State of Louisiana

Coastal Protection and Restoration Authority of Louisiana (CPRA)

2015 Operations, Maintenance, and Monitoring Report

for

Terrebonne Bay Shore Protection Demonstration (TE-45)

State Project Number TE-45
Priority Project List 10

November 2015
Terrebonne Parish

Prepared by:
Earl J. Melancon, Jr.
Glen P. Curole
Brian J. Babin
and
Quenton C. Fontenot

Operations Division
Thibodaux Field Office
1440 Tiger Drive, Suite B
Thibodaux, LA 70301

Suggested Citation:

Melancon, E. J. Jr., G. P. Curole, B. J. Babin, and Q. C. Fontenot. 2015. *2015 Operations, Maintenance, and Monitoring Report for Terrebonne Bay Shore Protection Demonstration (TE-45), Coastal Protection and Restoration Authority of Louisiana, Thibodaux, Louisiana. 97 pp. and Appendices.*

Operations, Maintenance, and Monitoring Report
for
Terrebonne Bay Shore Protection Demonstration
(TE-45)

Table of Contents

Preface

This report includes monitoring data collected from November 2007 through December 2014, and annual Maintenance Inspections through February 2015. The Terrebonne Bay Shore Protection Demonstration (TE-45) is 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 the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA, Public Law 101-646, Title III). TE-45 is listed on the 10th CWPPRA Priority Project List (PPL-10).

The 2015 report is the 3rd report in a series of three OM&M reports since the end of construction of this project in December 2007. This Operations, Maintenance, and Monitoring Report as well as earlier reports (Melancon et al. 2010; Melancon et al. 2013) in this series are posted on the Coastal Protection and Restoration Authority (CPRA) website at *http://cims.coastal.louisiana.gov/DocLibrary/DocumentSearch.aspx*.

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 Barre, which is part of the Terrebonne Basin system (Figure 1). 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 was 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) can also 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 (a.k.a. Triangular Units) structures (foreshore), A-Jack structures (onshore), and Gabion Mat (onshore) structures. The following synopsis was summarized from the TE-45 project completion report (TBS 2008). All three features and reference areas were installed at Reach A, Reach B, and

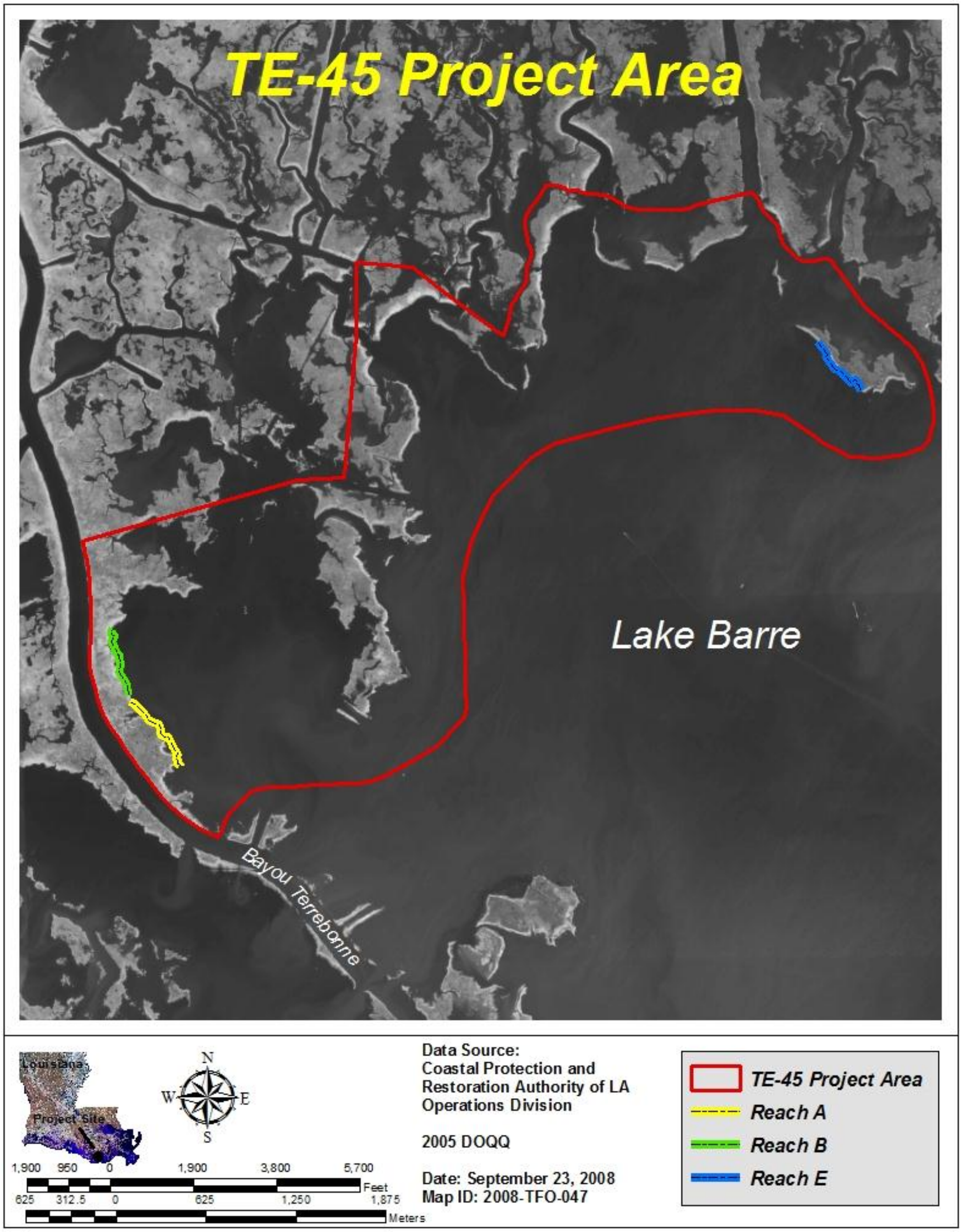


Figure 1. Location of the Terrebonne Bay Shore Protection Demonstration (TE-45) project area with the delineated shoreline Reaches investigated and selected for protection.

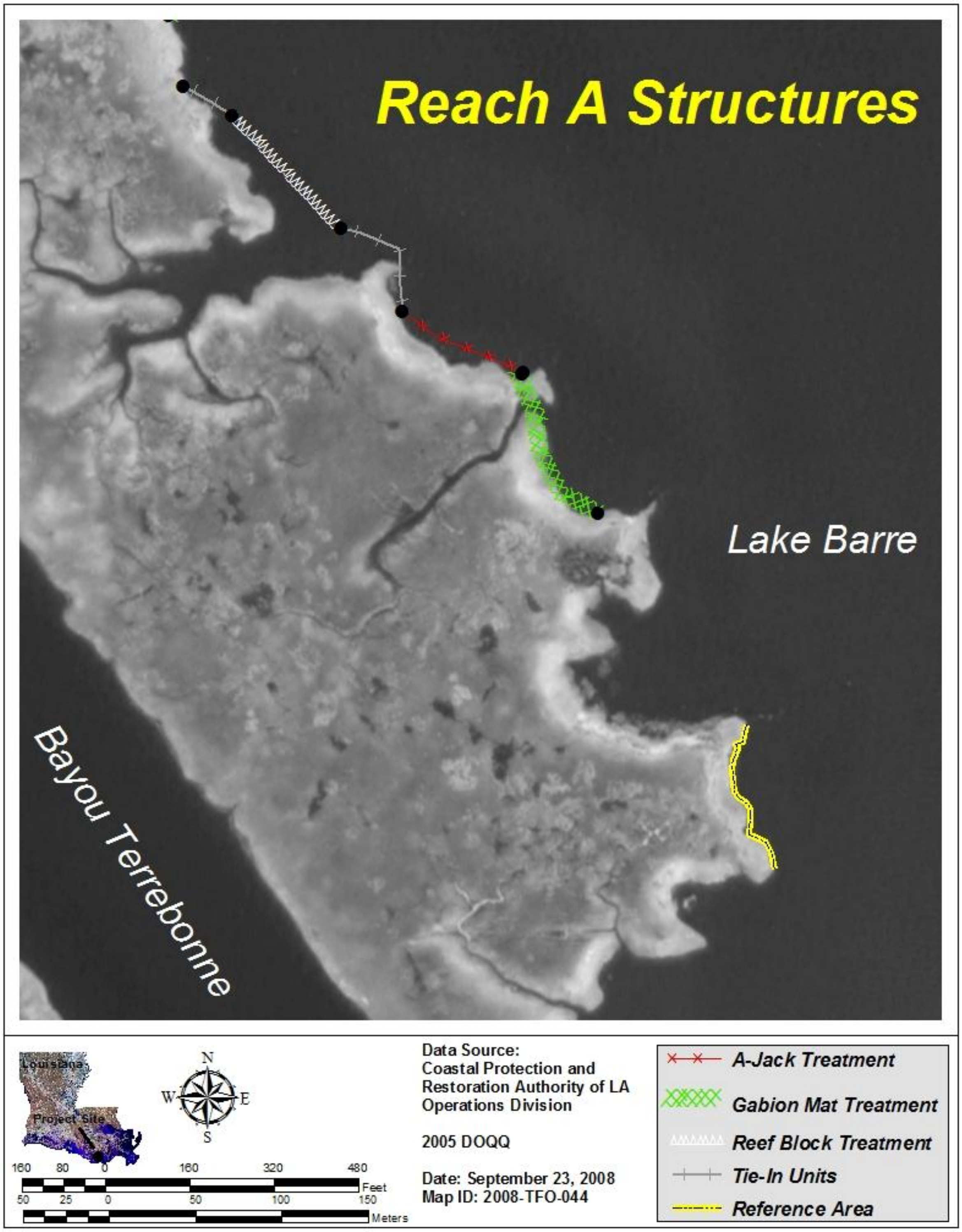


Figure 2. **Location of the Reach A project features (structure treatments) at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

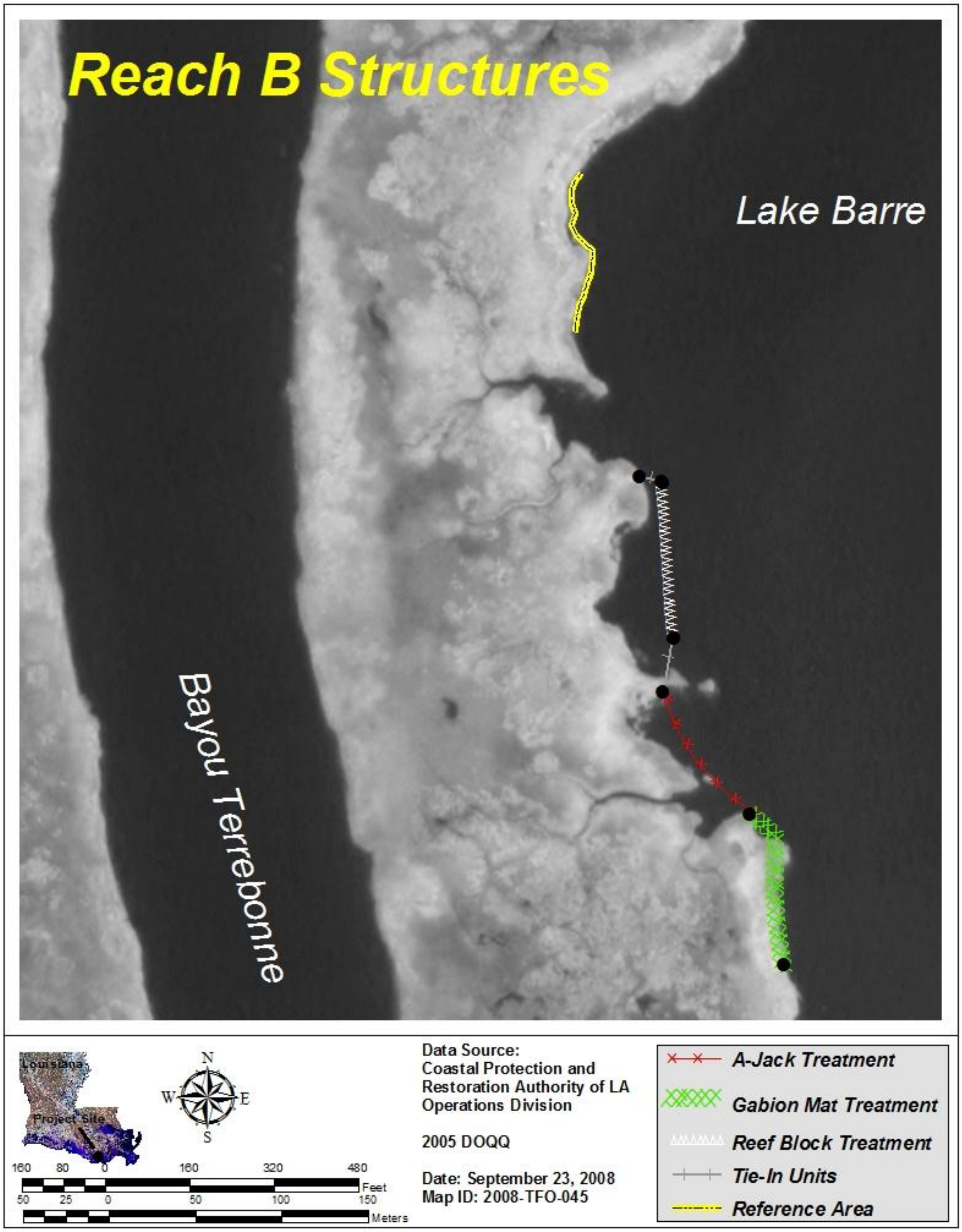


Figure 3. **Location of the Reach B project features (structure treatments) at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

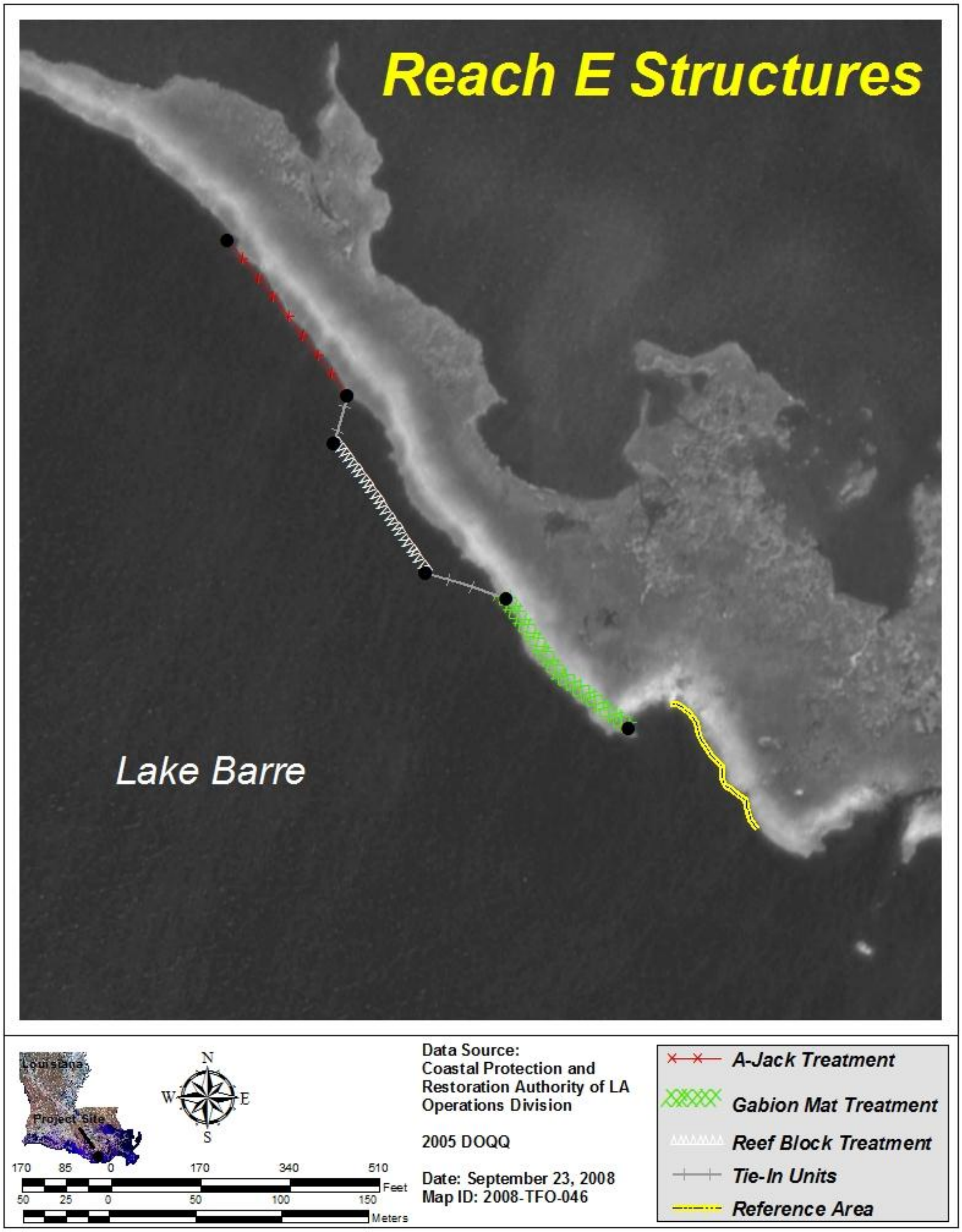


Figure 4. **Location of the Reach E project features (structure treatments) at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

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) and were constructed with the A-Jack structures. The ReefBlk structures, the A-Jack structures, and the 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. Coastal Louisiana is estimated to have lost an area about the size of Delaware between 1932 and 2010, with recent estimate averaging 42.9 km^2 per year (10, 601 acres per year) (Couvillion et al. 2011).

