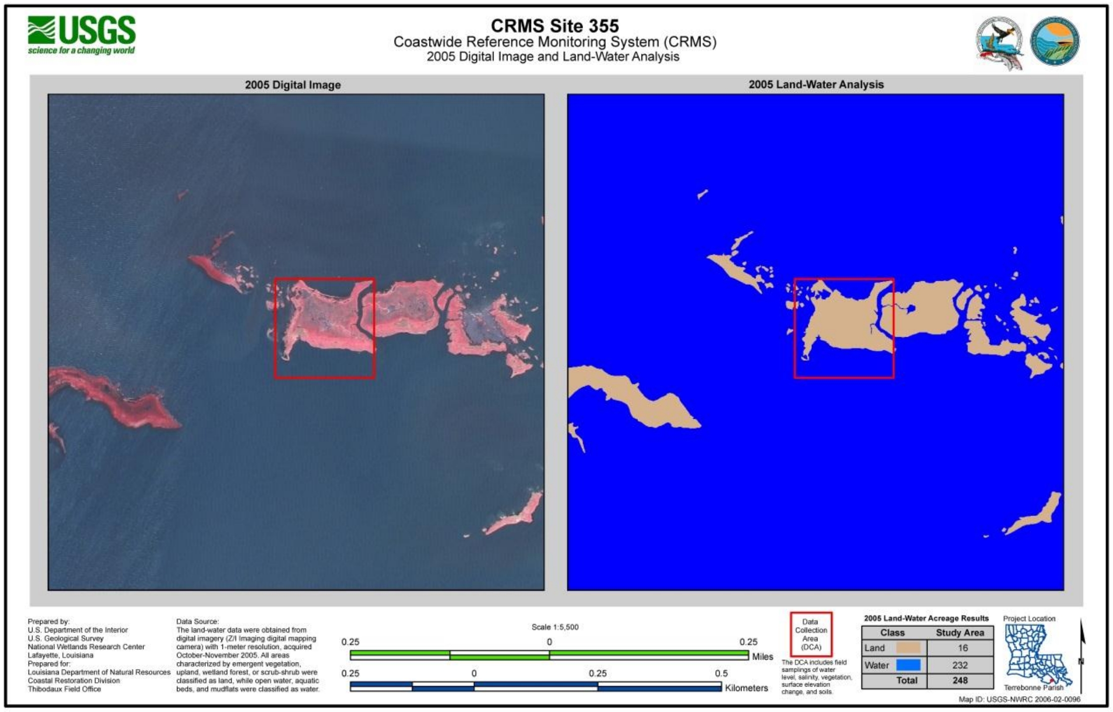


Figure G-3. 2005 land/water classification of the CRMS0355 1 km square.

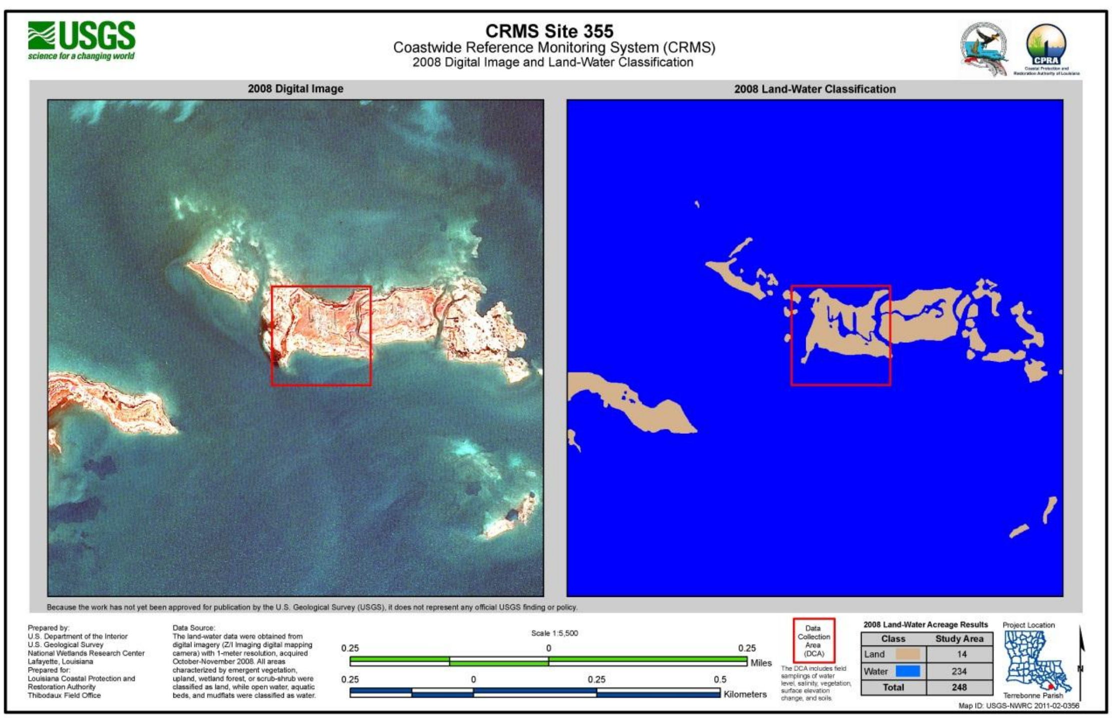


Figure G-4. 2008 land/water classification of the CRMS0355 1 km square.