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 metamorphosing 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 0.4 mm (0.016 in.) in size, and are very vulnerable to predation and to burial due to sediment overburden (Dekshenieks et al. 1993).

A hard substrate that provides refuge from predators and provides vertical relief from sediments can increase the chance for oyster survival. Once the larva has set, it is designated as a "spat oyster" until it is 25 mm (1 inch) in shell height (colloquially referred to as 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 height within 15-18 months in Louisiana waters with adequate food and salinity. 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, but five (5) years is usually considered a long life.

The oyster occurs in salinities ranging from 5-40 psu (Shumway 1996). Optimal growth and survival of commercially viable oyster populations require a salinity range of 5-15 psu, when coupled with an appropriate temperature regime (Melancon et al. 1998). This narrow ecological salinity range reduces the abundance of higher-salinity oyster predators and disease while still allowing 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). Local precipitation can influence the salinity of Terrebone Estuary. The estuary has a higher salinity during drought periods and lower salinity during rainy periods. 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 sustaining 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 (Grabowski et al. 2012). 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 that 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.

Since the inception of this project in the fall of 2007, there have many living shoreline projects in Louisiana and throughout the northern Gulf of Mexico (Coen 2015). However, the TE-45 project is the oldest and longest monitored living shoreline project in Louisiana, and perhaps in the northern Gulf of Mexico (Casas et al. 2015; LaPeyre et al., in review.). The Louisiana projects range from experimental oyster reefs using loose shell cultch (LaPeyre et al. 2014; Casas et al. 2015) to bio-engineered reefs as in this project (Melancon et al. 2010; Melancon et al. 2013), all of the above within the Terrebonne estuary. Within the Barataria estuary, there is a barrier island project on the leeward side of Grand Isle, and a marsh shoreline projects in Breton Sound (LaPeyre et al. 2013). So much interest has developed that there was a need to develop recommendations for universal standards on how to monitor and assess success or failure of living shoreline projects (Baggert et al. 2014).

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.

Because 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 (CPRA 2010). The 2015 inspection was the seventh (7^{th}) of eight (8) 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 February 18, 2015. In attendance were Travis Byland, Brian Babin, and Glen Curole from CPRA and Robert Dubois from US Fish and Wildlife Service. The inspection began at approximately 10:00 am at Reach A and ended at approximately 12:00 pm at Reach E. The trip included a visual inspection of the nine (9) shoreline protection treatments (three (3) treatment types at each of the three (3) reaches), the tie-in units, and all warning signs for the project. Photographs of the structures are included in Appendix B.

b. Inspection Results

The project inspection began at the southern end of Reach A near the beginning of the Triton Gabion Mats and proceeded northward along the shoreline to the northern extent of Reach B. Due to extreme low water levels, the inspection team was unable to determine the water elevations from two (2) of the CRMS station gauges near Reaches B and E. The water levels during the site visit were low enough to view a large portion of the shoreline protection treatments units along much of the marsh bank. Upon arrival at Reach A, we encountered Dr. Earl Melancon and a couple of graduate students from Nicholls State University collecting samples for their oyster colonization study. This is the final year of data collection by NSU to evaluate the oyster production as it relates to each treatment. Below is a detailed assessment of the physical conditions of shoreline protection units along each reach:

<u>Reaches A&B</u>

The Gabion mats at Reaches A and B were in very good condition with no obvious movement, tears or degradation of the geotextile material or loss of rock fill. The mats were still situated firmly on the marsh along a majority of Reaches A and B. There was a small section of marsh edge behind the Gabion Mats near transect 10+00 that appeared to have eroded slightly. Overall, the Gabion Mats at Reaches A and B seemed to be performing as intended.

The concrete A-Jacks and bank closure treatments were also in good condition with no noticeable movement or tilting of the structure. We did notice moderate erosion of the marsh edge behind the A-Jack structure along Reach A. Due to the low water levels, we were able to see the upper half of the structure which appeared to be stable and in good condition.

The ReefBlks off-shore treatment was mostly exposed during the inspection and appeared to be in good condition. The structure itself was somewhat corroded due to the saline environment, but there was no visual signs of broken steel rebar or connections. The Triton mat material between the rebar was in good condition with no rips or loss of stone material. Oyster development on top of the structure was dense and plentiful.

Reaches E

Inspection of Reach E began at the northern extent of the reach and proceeded south to the southern extent of the Gabion Mats. Due to the extreme low water levels, the staff gauge at CRMS station near Reach E was corroded and not readable. The A-Jack units along the shoreline on the northern extent of Reach E were in good condition; however, the A-Jack tie-ins from the shoreline to the ReefBlks and from the ReefBlks to the Gabion Mats appear to have settled significantly. Even with the extreme low tides, the A-Jack tie-ins were not visible. The off-shore ReefBlks were also in good condition with minor settlement on the southern end of the treatment. The colonization of oysters along the top of the ReefBlks was dense and plentiful. The on-shore Gabion Mats were also in good condition with no obvious defects or damage. We did notice considerable erosion on the southern end of the marsh island where the Gabion Mats ended. Overall, Reach E is in good condition with minor deficiencies as noted above. Reach E is located at the southern point of an existing marsh island and is more exposed to wave action and other forces which could explain the condition of the features and marsh erosion we have reported.

The only damage noted along Reaches A, B and E was a couple of damaged warning signs on the lake side of the shoreline treatments. The timber piling supports were in good condition, but the signs were bent and distorted around the piling.

c. Maintenance Recommendations

Based on the 2015 Annual Inspection, there was no noticeable damage or deficiencies to the shoreline protection treatments related to the Terrebonne Bay Shoreline Demonstration (TE-45) project. It was noted that some of the aluminum warning signs at Reaches B and E were damaged from apparent extreme weather events. The signs were still visible but were bent and contorted around the timber pilings. Since there are no funds in the operations and maintenance budget to replace signage, we are not recommending replacement at this time. As for the condition of the existing marsh, we did note erosion near the southern point of the marsh island along Reach E behind the gabion mat treatment units. Overall the project appeared to have halted or slowed erosion along all of the reaches with small isolated areas of erosion.

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's O&M budget for maintenance events. Only the costs associated with annual inspections are provided in the project's O&M budget.

III. Operations Activity

a. Operation Plan

There are no operations for the TE-45 project.

b. Actual Operations

There are no operations for the TE-45 project.

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:

Elevation

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 and May 2015) 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, February 2011, and May 2015 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, February 2008-Feburary 2011, and February 2008-May 2015 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, February 2011, and May 2015) 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 and February 2008-May 2015 intervals 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, February 2011 and May 2015 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 and February 2008-May 2015 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).

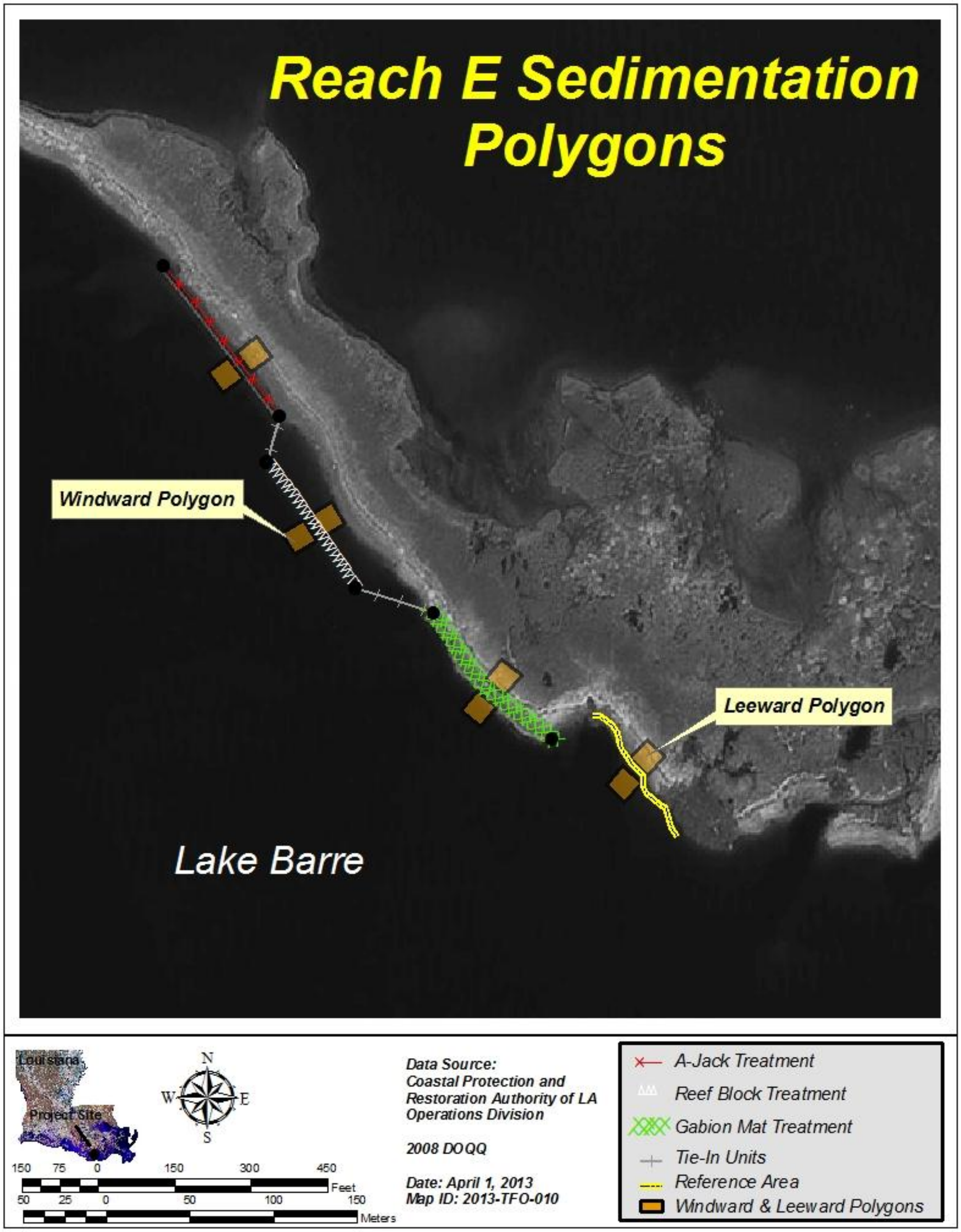


Figure 5. Layout of the windward and leeward sedimentation polygons at the Terrebonne Bay Shore Protection Demonstration (TE-45) project. Although only the Reach E polygons are shown, the layout is the same for Reaches A and B.

Wind Analysis

Hourly wind speed, wind gusts, and direction data was obtained from the National Oceanic and Atmospheric Administration (NOAA), Center for Operational Oceanographic Products and Services (CO-OPS) Grand Isle, LA (Station ID: 8761724) Wind Gauge to characterize extratropical wind energy (cold fronts) in the vicinity of the TE-45 project. Wind data was acquired for the period from October 1 thru April 30 for all consecutive years of the project life (2007-2015) because extratropical weather events generate the majority of their energy (greater frequency and intensity) during this period. A wind rose and frequency table was developed from this data using the Lakes' Environmental WRPLOT View™ software. The wind speed and gust data were further analyzed using the Tukey-Kramer HSD statistical test with JMP (v10) software.

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), October 28, 2012 (5 years post-con), and October 15, 2014 (7 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, October 2012, and October 2015 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), July 2010-October 2012 (post-con), October 2012-October 2014 (post-con), and September 2007-October 2014 (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. 2014). 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 taken while in the field using either a Hydrolab MS-5 or an YSI-30 meter for comparison to the continuous sonde data. Discrete data using the meter included water temperature, salinity, turbidity, pH, D.O., and percentage D.O. saturation. Meters were calibrated prior to use in the field.

Discrete water samples were also collected for chlorophyll-a (µg/L) and total particulate matter (µg/L). For chlorophyll-a and total particulate matter measurements, three 500 ml water samples were collected at each site in dark Nalgene bottles, immediately placed on ice and returned to the marine laboratory at Nicholls State University for processing. Under dim lights, triplicate 25 mL water samples for each site were filtered through a pre-weighed Whatman 25 mm glass-fiber filter. If processing could not be immediate, the filter was placed in a labeled foil packet and stored at −80º C (-112º F) until processing following EPA Method 445.0. For total particulate matter (TPM), a 200 ml water sample was filtered through a pre-weighed Whatman 47 mm glass-fiber filter and dried at 105º C (221º F) until constant weight achieved. TPM was calculated by subtracting the filter weight from the dried weight. The filter was then ashed by placing in a muffle furnace at 560º C (1,040º F) for 30 min and then weighed again to calculate Particulate Organic Matter (POM). POM was calculated by subtracting the ashed weight from the TPM weight (Boyd 1979).

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 9 times from July 2010 to May 2011. Clod cards were returned to the laboratory 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.

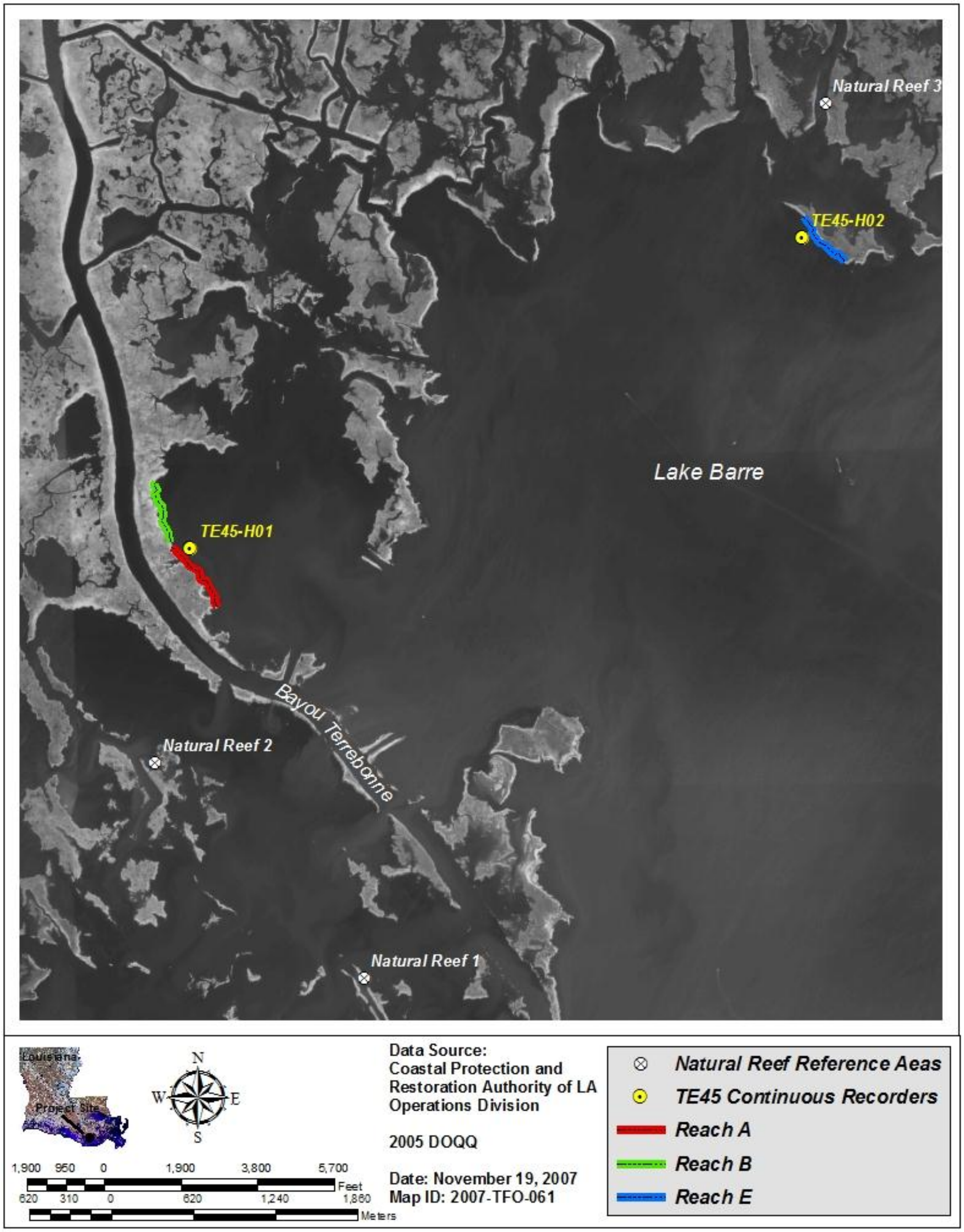


Figure 6. **Location of continuous recorder stations and natural intertidal oyster reefs used as reference areas to treatments at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

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 could 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 be passed later 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 1.9 cm 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 of 3.8 cm (1.5 inch x 1.5 inch). Cages were placed subtidal at about 1 m depth (3.3 ft.) adjacent to the windward side of the bio-engineered 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.

Recruitment to Bio-engineered Structures

Each bio-engineered structure's shape required placing the PVC quadrat frame (used for density estimates) in a unique way, and required measurements to be taken when exposed at extreme low tides, usually in winter after passage of cold fronts. Winter was also advantageous because all structures had been exposed to traditional oyster spring-through-fall spawning and recruitment cycles.

Through the four (4) winters of 2008, 2009, 2011, and 2014, when tides were lowest, and after the prior oyster recruitment peaks in spring and fall were complete, the structures were quantitatively examined. The surficial (surface) layer of attached eastern oysters and its major competitors for space, barnacles (*Balanus spp*.), and mussels were measured. The dominant mussel was the hooked mussel, *Ischadium recurvum.* Hooked mussels accounted for 98.6% of all attached mussels, with the ribbed mussel, *Geukensia demissa*, accounting for 1.3%, and the Conrad's false mussel, *Mytilopsis leucophaeata*, accounting for 0.1%.

Throughout the study, ***Consolidated reef*** was defined as those oysters fused into a clump or mass with some having relatively good shell height (>50 mm), and with relatively good three-dimensional structure and elevation above structure of ≥ 0.075 m (3 inches). Baggett et al. (2014) for natural oyster habitat used the term "reef" as having significant vertical relief, >0.2 m above the surrounding substrate (bay bottom), while beds have lower relief, <0.2 m. Since reef growth, and therefore elevation on the structures, are influenced by a very small microtidal range, a relief of 0.2 m above the structures was not attainable, although the constructed structures themselves were above 0.2 m in elevation without oysters. For all three structure types, our definition of reef 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 dimensional relief.

A live oyster and mussel was defined as having closed valves with an articulated (hinged) shell. A dead oyster and mussel was defined as having open valves, with or without meat, with an articulated shell. A mussel was also counted as dead if the animal was gone, but byssal threads were still present and attached to the substrate. Barnacles were enumerated but no differentiation was made between live and dead.

Each winter assessment required modified methods to achieve objectives without compromising the final assessment in winter 2014. The winter 2008 and winter 2009 surveys were visual inspections to enumerate and measure fauna, but the winter 2011 and winter 2014 surveys excavated (removed) material and fauna for assessments. Each of the four winter assessments employed a stratified random design for determining locations of replicates per structure type. If a replicate chosen had been previously excavated in a prior survey, then the structure next to it was chosen as its replacement. Each winter assessment was as follow:

(1) **<u>Winters 2008 and 2009 surveys</u>**: *The objective was to measure organism density information without physically disturbing oyster populations on the newly created bio-engineered structures.*

Surficial counts were restricted to only what could be seen while viewed from above the water line at low tide and without moving or destroying any oysters, rocks, or shells. Surficial quantitative density counts, oyster shell height, and faunal percent coverage (oysters + barnacles + hooked mussels) were used as indices to measure recruitment to each structure type. Surficial faunal coverage was collected from 15-structures per type per Reach each winter using a quadrat frame. Additionally, surficial density counts (#/m^2) during both winters was collected on five (5) of the 15 samples per structure type per Reach; this equaled 15 quadrats total for Gabion Mats, 15 quadrats for A-Jacks, and 15 quadrats for ReefBlks. Each structure's shape required placing the quadrat frame in a unique way. GPS coordinates were recorded for each location using a Trimble GeoXT GPS hand held unit.

Gabion Mat's surficial density was measured using a 0.25 m^2 quadrat frame that was subdivided into four equal subsections with each subsection quad measuring 0.0625 m^2, and placed at three intertidal heights along its 6 m (20 ft.) length; high-intertidal at 0.5 m above the mean high tidemark (from bottom of quadrat frame), mid-intertidal (from top of quadrat frame) as denoted by the high-water mark on the mat (usually 3.0-3.5 m from the top of the mat), and low-intertidal at 0.5 m above the mat's low end (bottom of quadrat frame). Once placed on the mat, one 0.0625 m^2 was randomly selected to quantify surficial densities of oysters, mussels and barnacles. Surficial oyster shell height data was also generated from each quadrat *in situ* (i.e., within its original place) using a flexible plastic ruler, except for the high intertidal sites that required counting oysters across the entire width of the mat 1.8 m (5 ft.) to obtain a sufficient sample. Percent oyster coverage and emergent reef coverage was obtained visually by flipping a quad-divided 1 m^2 frame from the top of the mat to the bottom and recording distance along the way, and thereby generating coverage for the entire length of the mat.

A-Jack's surficial density was obtained by laying a PVC quadrat frame that was 250 mm (0.8 ft.) wide and 350 mm (1.1 ft.) long and placed on top of the structure, resulting in a 0.0875 m^2 quadrat area. This generated an area equivalent to half the width of the A-Jacks and allowing data to be differentiated into leeward (facing the marsh shore) and windward (facing the bay) by flipping the frame over. All concrete arms within a quadrat were counted for surficial oyster, hooked mussel and barnacle densities. There were no significant statistical differences in leeward and windward oyster densities and therefore the two areas are combined as one in the results and discussions that follow. Surficial oyster shell height data were also generated from each quadrat in situ using a flexible plastic ruler. Only oysters that could be accurately measured to nearest millimeter were recorded for shell height.

ReefBlk's surficial density per unit was obtained by holding a 250 mm (0.8 ft.) wide quadrat PVC frame parallel to a side's top horizontal rebar and counting all within 0.33 meters downward, resulting in a quadrat 0.075 m^2 in area. Since a ReefBlk is a triangular-shaped structure with each side measuring 1.5 m (5 ft.) in width, the frame was randomly placed along its width. Surficial oysters, mussels and barnacles within the frame on the vertical structure were counted. At low tide, a minimum of 250 mm (0.8 ft.) of exposed vertical surface height was required for measurement. Per ReefBlk, four sides were measured; all three exterior sides and the interior side positioned parallel to the shoreline. The triangular ReefBlk units pointed leeward (towards marsh shore) and windward (towards the bay), but no significant statistical differences in oyster densities were detected. Therefore, a unit was not referenced by its orientation. Surficial oyster shell height data were also generated from each quadrat *in situ* using a flexible plastic ruler. The percent of shells in each ReefBlk was calculated by randomly assessing 15 blocks and all of its sides at each Reach.

(2) <u>Winter 2011 Survey</u>: *The objective was to quantify population information by excavating samples from the bio-engineered structures. Footprints of areas excavated (quadrats) needed to be minimal, while also preserving data integrity for analysis and interpretation.*

Quadrats were 0.0625 m^2 for Gabion Mats using a PVC frame to outline the area to be excavated. Excavation included all limestone rocks down through the structure to the bottom, which was buried in mud. Oyster and mussel data was segregated into surficial attached fauna (top layer of rocks) and those rocks below the top layer with attached fauna. Only oysters and mussels were enumerated and measured while overall barnacle concentrations were only noted as abundant or minimal. All rocks were placed in buckets, labeled, and returned to the marine biology laboratory at Nicholls State University for storage in a walk-in cooler at 3º C (37º F) until processed. Gabion Mat quadrats were taken from the middle length of the mat, 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. Melancon et al. (2010) indicated that there was no significant difference ($P < 0.05$) between mid-mat and bottom-mat oyster densities, and therefore one quadrat sample per mat was taken. Quadrats samples were taken in a stratified random design where the 60 mats from each reef were divided into three 20-mat regions and five (5) random mats assessed. Therefore, 15 samples per Reach were collected for a total combined 45 quadrats.

A-Jack quadrats were taken in a stratified random design from windward and leeward arms by using a metal scraper and cleaning an area equivalent to 0.0625 m^2, usually the equivalent of three flat sides per arm per site. At each Reach, the A-Jacks were divided into three sections and five (5) random sites taken per section, alternating between windward and leeward. At each site, two arms were from a top orientation of the structure and one was from a vertical orientation. The scraped fauna was placed in a plastic bag, labeled, returned to the marine biology laboratory at Nicholls State University for storage in a walk-in cooler at 3º C (37º F) until processed.

ReefBlk quadrats, as with A-Jack quadrats, took into consideration windward and leeward facing structures when selecting sites for obtaining density samples. Samples were collected in a stratified random design similar to the A-Jacks. However, unlike Gabion Mats and A-Jacks, for ReefBlks the quadrat consisted of 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 of its height and contents. Total area of the excavated bag (quadrat) was 0.168 m^2. The quadrat bags were refilled immediately after excavation with oyster shell that had been sun-dried for at least one year.

In addition to density quadrat samples from each structure type, also collected were quadrat samples that calculated the percent of structure covered with oysters and percent of that coverage which was actual consolidated reef. Oyster and mussel shell height data was also collected while collecting quadrat density data. Methods for cover and shell heights followed the same procedures as described in the winter 2009 survey methods. The percent of shells in each ReefBlk was calculated by assessing every side within every block at all three Reaches.

(3) <u>Winter 2014 Survey:</u> *The objective was to quantify population information by excavating samples from the bio-engineered structures. This was final survey during the project contract period, and therefore the final assessment of each structure for oyster population development. Therefore, the footprint of areas excavated (quadrats) for analysis and interpretation could be larger in area. It should also be noted that ReefBlk bags that were refilled with new sun-dried oyster shell during the winter 2011 survey were not included in the winter 2014 assessment for percent shell loss.*

Methods employed in the winter 2014 survey did not deviate much from the methods used during the winter 2011 survey, with the exception of the following:

- Quadrat area for each Gabion Mat site was twice as large (0.125 m^2) as the winter 2011 survey. Fifteen (15) sites per Reach were assessed for quadrat density.
- Quadrat area for each A-Jacks site included the scraped area of all of three arms on windward side, plus all of three arms from leeward side, plus three arm surfaces from the top. The top and leeward arms were designated at "leeward" in the assessment, and the windward arms as "windward." Total quadrat area per site equaled 0.57 m^2. Twelve (12) sites per Reach were assessed for quadrat density.
- All ReefBlks at all three Reaches had failed by winter 2014 survey. No analysis, other than percent shell loss per ReefBlk was assessed. All ReefBlks per Reach were measured for shell loss by taking a metric ruler measurement of shell depth per bag and obtaining an average per block (9 bags measured per block, 60 to 62 blocks per Reach).

(4) <u>Natural Intertidal Reef Reference Areas</u>

Three reference sites were established on nearby natural intertidal oyster reefs. These reefs are located north of Reach E and south of Reaches A and B (Figure 6). The reference sites were situated in shallow-water areas 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 for the winter 2009 survey, the 0.25 m^2 frame was randomly placed on the reference area wherever reef or oyster clusters existed, and not on bare mud habitat. There was no density data taken on the natural reef after winter 2009, but during the winter 2014 survey the same reefs were accessed for oyster shell height frequency data.

<u>Cost-effectiveness</u>

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 (TBS 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, oysters per linear meter of shoreline, structure settlement, and structure sedimentation. Once the costs and performance measures were evaluated, the cost-effectiveness of the structure treatments was ranked.

c. Monitoring Results and Discussion

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-May 2015) are illustrated in figures 10 (Reaches A and B) and 11 (Reach E). Elevation grid models for the pre-construction, as-built, and post-construction surveys are also provided in Appendix D (Figures D-1 to D-8). 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). The initial post-construction interval (February 2008-February 2011) also displayed continued loss of sediment volume at all reaches (Melancon et al. 2013). For the second post-construction interval (2008-2015), sediment volume declined by approximately 11,596 m^3 (15,166 yd^3) at Reaches A and B (Figure 10) and 8,200 m^3 (10,725 yd^3) at Reach E (Figure 11). The reference areas also experienced volume losses for the post-construction interval, Reach A [1,503 m^3 (1,966 yd^3)], Reach B [774 m^3 (1,012 yd^3)], and Reach E [2,111 m^3 (2,761 yd^3)] (Figures 10 and 11). Although the sediment volume reductions for the second post interval are cumulative (intervals overlap 2008-2011 and 2008-2015), the results all point towards a chronic degradation of the TE-45 shoreface because sediment volumes persistently diminished throughout the post-construction study period at both project and reference areas. The Reach A and B project area and reference areas A and E experienced a greater sediment volume loss for the 2008-2011 period (59%, 61%, and 64%) (Melancon et al. 2013) while the Reach E project area and the Reach B reference area recorded greater volume deficits for the second half of the 2008-2015 (after Feb 2011) period (both at 70%). Moreover, the Reach A and B and Reach E volume deficits increased considerably for the post-construction intervals. In addition, the Reach A, B, and E reference areas had substantial volume reductions for areas of less than one acre. Figures 10-11 and Melancon et al. (2013) provide evidence showing that the volume losses in these reference areas were primarily induced by erosion along their shorelines. Moreover, shoreline scouring can be seen in all the post-construction change models and is especially prominent in Figure 13. This figure exhibits considerable shoreline scouring in the reference area, windward of the Gabion Mats, and at the Tie-in units. Indeed, the Reach E Tie-in units have subsided to the point of always being subtidal (never visible) and are allowing erosion to bisect across and scour the shoreline and the lee of the Reefblks. All iterations of this elevational analysis suggest that the Reaches are releasing sediment volume through compactional (Roberts et al. 1994; Morton et al. 2003) and erosional mechanisms (Stone et al. 1997; Watzke 2004; Trosclair 2013).

The TE-45 structures and reference areas sustained sedimentation deficits for all post-construction intervals in both the windward and leeward positions. During the first post-construction interval (2008-2011), Melancon et al. (2013) observed that the volume losses in the leeward position (behind the structures) were significantly smaller than the losses in the windward position. Subsequent sedimentation intervals (2008-2015) show very little volume

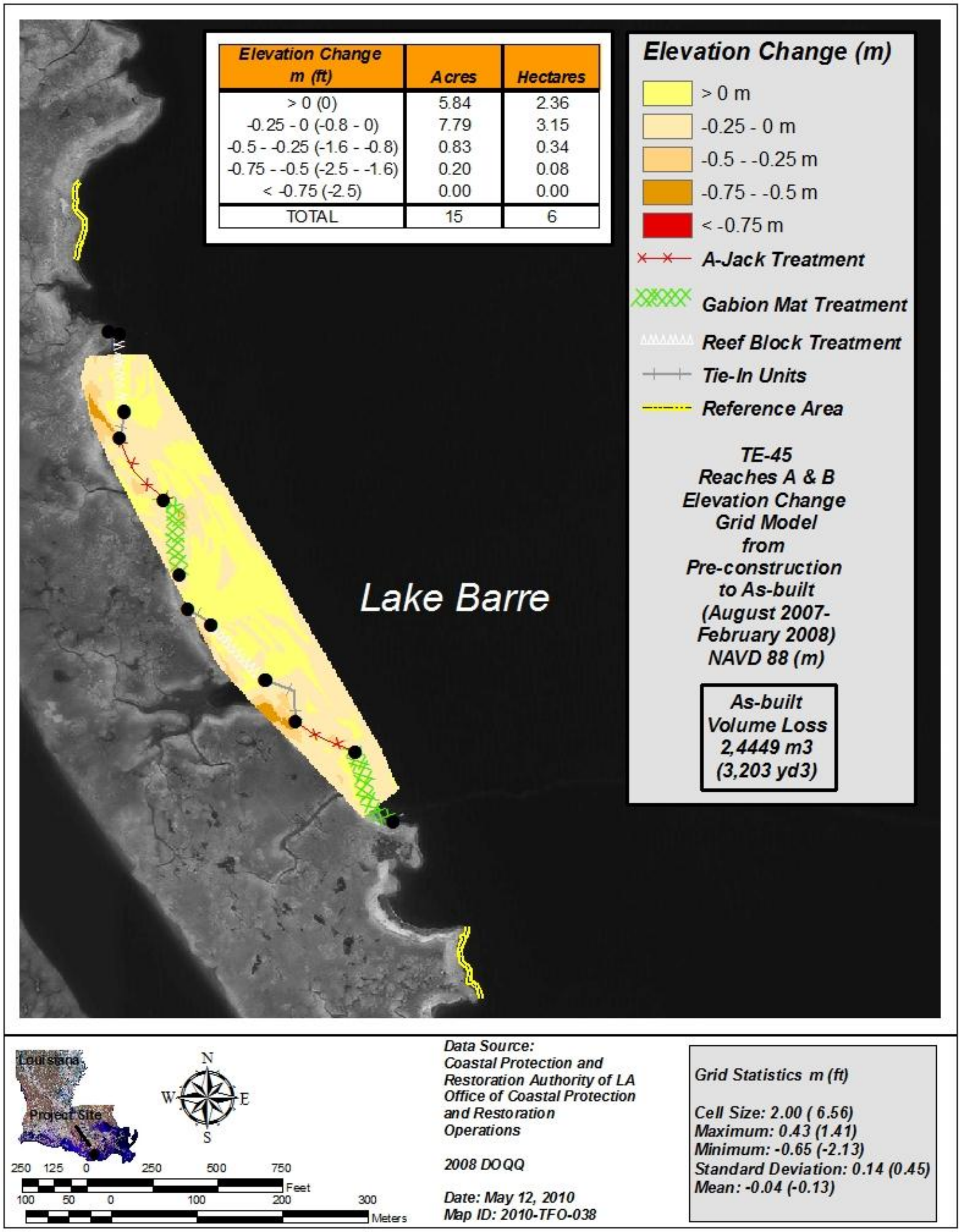


Figure 8. **Elevation and volume change grid model from pre-construction (Aug 2007) to as-built (Feb 2008) for Reaches A and B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

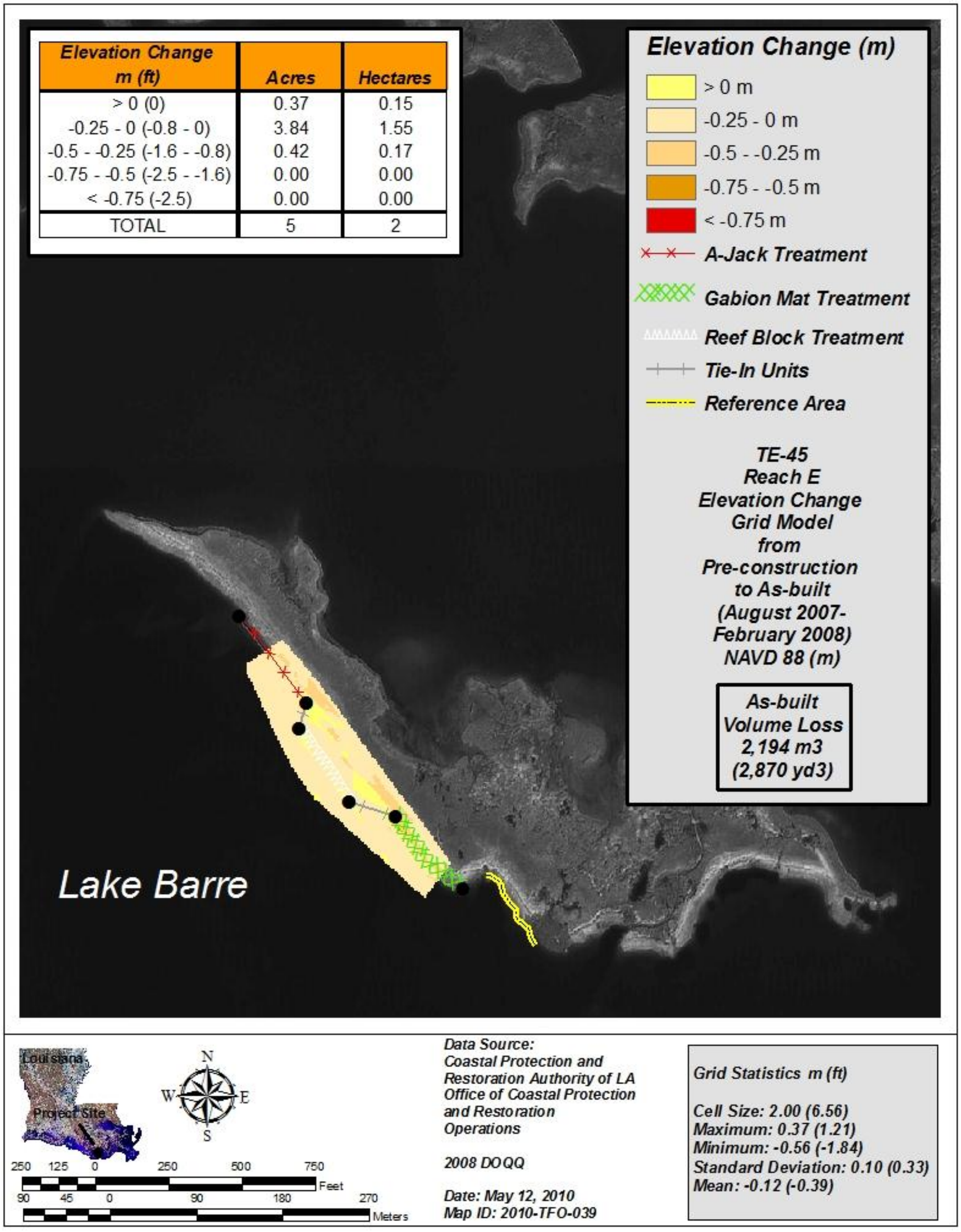


Figure 9. **Elevation and volume change grid model from pre-construction (Aug 2007) to as-built (Feb 2008) for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

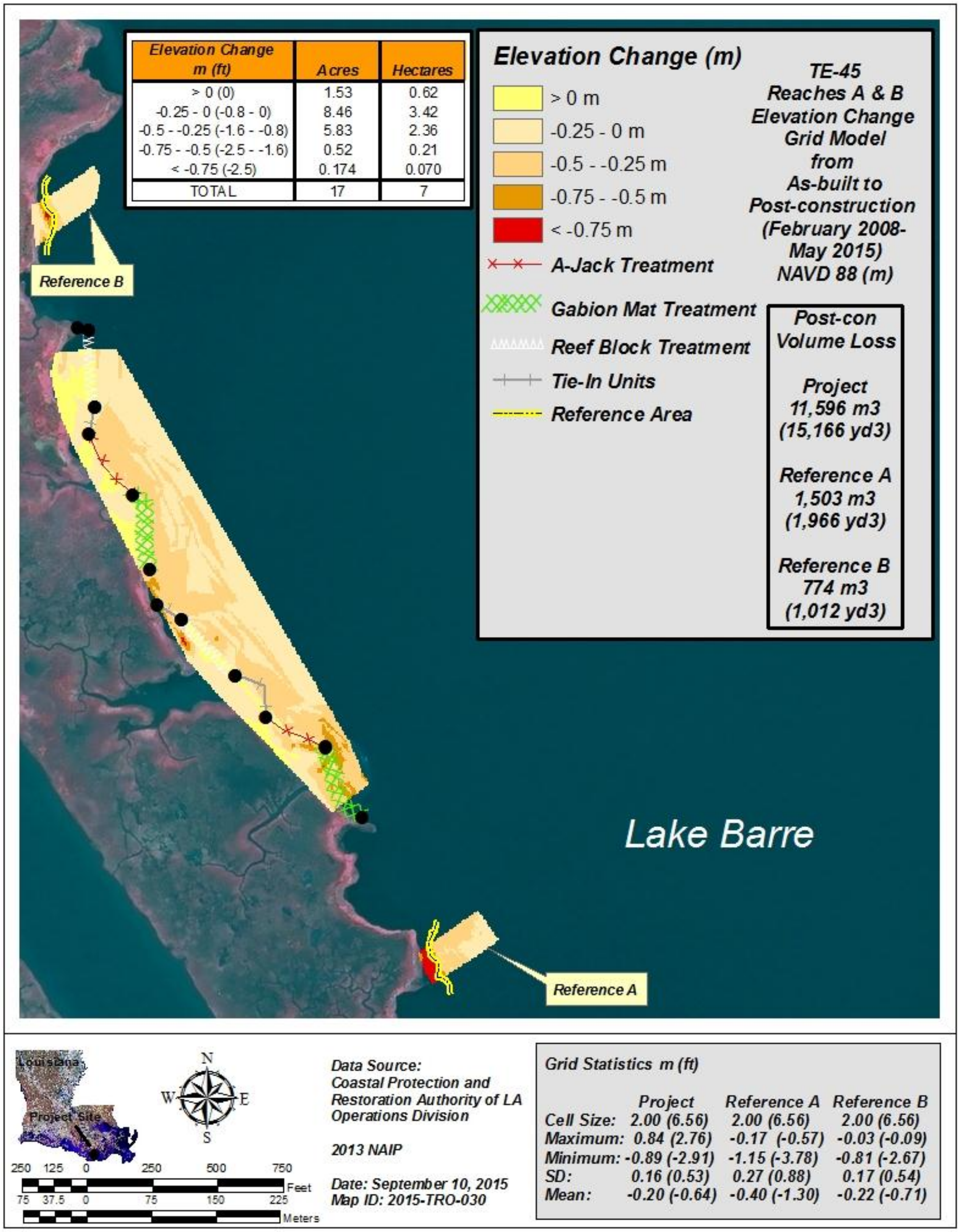


Figure 10. Elevation and volume change grid model from as-built (Feb 2008) to post-construction (May 2015) for Reaches A and B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

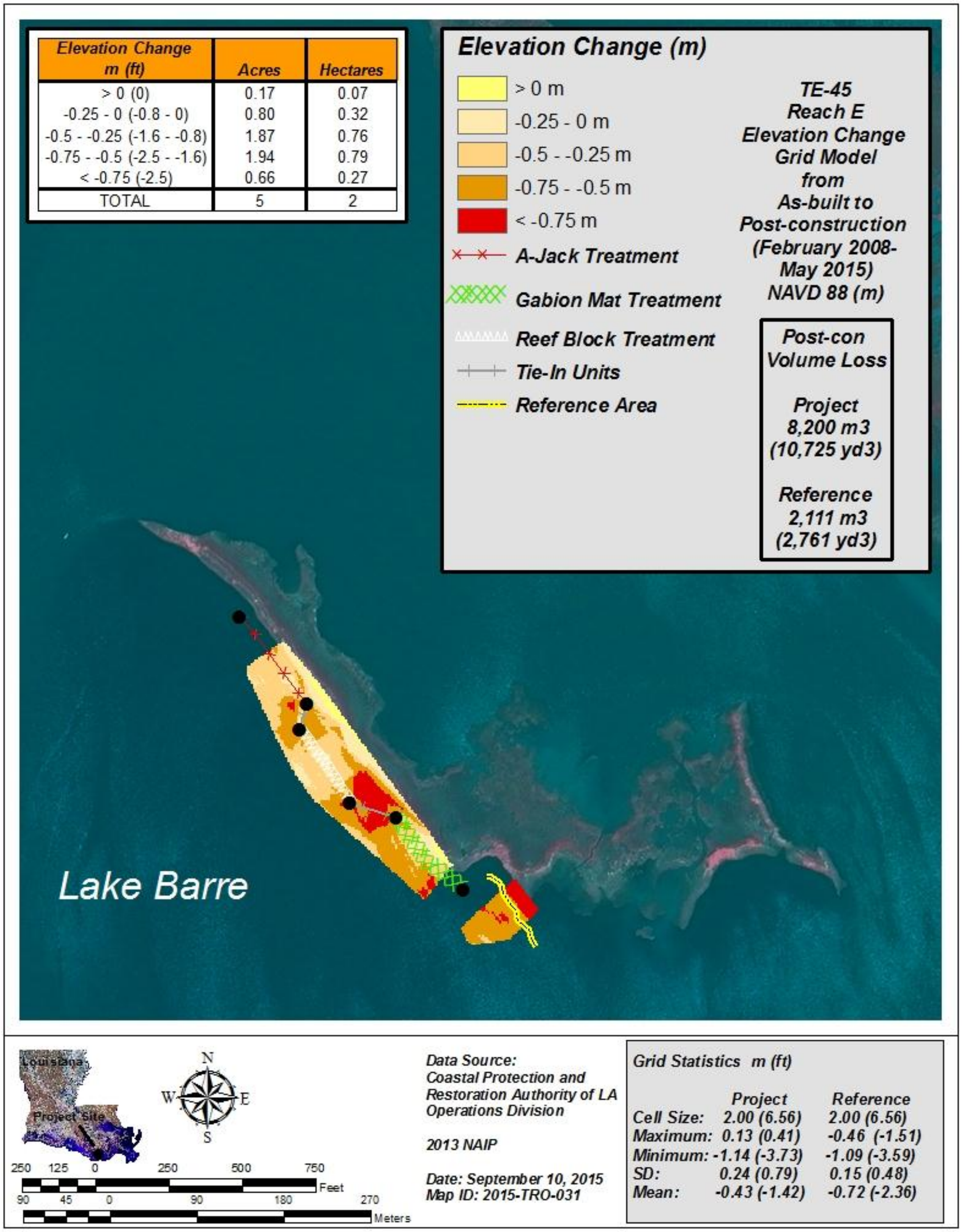


Figure 11. **Elevation and volume change grid model from as-built (Feb 2008) to post-construction (May 2015) for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

gains and volume reductions in the leeward position (Table 1). Only the Reefblk structures displayed negligible volume increases, and shoreline erosion in all reference areas induced about half of the leeward volume losses (Figures 10 and 11; and Table 1). Over the seven year duration of the assessment, the TE-45 treatments recorded sediment deficits of -84±10 m^3 (-110±13 yd^3) in the windward and -68±22 m^3 (-89±28 yd^3) in the leeward positions. These differences were not significantly different ($P > 0.05$). 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 A and E Gabion Mats and Reach E reference) and leeward (Reach A and E reference) positions. Interestingly, Lear et al. (2011) found that structures fronting shallow embayments facilitated higher rates of sedimentation than structures fronting linear segments of shoreline. Because 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 and leeward 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 (Roberts et al. 1994; Morton et al. 2003), and tropical and winter storm forcing (Stone et al. 1997; Watzke 2004; Morton and Barras 2010; Trosclair 2013). In closing, the TE-45 structures have not been effective in capturing and retaining sediments to date.

Table 1. Post-construction (2008-2015) volume change in the windward and leeward positions at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

Reach	*Treatment*	*Windward Position Volume Change 2008-2015 m3 (yd3)*	*Leeward Position Volume Change 2008-2015 m3 (yd3)*
A	*A-Jack*	-73 (-95)	-71 (-93)
B	*A-Jack*	-75 (-98)	-26 (-34)
E	*A-Jack*	-74 (-97)	-69 (-90)
A	*Gabion Mat*	-118 (-154)	-79 (-103)
B	*Gabion Mat*	-73 (-99)	-8 (-10)
E	*Gabion Mat*	-129 (-169)	-14 (-18)
A	*ReefBlks*	-92 (-120)	14 (18)
B	*ReefBlks*	-27 (-35)	6 (8)
E	*ReefBlks*	-73 (-95)	-57 (-75)
A	*Reference*	-64 (-84)	-213 (-279)
B	*Reference*	-51 (-67)	-92 (-120)
E	*Reference*	-158 (-207)	-205 (-268)
Mean	-	-84±10 (-110±13)	-68±22 (-89±28)

The results of the structure settlement analysis reveal that the Reach E structures were established and remain at a lower vertical position and the Gabion Mat treatment experienced the highest level of secondary settlement over the seven year assessment period. The TE-45 structures were initially constructed to a mean elevation of 0.29±0.02 m (0.94±0.06 ft) NAVD 88. 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 (Table 2). From 2008 to 2011, the A-Jack, Gabion Mat, and ReefBlk vertical positions were diminished as the structures settled. While there were no sizeable differences in settlement by treatment, the Reach E structures settled at a rate greater than the mean (Table 3 and Melancon et al. 2013). The results for the entire study period (2008-2015) differ slightly from the earlier post-construction period. For the 2008-2015 period, the Gabion Mat [-0.21±0.02 m (-0.68±0.07 ft)] treatment incurred the greatest settlement followed by the A-Jack [-0.14±0.03 m (-0.46±0.09 ft)] and ReefBlk [-0.11±0.03 m (-0.35±0.10 ft)] structures (Table 3). Indeed, the Reefblks sustained less settlement over time than the other structures despite being installed off the shoreline. These results are not that surprising because the Gabion Mats were the heaviest structure installed followed by the A-Jacks and these structures produced a greater overburden on the underlying soils than the Reefblks. Lear et al. (2011) also found the weighting of structures to influence settlement in poor load bearing soils. All three reaches settled at comparable rates for the length of the assessment (2008-2015) with Reach A showing the greatest variation and Reach E producing a more consistent response. Although notable, these differences in settlement are not statistically significant ($P > 0.05$) and this outcome was predicted in the pre-construction geotechnical assessment (Eustis 2002). The 2015 structure elevations illustrate that the ReefBlks [0.20±0.07 m (0.65±0.23 ft)] sustained the highest elevations over the study period followed by the A-Jack 0.12±0.04 m (0.40±0.13 ft)] and Gabion Mat [0.09±0.03 m (0.29±0.10 ft)] treatments (Table 3). The large variability in the Reefblk elevations is

Table 2. **Structure elevations (as-built and post-construction) 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 Elevation 2015 m (ft) NAVD 88*
A	*A-Jack*	0.28 (0.92)	0.23 (0.75)	0.11 (0.35)
B	*A-Jack*	0.28 (0.92)	0.24 (0.79)	0.20 (0.64)
E	*A-Jack*	0.22 (0.72)	0.13 (0.43)	0.06 (0.20)
A	*Gabion Mat*	0.29 (0.95)	0.23 (0.75)	0.04 (0.14)
B	*Gabion Mat*	0.35 (1.15)	0.29 (0.95)	0.15 (0.49)
E	*Gabion Mat*	0.25 (0.82)	0.19 (0.62)	0.08 (0.25)
A	*ReefBlks*	0.30 (0.98)	0.28 (0.92)	0.25 (0.81)
B	*ReefBlks*	0.40 (1.31)	0.32 (1.05)	0.29 (0.95)
E	*ReefBlks*	0.22 (0.72)	0.07 (0.23)	0.06 (0.19)
Mean	-	0.29±0.02 (0.94±0.06)	0.22±0.03 (0.72±0.09)	0.14±0.03 (0.45±0.10)

primarily due to the settlement of the Reach E structures and the low relief at installation. In fact, the Reach A and B Reefblks had higher vertical positions in 2015 than the Reach E Reefblks had immediately after construction in 2008 (as-built elevations) (Table 2). The Reach B structures maintained the highest vertical positioning for the duration of the study. However, it must be noted that the Reach B structures were installed to the highest elevations and the Reach E structures were installed to the lowest (Table 2). The lower vertical relief of the TE-45 structures seven years after construction is probably influencing the ecology (Lenihan and Peterson 1998) and shoreline protection capacity of the created reefs (Hardaway et al. 2010; USACE 2004). Currently, only the Reach A Reefblks and the Reach B structures (ReefBlk, A-Jack, and Gabion Mat) have vertical profiles larger than the 2015 mean (Table 2).

Table 3. Structure settlement (as-built and post-construction) at the Terrebonne Bay Shore Protection Demonstration (TE-45) project over time.

Reach	*Treatment*	*Structure Settlement 2008-2011 m (ft)*	*Structure Settlement 2008-2015 m (ft)*
A	*A-Jack*	-0.05 (-0.15)	-0.17 (-0.57)
B	*A-Jack*	-0.04 (-0.14)	-0.09 (-0.28)
E	*A-Jack*	-0.09 (-0.29)	-0.16 (-0.52)
A	*Gabion Mat*	-0.07 (-0.24)	-0.25 (-0.81)
B	*Gabion Mat*	-0.06 (-0.20)	-0.20 (-0.66)
E	*Gabion Mat*	-0.07 (-0.22)	-0.17 (-0.57)
A	*ReefBlks*	-0.01 (-0.04)	-0.05 (-0.17)
B	*ReefBlks*	-0.09 (-0.3)	-0.11 (-0.36)
E	*ReefBlks*	-0.14 (-0.47)	-0.16 (-0.53)
Mean	-	-0.07±0.01 (-0.23±0.04)	-0.15±0.02 (-0.50±0.07)

Wind Analysis

An analysis of October-April wind direction at the NOAA CO-OPS Grand Isle (8761724) weather station indicated that for the seven year period of the study the wind energy predominantly originated out of the northeast (35%) or southeast (34%) directional quadrants while the winds originated out of the northwest (18%) or southwest (13%) directional quadrants less frequently (Figure 12). Hourly wind speed ranged from 0-17 m/s (0-32 kn) but averaged 4.3 m/s (8.4 kn). Wind gust ranged from 0-21 m/s (0-41 kn) but averaged 6.1 m/s (11.9 kn). The strongest winds primarily developed from the northwestern quadrant (Figure 12). Feng (2009) also found the strongest winds in coastal Louisiana to be derived

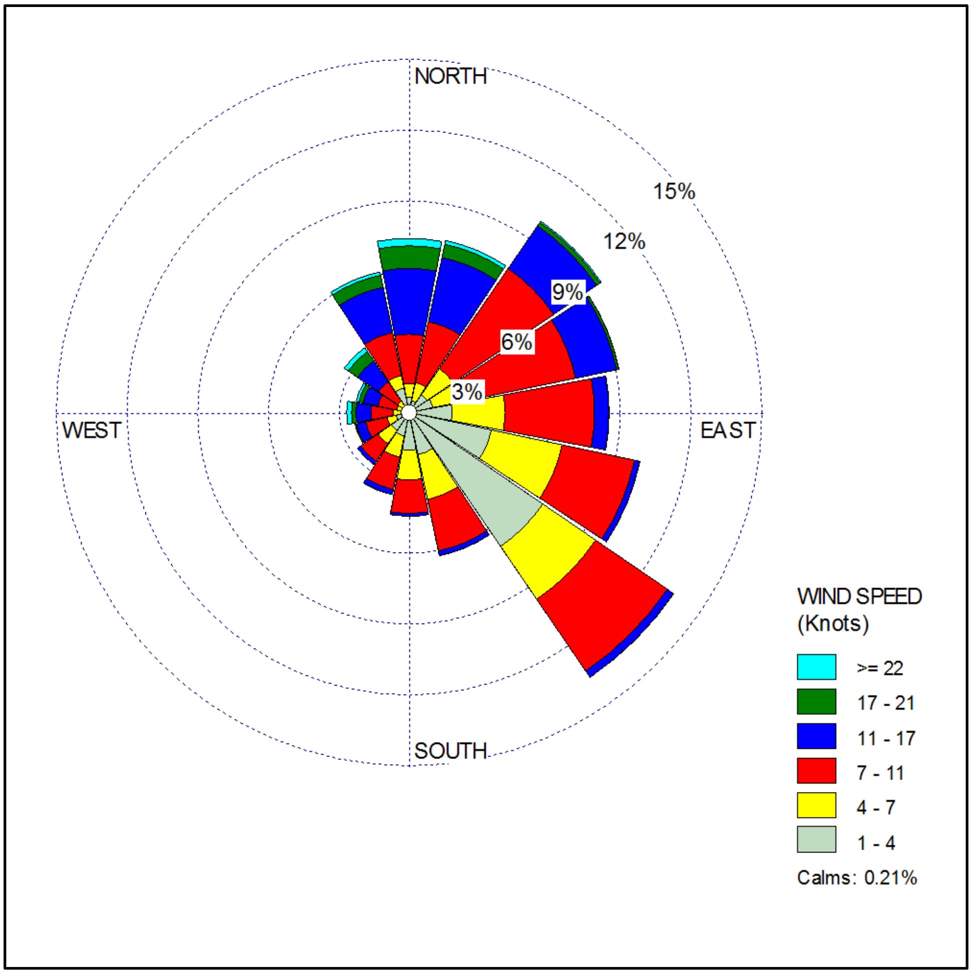


Figure 12. **Wind rose showing the distribution of winds from the NOAA CO-OPS Grand Isle (8761724) weather station in October-April for the period of the study (2007-2015). Note the prevailing winds are frequently from the northeast or southeast quadrants while the highest velocity winds regularly flow from the Northwest.**

from the northwestern quadrant and associated these high energy events with extratropical (cold front) storms. Additionally, Feng (2009) defined strong winds as greater than 10 m/s (19 kn). Table 4 list the mean wind direction, wind speed, and wind gust data for all the seven month periods that were studied (2007-2008, 2008-2009, 2009-2010, 2010-2011, 2011-2012, 2012-2013, 2013-2014, and 2014-2015). This table also details the percentage of time that winds equaled or exceeded 6 m/s (11kn) for each October-April recurrent period. A density graph (Figure 13) is also provided to show trends in the wind data for each interval. The results demonstrate that the 2009-2010 period had the highest mean wind speed, mean wind gust, and wind speed percentage and was generally followed by the 2013-2014 interval (Table 4). Although the 2008-2009 period had a higher mean wind speed than the 2013-2014 inteval, the mean wind gust and the percentage of high winds were greater in 2013-2014 (Table 4).

Table 4. **Mean wind direction, speed, gust, and percent strong wind frequency [≥ 6 m/s (11 kn)] for all recurring periods during the TE-45 project life.**

Period	*Wind Direction degrees*	*Wind Speed m/s (kn)*	*Wind Gusts m/s (kn)*	*% Winds ≥ 6 m/s (11 kn)*
2007-2008	147 (SE)	4.09 (7.96)	5.78 (11.23)	19.9
2008-2009	142 (SE)	4.39 (8.53)	6.16 (11.97)	20.1
2009-2010	155 (SE)	4.78 (9.29)	6.63 (12.90)	28.0
2010-2011	146 (SE)	4.19 (8.15)	6.03 (11.71)	18.5
2011-2012	134 (SE)	4.30 (8.36)	6.14 (11.93)	21.3
2012-2013	143 (SE)	4.24 (8.24)	6.03 (11.72)	20.7
2013-2014	134 (SE)	4.35 (8.46)	6.20 (12.04)	23.1
2014-2015	137 (SE)	4.14 (8.05)	5.83 (11.33)	20.5
Total	142 (SE)	4.31 (8.38)	6.10 (11.86)	20.6

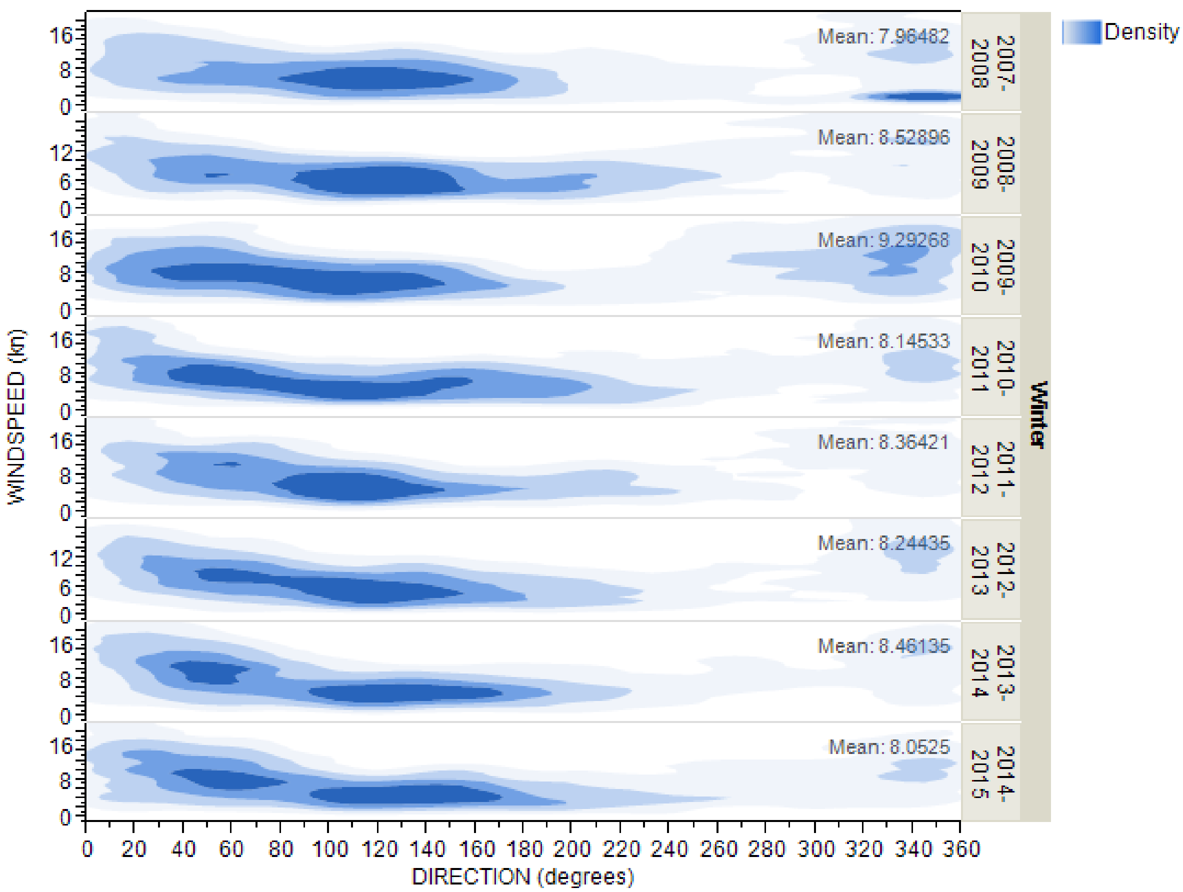


Figure 13. **Graph illustrating the intensity of the hourly winds at the NOAA CO-OPS Grand Isle (8761724) weather station for all directions and all sampling periods. Note the mean wind speed in knots (kn) is displayed on the top right corner of each interval.**

The Tukey-Kramer HSD statistical assessments show that the 2009-2010 period had significantly higher ($P < 0.05$) wind speed and gust than the other intervals analyzed while the 2008-2009 and 2013-2014 cycles were only significantly different ($P < 0.05$) from periods with low wind speed and gust energy. Therefore, it seems likely that the cold fronts generated for the 2009-2010 period caused higher wind energy and heightened prolonged forcing than the other intervals. The 2013-2014 and 2008-2009 periods also likely produced greater cold front forcing than the other cycles sampled but on a smaller scale and intensity level than the 2009-2010 interval.

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 14). Post-construction results for the intervals from September 2007 to October 2008 (1 year post-con), October 2008 to July 2010 (3 years post-con), and July 2010 to October 2012 (5 years post-con) exhibited declines from pre-construction erosion rates (Melancon et al. 2010, 2013). For the final interval, October 2012 to October 2014 (7 years post-con) the erosion rates were -1.3 m/yr (-4.3 ft/yr) in the project area

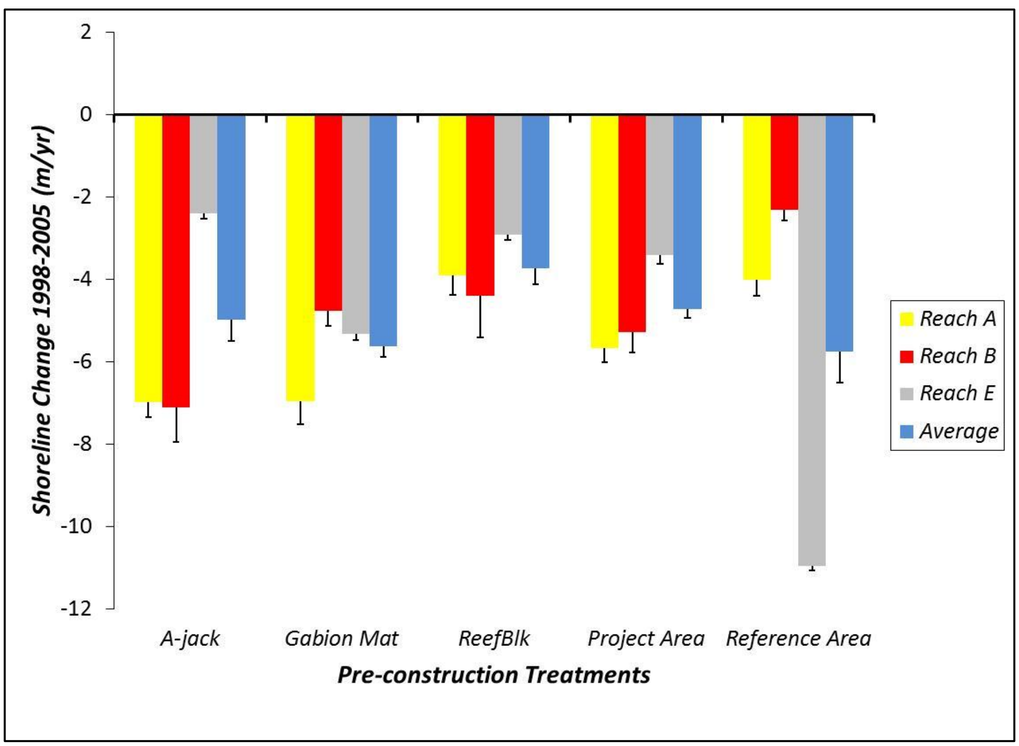


Figure 14. Pre-construction (1998-2005) shoreline erosion rates for each treatment and each Reach at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

and -4.2 m/yr (-13.8 ft/yr) in the reference area (Figure 15). The total erosion behind the structures and along the reference shorelines for the entire seven year period (2007-2014) of the study was -1.0 m/yr (-3.2 ft/yr) in the project area and -3.1 m/yr (-10.1 ft/yr) in the reference area (Figure 16). 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 17).

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 E (Figures E-1 to E-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 14). 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 14). 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 14). Moreover, the Reach E reference area transgressed at a considerably faster rate than the other TE-45 shorelines in the pre-construction period. Although the pre-construction shoreline erosion rates were inconsistent, these differences were not significant ($P > 0.05$) (Figures 14 and 18). 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 17).

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 all post-construction intervals were significantly less than the -4.7 m/yr (-15.4 ft/yr) rate recorded during the pre-construction interval (Melancon et al. 2010, 2013). However, for the 2008-2010 and 2012-2014 intervals erosion rates expanded to -1.5 m/yr (-5.0 ft/yr) (Melancon et al. 2013) and -1.3 m/yr (-4.3 ft/yr) (Figure 15). This increase in erosion rates is probably derived from an increase in cold front forcing (greater wind and gust energy) during these intervals (Table 4 and Figure 13). While these rates are three times the initial post-construction rate -0.5 m/yr (-1.6 ft/yr) (Melancon et al. 2010), they are considerably lower than the pre- construction rate. Shoreline change data for most time periods [1998-2005 (pre), 2007-2008 (post 1), 2008-2010 (post 2), 2010-2012 (post 3), and 2012-2014 (post 4)] were significantly different ($P < 0.05$). Shoreline change graphics for the post-construction period are provided in Appendix E (Figures E-4 to E-18).

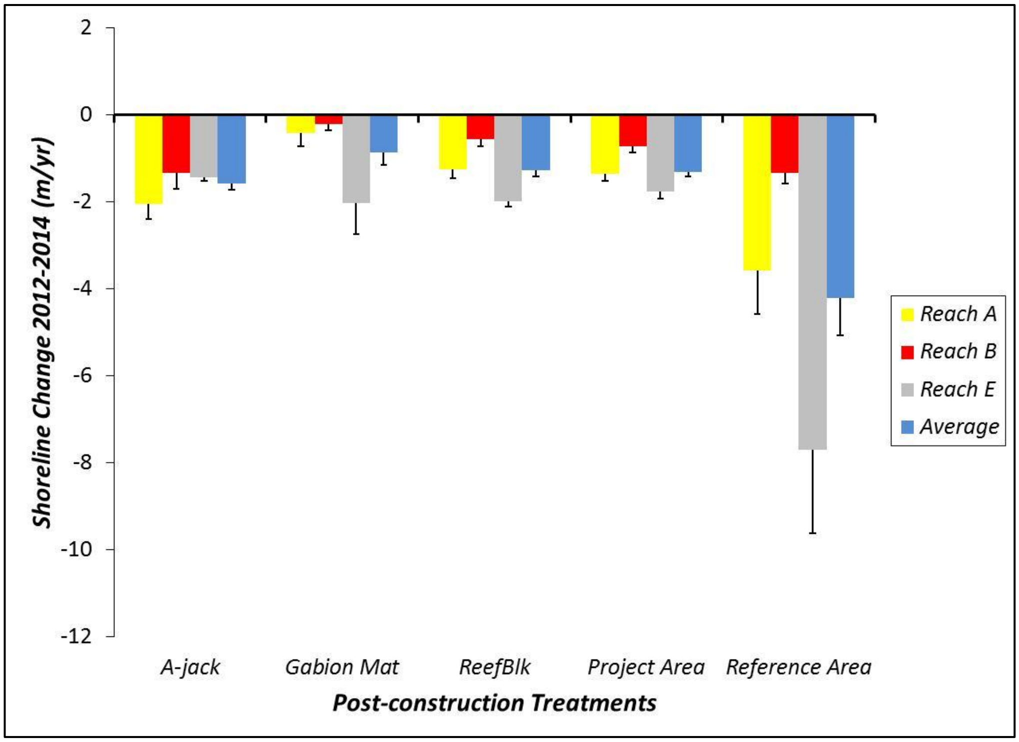


Figure 15. **Post-construction (2012-2014) shoreline erosion rates for each treatment and each Reach at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

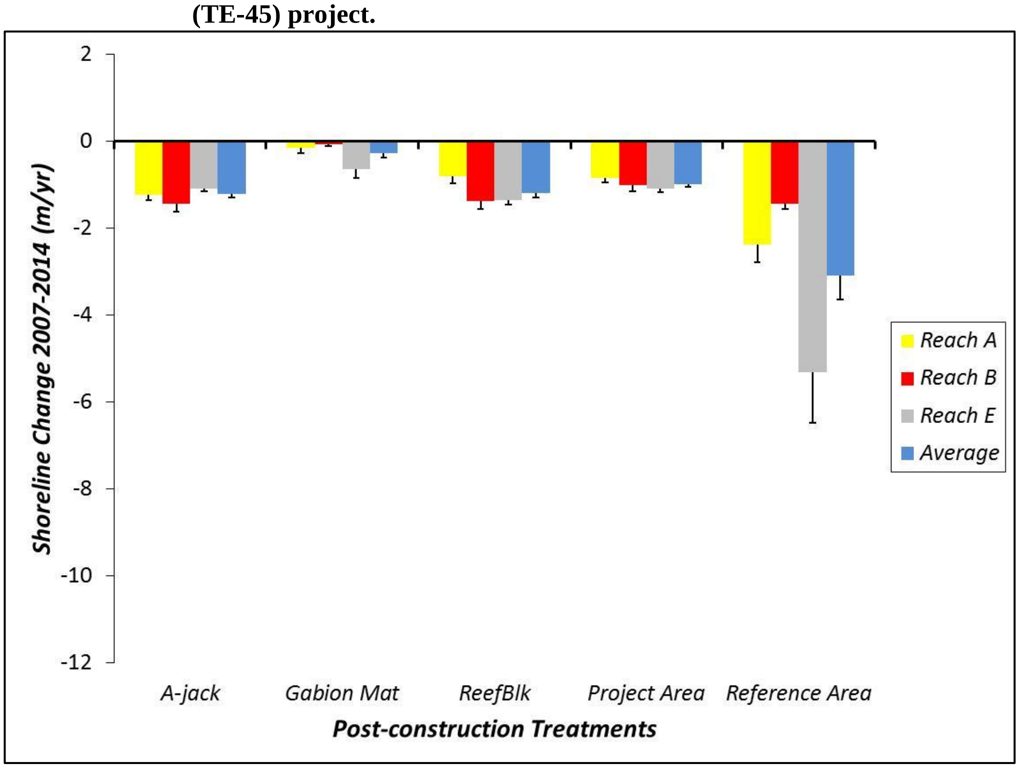


Figure 16. **Post-construction (2007-2014) shoreline erosion rates for each treatment and each Reach for the entire length of the Terrebonne Bay Shore Protection Demonstration (TE-45) study.**

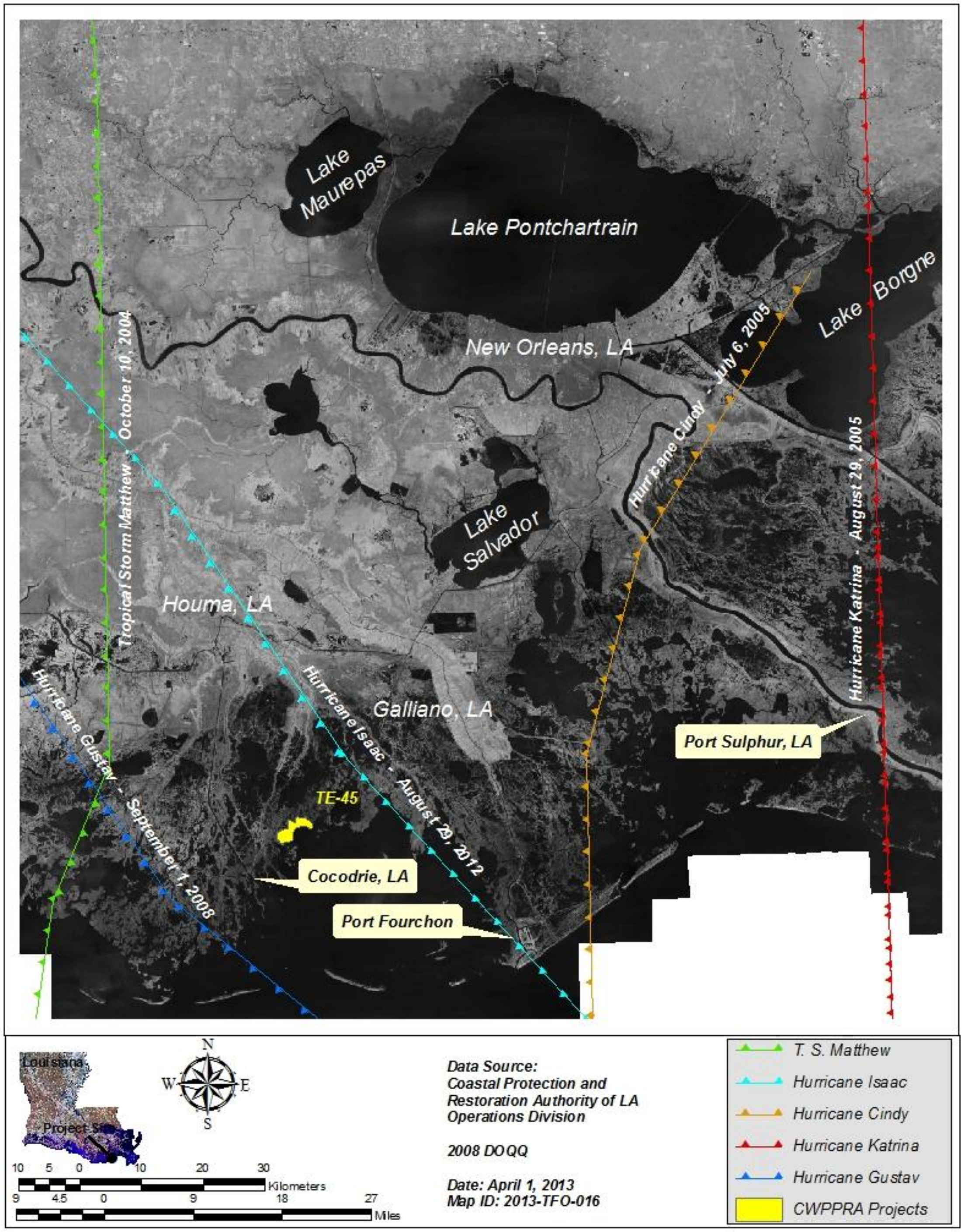


Figure 17. Pre-construction (2004 & 2005) and post-construction (2008 & 2012) tropical storms impacting the Terrebonne Bay Shore Protection Demonstration (TE-45) project area shoreline. Hurricanes Ivan (2004), Rita (2005), Ike (2008), and Tropical Storm Lee (2011) are not shown because the eye wall of these storms traveled further to the south outside the extent of the map.

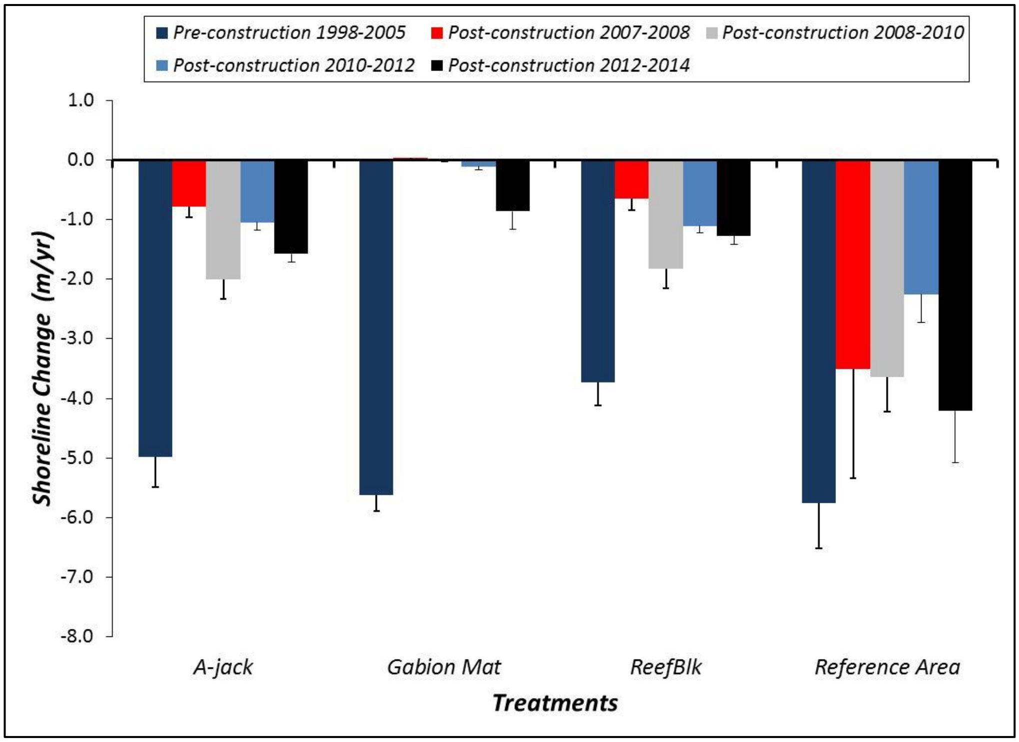


Figure 18. **Comparison of shoreline change means for the pre-construction (mean of 8 years) and post-construction (mean of 1, 3, 5, and 7 years) time periods.**

The shorelines below the Gabion Mat treatment documented the lowest erosion rates during all post-construction intervals (Figures 15, 16, 18 and Melancon et al 2010, 2013). 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 18 and Melancon et al. 2013). Although not included in the shoreline data, the Reach E Gabion Mats experienced approximately 15 m (50 ft) of flanking erosion from project inception through 2012 (Melancon et al. 2013). The amount of flanking erosion doubled between 2012 and 2014 because the marshes behind the Reach E Gabion Mats incurred an additional 15 m (50 ft) of erosion during this interval (Figure 19). The primary cause of this erosion was the exposure of unprotected flanking marshes to wind, wave, and tidal forcing due to the offset position of the shoreline and the high rate of erosion in the reference area (USACE 2004). In addition, a secondary contributor to this erosion was oiling of these marshes during the Deepwater Horizon (DWH) oil spill in 2010 (Figure 20). The flanking erosion could have been prevented if the structure was extended to protect the displaced segment of the shoreline eliminating the exposure of the fringing shore to wave energy. However, it must be noted that the Gabion Mat structure seems prone to erosion at its terminal ends since all but one Reach B end sustained edge erosion (Figure 21). In fact, a considerable portion of the shoreline transgressions behind the mats can be attributed to edge erosion. Although edge erosion did transpire at the other Gabion Mat terminal ends, the erosion of the ends were not as pronounced as the southern Reach E end because the unprotected shorelines near the structure ends were not offset and flanking erosion did not occur (Figure 19). The remaining erosion behind the Gabion Mat structures can be attributed to mat placement and structure settlement issues (Table 3). Each reach had several mats that were placed only on the mudflats and the bottom of the lake falling short of the marsh surface (Figure 21). Erosion was identified behind these misplaced mats. Also, the Reach E Gabion Mats were not installed perpendicular to the shoreline while the mats at the other reaches were. The Reach E mats were orientated at an angle that was approximately 60° west of perpendicular (Figure 21). This misdirection of the mats appears to have increased the erosion behind the Reach E mats. For best results, the mat structures need to bisect the marsh, mudflat, and the benthic layer and be oriented perpendicular to the shoreline. The settlement of the structures also seems to be having an effect on the erosion in the lee of the mat structures (Tables 2 and 3). The only solution to settlement is to reduce the weight (thickness of mats) of the Gabion Mats when soils are structurally deficient, like the TE-45 soils (Eustis 2002). Though the Gabion Mat structures were very successful at lowering erosion rates at all reaches, proper placement and weighting of these structures likely would have reduced erosion rates further. The post-construction shoreline transgressions behind the ReefBlk and A- treatments were temporally similar (Figures 15, 16, 18 and Melancon et al 2010, 2013). 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 and 2012-2014 intervals. However, cold front energy seems to be greater during these intervals (Table 4 and Figure 13), and the ReefBlk and A-Jack structures are possibly more susceptible to cold front derived erosion than the Gabion Mats. Furthermore, the reference areas also eroded at a faster rate during these intervals. 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 18).

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 whereas the Reach B reference area has eroded at a lower rate (Figures 15, 16, 18 and Melancon et al 2010, 2013). These spatial differences between Reaches were significant ($P < 0.05$). No temporal significant differences ($P > 0.05$) were found between the post-construction reference areas (2007-2008, 2008-2010, 2010-2012, and 2012-2014). In contrast, comparisons between pre- vs. post-construction reference areas and project vs. reference areas were significant ($P < 0.05$) (Figure 18). 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 14). This trend has continued during the post-construction period (Figures 15, 16, 18, and Melancon et al 2010, 2013) 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 compared to the reference areas. Though the ReefBlk and A- Jack structures have produced variable erosion rates, the Gabion Mat treatment is maintaining

Figure 19. **November 14, 2012 and January 15, 2015 images depicting flanking erosion behind the Reach E Gabion Mat treatment at the Terrebonne Bay Shore Protection Demonstration (TE-45) project. Note the increased erosion in 2015. Images reproduced from Google Earth.**

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 populations during tropical (Figure 17) and extratropical storms. Though the triangular frames of the Reefblk structures have proven to be durable over the duration of the TE-45 project, the internal oyster shells placed in the mesh bags are disintegrating creating void spaces in the mesh bags and impacting oyster populations. This phenomenon is particularly prominent at Reach E and is likely a result of the low relief (Table 2) and constant inundation of these structures. This topic is examined in greater detail in the oyster population discussions that follow. Both hurricanes (Stone et al. 1997; Morton and Barras 2010) and cold fronts (Watzke 2004; Trosclair 2013) have been found to erode coastal marshes. Other oyster reefs have reduced marsh erosion in low energy environments (Meyer et al. 1997; Piazza et al. 2005). 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 seven years since construction are encouraging, the continued settlement of these structures (Tables 3 and 4) in these low bearing soils (Eustis 2002) could advance shoreline transgressions behind these treatments. Therefore, only additional temporal data can determine if these low erosion rates behind these structures are sustainable.

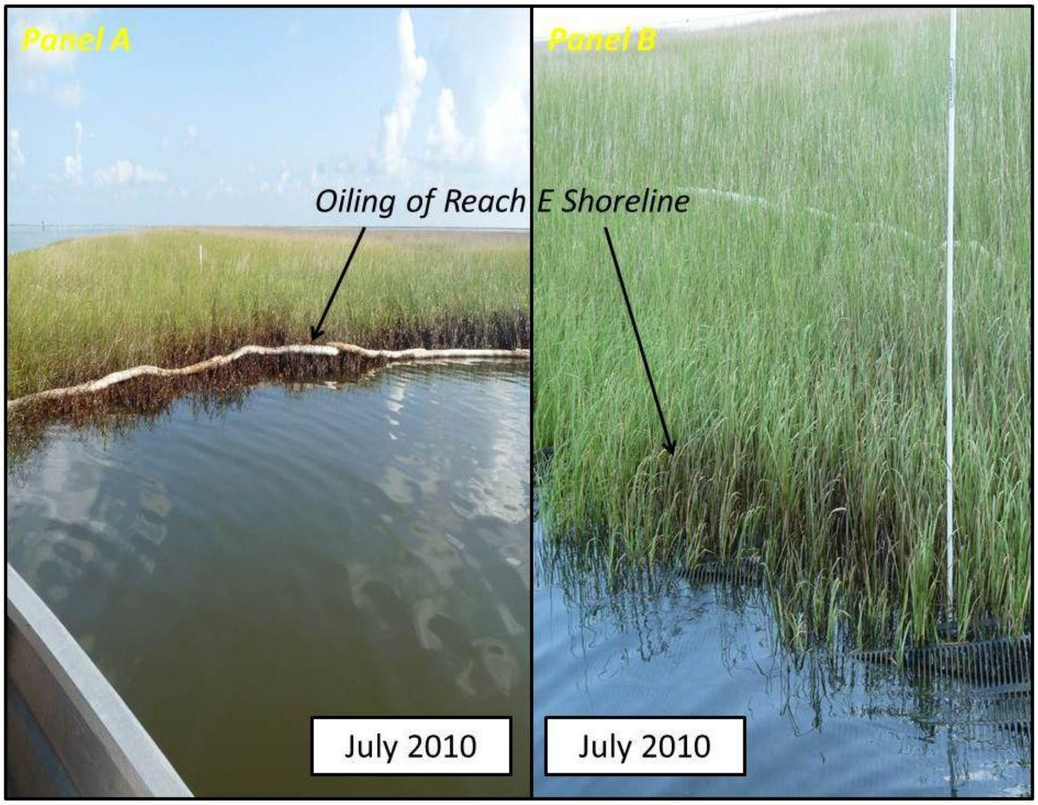


Figure 20. Oblique photographs showing oiling of the Reach E Gabion Mat shoreline in the aftermath of the DWH oil spill in 2010.

Figure 21. Oblique photographs illustrating Gabion Mat edge erosion (Reach A) and placement issues (Reaches A & E). Orange arrow delineates the angle of the Reach E structures.

Hydrology Metrics

Water temperature and salinity affect nearly every aspect of oyster biology (Shumway 1996). Water temperatures throughout the study followed a typical (Day et al. 1973) coastal Louisiana annual sinusoidal pattern at both sites with no significant difference between the two (Figure 22). Highest mean monthly water temperatures occurred in July and August of each year and were above 30°C (86°F), and peaked at 32°C (89.6°F) in August 2011. Mean monthly winter water temperatures dipped to between 10-15°C (50-59°F) in January of each year, with the lowest mean monthly temperature in January 2014 at 9.8°C (49.6°F). Water temperatures were well within the upper and lower tolerance limits for Gulf of Mexico (Cake 1983). Reef oysters have been documented to survive temperatures as high as 49.5°C (121.1°F) (Ingle et al. 1971). Water temperatures in the spring and fall of each year were also well within the tolerance limit of oyster larvae and spat (Kennedy 1996).

Salinity fluctuated throughout the study and ranged from a low of 3.7 psu to a high of 27.6 psu (Figure 22). The mean monthly salinity for site A/B was 15.3 psu (± 0.03) and for site E, 17.6 psu (± 0.02). Site E had a slightly higher salinity throughout most of the study period, November 2007 to January 2015. Salinity at both sites was mostly in the range, 5-15 psu, which is considered best for oyster survival from predators and disease (Cake 1983). However, salinities at both sites, but especially at site E, were at times in the high teens to mid-twenties for prolonged periods and could potentially stimulate the colonization of subtidal oyster shell pests such as boring sponges (Carver et al. 2010) and boring Polychaete worms (Brown 2012), both capable of making shells brittle and easily broken.

Phytoplankton is considered a principal food source for the filter-feeding oyster (Langdon and Newell 1996). Therefore, once oyster populations had been established on the bio-engineered structures chlorophyll-a was measured (as an index of Phytoplankton abundance) at all three Reaches from July 2009 to September 2014 (Figure 23). Chlorophyll-a averaged 14.1 μgL^{-1} ± .01 during the five years measured with a range of 1.0-40.5 μgL^{-1}. La Peyre et al. (2012), over a three-year study assessment of 260 m^2 of oyster reef habitat in Sister Lake, Louisiana, documented a mean chlorophyll-a concentration of 14.6 $\mu g\ L^{-1}$ ± .04 with a range from 1.8-43.6 μgL^{-1}. Chlorophyll-a was within an acceptable range to maintain good oyster reef development at all three Reaches, A, B and E.

Oysters are filter-feeding omnivores (Langdon and Newell 1996) and therefore can obtain food from other sources other than phytoplankton. Therefore, besides measuring for chlorophyll we measured for total water-suspended seston (Figure 24) in the form of Total Particulate Matter (TPM), and then combusted TPM to derive the percentage of Particulate Organic Matter (POM) from within the sample (Figure 25). Overall mean concentrations of TPM ranged from 1.0-39.3 mg L^{-1}, but were significantly different ($P < 0.05$) between Reaches for A, B, and E at 8.0 mg L^{-1} ± 0.42, 8.5 mg L^{-1} ± 0.45 and 7.7 mg L^{-1} ± 0.46, respectively. However, once the TPM samples were combusted the resulting POM did not vary significantly between Reaches, with an overall mean of 2.7 mg L^{-1} ± 0.1, with a range of 7.6 mg L^{-1}.

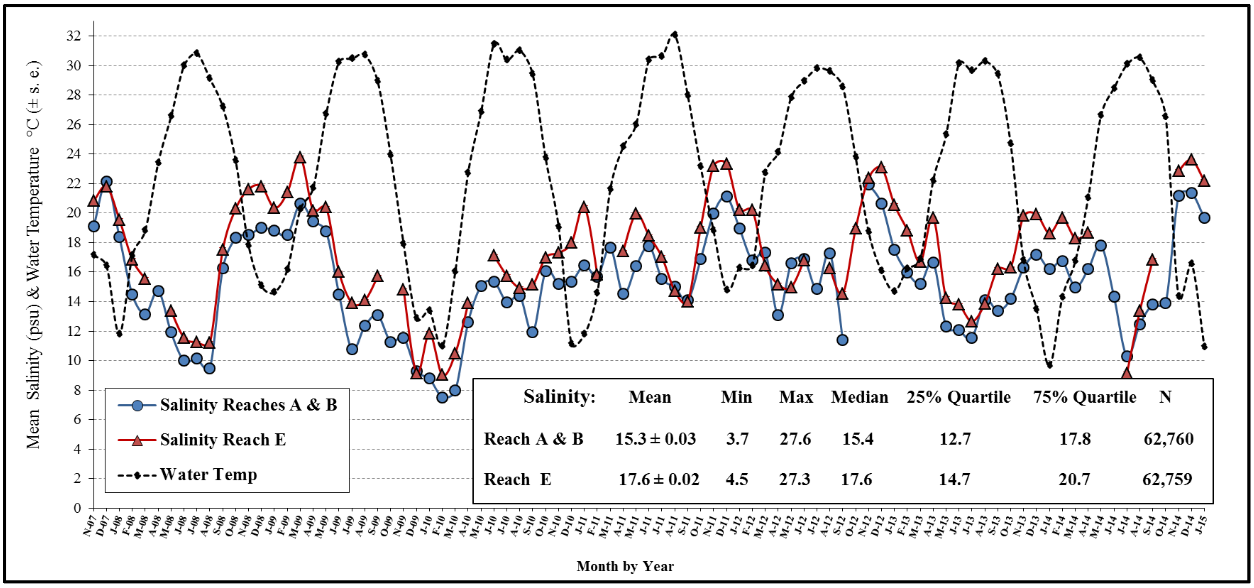


Figure 22. **Mean monthly salinity and water temperature by Reach from November 2007 to January 2015. A Kruskal-Wallace One-Way ANOVA on Ranks indicated a significant difference (P < 0.05) between A&B vs. E for salinity, but not for water temperature and is therefore represented by Reach A&B data.**

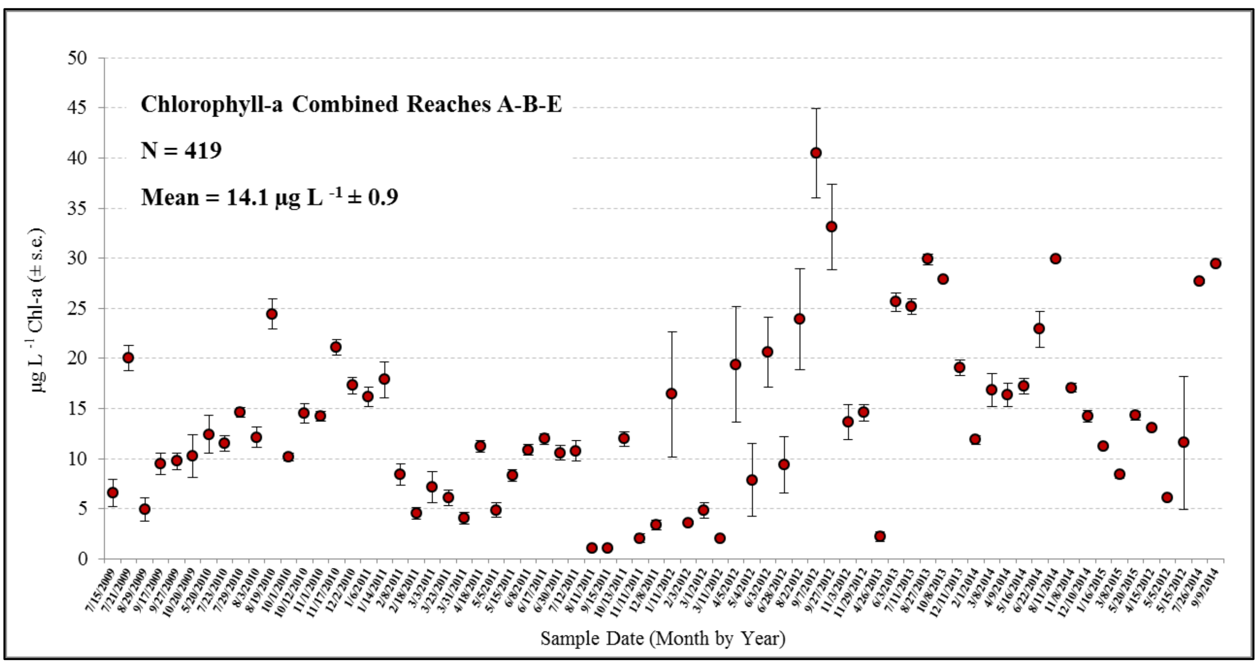


Figure 23. **Mean monthly chlorophyll-a for Reaches A, B and E combined. A Kruskal-Wallace One-Way ANOVA on Ranks indicated no significant differences between Reaches, therefore combined (P < 0.05).**

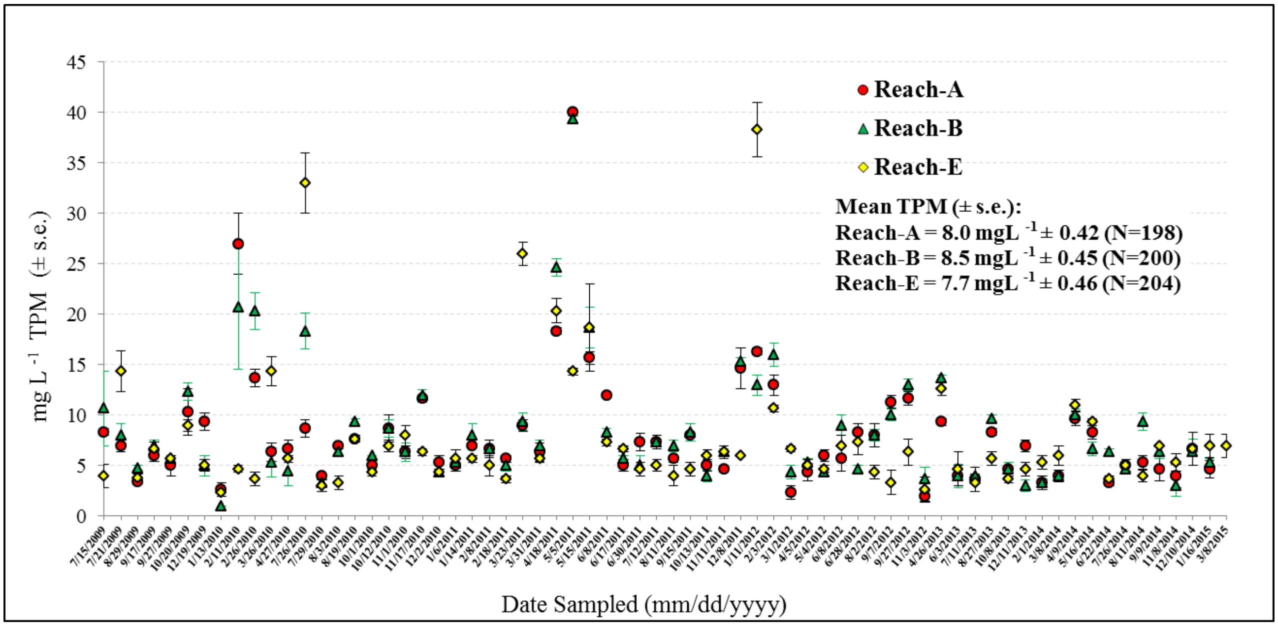


Figure 24. **Mean monthly Total Particulate Matter (TPM) by Reach. A Kruskal-Wallace One-Way ANOVA on Ranks indicated significant differences between two Reaches ($P < 0.05$): A vs. B = No, A vs. E = No, B vs. E = Yes.**

In Sister Lake, La Peyre et al. (2014) measured TPM mean concentration at 39.2 ± 2.5 7 mg L^{-1} with a range of 4.0-296 mg L^{-1}. Sister Lake POM was 10.7 mg L^{-1} ± 0.4 with a range of 2.0-45.3 mg L^{-1}. It is not known why the Sister Lake TPM and POM values were so much higher than the Terrebonne values. For comparison, Dekshenieks et al. (2000) modeling seston food availability as POM in Galveston Bay for oyster larvae and adults used a low range of 1.5-1.6 mg L^{-1} and a high range of 2.1-2.2 mg L^{-1}, which are more nearer the Terrebonne values.

Dissolved oxygen (D.O.) was measured at the three Reaches of the TE-45 project (Figure 26). Langdon and Newell (1996) have documented that low D.O. (sever hypoxia, ≤ 2.0 mg L^{-1}) can influence oyster larvae and adult survival. However, over relatively short periods, oysters have the ability to respire anaerobically to cope with hypoxia (Widdows et al. 1989). The respiratory physiology of *C. virginica* is highly adapted to life in a fluctuating environment such as an estuary (Shumway 1996). During daylight hours, when data was collected, D.O. for the TE-45 project ranged from 4.2-13.0 mg L^{-1} and did not appear to play any negative role in oyster recruitment, growth, or survival.

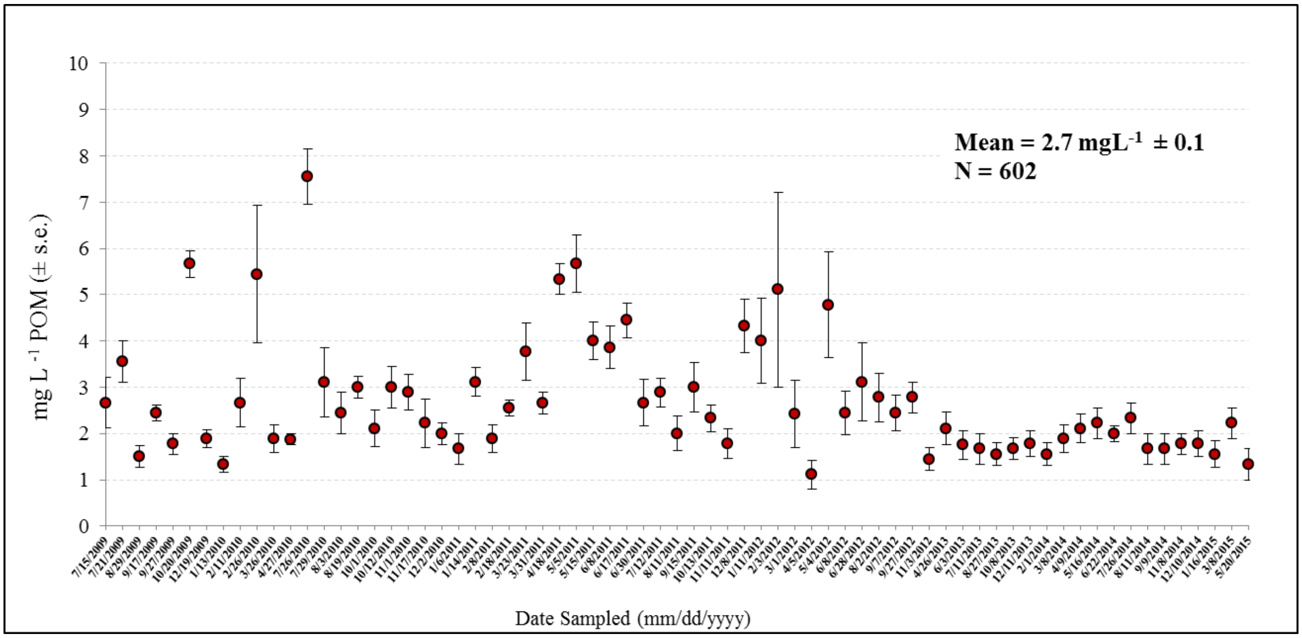


Figure 25. **Mean monthly Particulate Organic Matter (POM) for Reaches A, B and E combined. A Kruskal-Wallace One-Way ANOVA on Ranks indicated no significant differences between Reaches, therefore combined ($P < 0.05$).**

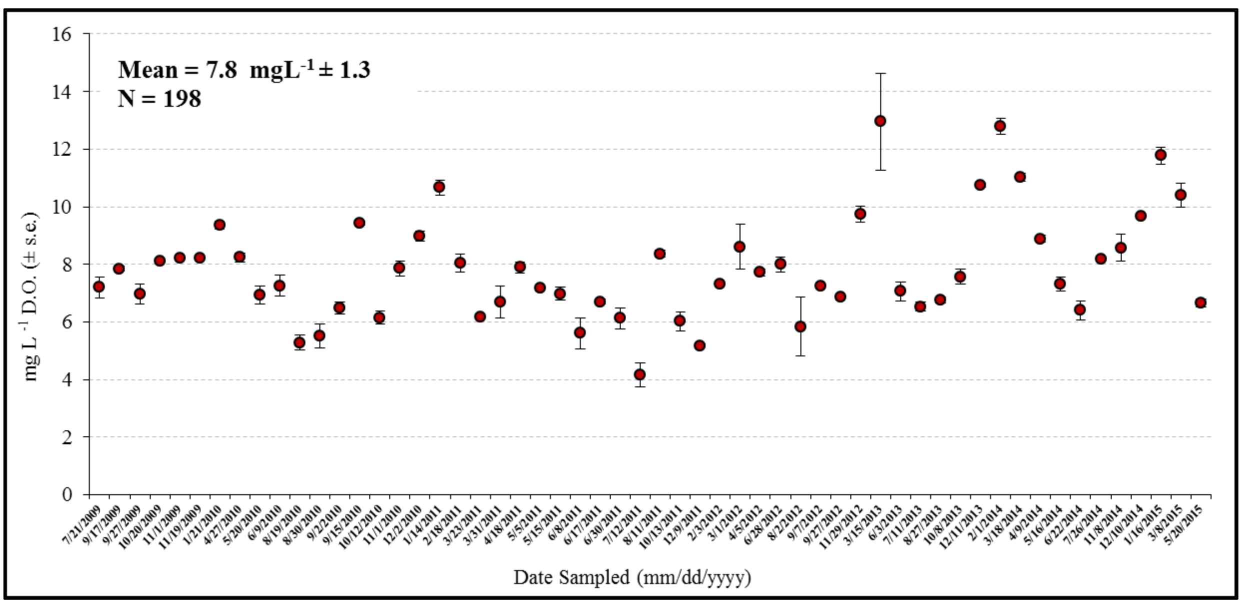


Figure 26. **Mean monthly Dissolved Oxygen (D.O.) for Reaches A, B and E combined. A Kruskal-Wallace One-Way ANOVA on Ranks indicated no significant differences between Reaches, therefore combined ($P < 0.05$).**

Recruitment Metrics

Before an adequate discussion of biological performance of each of the three bio-engineered structure types, i.e., Gabion Mats, A-Jacks and ReefBlks, there is a need to document oyster recruitment potential to the structures. There is also a need to document recruitment potential of the two major competitors for space and food with oysters, barnacles, and hooked mussels. Oyster recruitment patterns to unglazed quarry tiles place subtidally near the structures from spring 2008 to winter 2014 followed the typical pattern of bimodal peaks in spring and fall of each year, with sporadic and smaller recruitment during the other months (Figure 27). Whenever the bimodal peaks occurred in the same year, the spring recruitment was always several times greater in magnitude to that of the fall recruitment. The one notable exception to this recruitment pattern occurred during the study, in the spring of 2010. The 2010 spring oyster recruitment was considered a failure because of the very low numbers.

The 2010 spring spawn occurred at the same time when oil from the Deepwater Horizon spill (DWH) was observed in the waters of northern Terrebonne Bay, and actually made landfall at Reach E (Figure 28). Also noteworthy to document is that efforts by cleanup crews to lay boom along the shoreline at Reach-E to prevent inner marsh oiling (Figure 29) may have

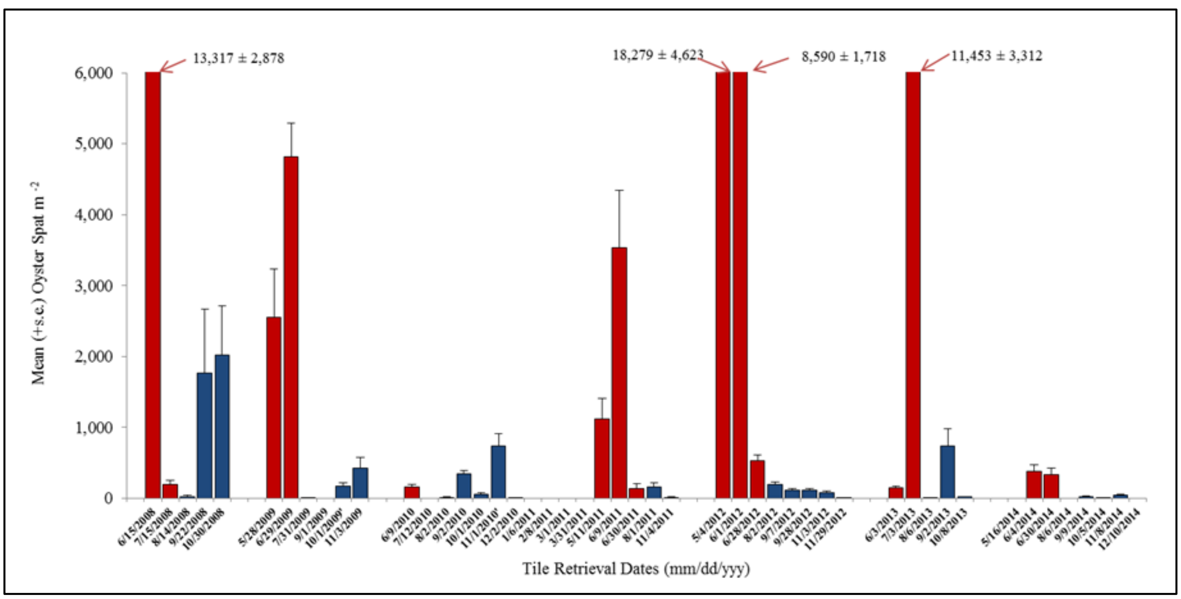


Figure 27. **Mean monthly number of oyster spat recruited to quarry tiles by combining all three Reaches, A, B and E. Red bars indicate spring spawning season.**

Figure 28. Boat laying oil boom in summer 2010 at Reach E because of the DWH oil spill in the Gulf of Mexico. Boom is being laid on a high tide as boat travels between marsh shoreline and bio-engineered structures.

Figure 29. Moderate oiling in summer 2010 at Reach-E from the DWH oil spill. White oil boom is also seen in the photo.

compromised the site for determining erosion estimates due the high volume of boat traffic between the marsh shoreline and the A-Jack and ReefBlks structures (Figure 30). Reach-E was the only location where this activity occurred within the study. All Reaches and structures within each experienced oyster spat failure in spring 2010. However, a visual comparison of oyster survival and oyster spat recruitment during 2010 did not differ between structure types or Reaches.

Figure 30. **Boat dual-propeller tracks remain behind A-Jacks at Reach-E showing how activities associated with laying oil boom impacted marsh shoreline. Winter 2010 photo several months after crews had removed the oil boom from the marsh. Similar tracks observed at Reach-E behind ReefBlks.**

Documenting oyster recruitment to tiles is helpful to identify that oyster larvae are present and that settlement (recruitment) is occurring. However, it does not insure or correlatively quantify numbers that will recruit to the bio-engineered structures, i.e., tile recruitment densities can be directly compared to other tiles, but cannot be directly compared to settlement on any structure or reef. Pollard (1973), working in coastal Louisiana found no correlation between larval abundance in the water and subsequent recruitment to nearby reefs. Perhaps the only caveat to this understanding between larvae and settlement is the spring 2010 decline in recruitment to tiles due to the oil spill that also correlated to very low observed oyster spat found on all bioengineered structures that same spring/early summer.

An interesting recruitment pattern to tiles developed as the study progressed through the years. As will be seen in the sections to follow that good oyster recruitment occurred to all structure types at all three Reaches. However, the tidal currents always seemed to be stronger at Reach-E than at Reaches A and B. Reach-E was located on a small island in direct line with several large bayous with good tidal currents and actively fished oyster leases. Perhaps because of its strategic location there were more oyster larvae encumbered within the tidal currents. Seventy-five percent of the oyster spat (recruits) came from the Reach-E tiles (Figure 31).

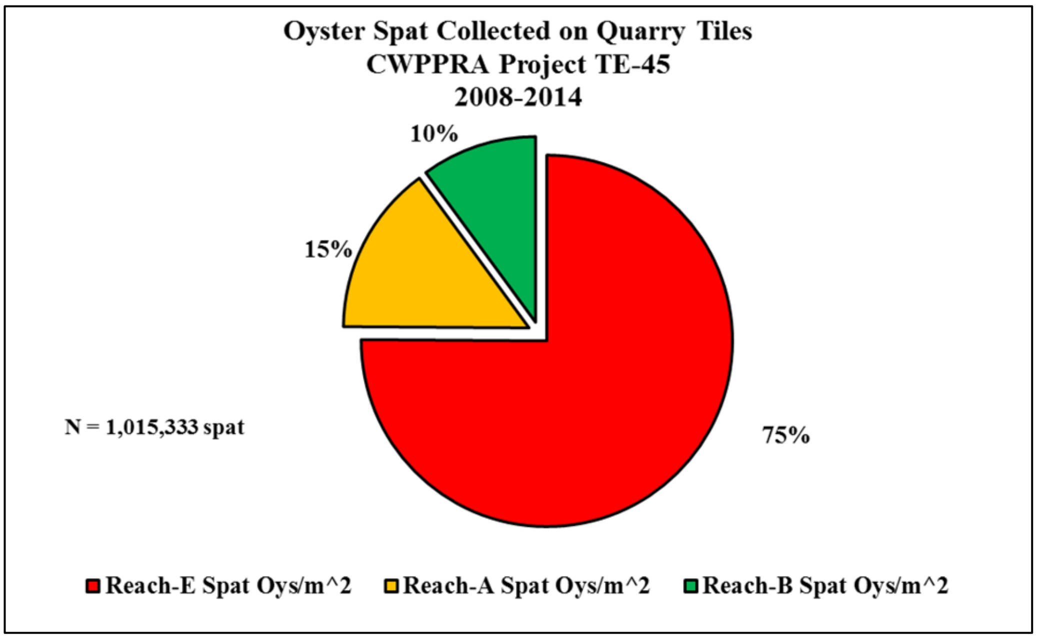


Figure 31. **Cumulative quantity of oyster spat recruitment to unglazed quarry tiles from spring 2008 to winter 2014**.

The two most conspicuous and abundant competitors for settlement habitat and food are the barnacles, *Balanus sp*., and the hooked mussel, *Ischadium recurvum*. Barnacles recruited to the structures in all months sampled, but peaked in late spring-early summer and early fall at the same time of dominant oyster recruitment (Figure 32). Hooked mussel recruitment was monitored from June 2010 to June 2011 (Figure 33) and peaked at the same time of oyster peak recruitments, spring and fall. Of the two species, the greatest competitor for the oyster appears to be the hooked mussel because of their large size, great numbers, and their ability to compete for the same food sources as oysters (Melancon et al. 2013). Ironically, the hooked mussel is also considered to be beneficial in oyster reef ecosystem services by filtering phytoplankton and contributing to better water quality in eutrophic systems such as Chesapeake Bay (Gedan et al. 2014).

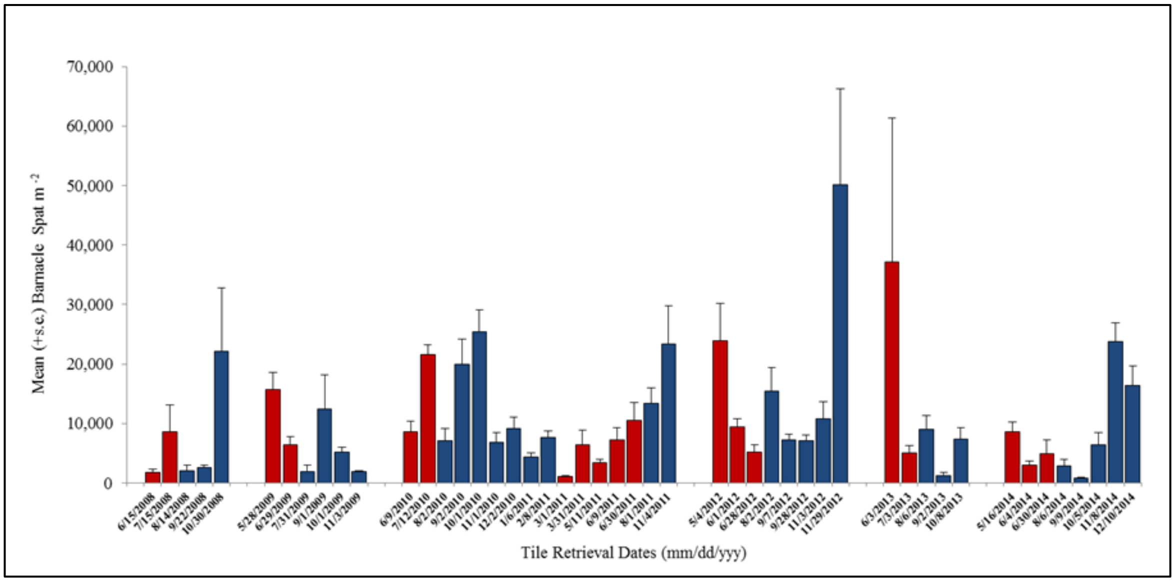


Figure 32. **Mean monthly number of barnacles (*Balanus sp*.) recruited to quarry tiles by combining all three Reaches, A, B and E. Red bars indicate spring oyster spawning season.**

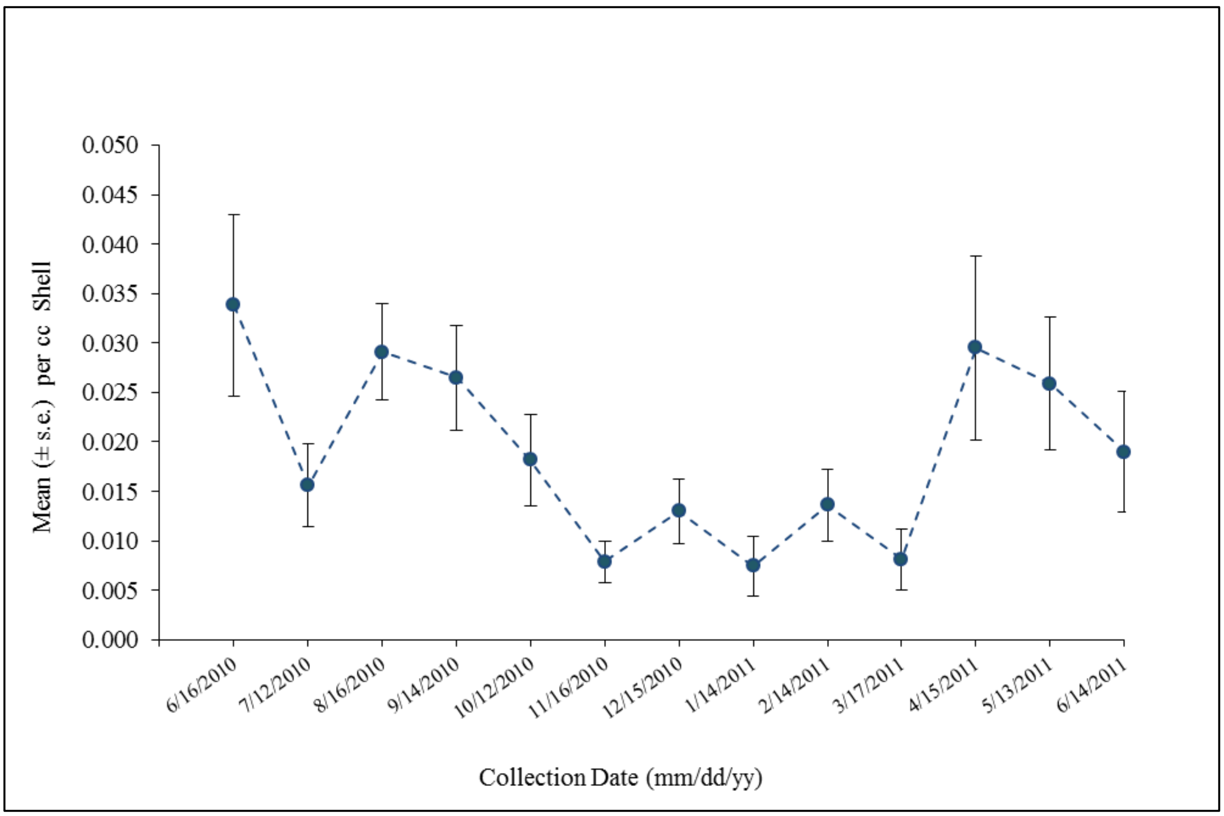


Figure 33. **Mean monthly number of hooked mussels recruited to bags of oyster halfshells and live oysters.**

Biological Metrics Overview

After documenting the three structure types for degree of wetlands shoreline protection, the next most important variable to document is the degree of oyster recruitment and reef-building success attained by the winter of 2014 after seven (7) years post construction. All three structures had oyster recruitment, but by year four (4) in winter 2011 it was apparent that the ReefBlks were experiencing wholesale loss of live oysters and its oyster shell substrate within its cultch bags; this will be discussed later. By winter 2014, only Gabion Mats and A-Jacks had oysters colonized and building reef in a meaningful way, and that will be the focus of most of this section of the report.

Oyster density (Figure 34) is portrayed in three formats. In the first method, number per square meter of the actual surface area excavated was calculated; oyster retrieved from each quadrat frame as it was laid on the Gabion Mats, or scraped from an arm of the A-Jacks, and then extrapolated to number per square meter. The second density quantity was measured from an aerial perspective looking down on a square meter of bay bottom. Notice that the density for Gabion Mats did not change but for the A-Jacks, it did (Figure 34). Gabion Mats are laid horizontally across the edge of the marsh shore and therefore by default quadrats are essentially in an aerial view perspective and thus same calculation as method one results. However, A-Jacks are vertical three-dimensional structures rising above the bay bottom with many angular arms within a square meter of an aerial view bay bottom. For example, the A-Jacks' surface area excavated was 0.57 m^2 per quadrate site, but the aerial view within a square meter of bay bottom encompassed 3.01 m^2 of total surface area of all arms, and therefore excavated density had to be extrapolated by that factor (Figure 34). In contrast to both previously mentioned methods, a linear meter of oyster density within a linear meter of marsh shoreline was calculated (Figure 34). A linear meter of shoreline did not need further extrapolation for A-Jacks because calculation is the same as for aerial view, but a Gabion Mat, measured 6.1 meters long (20 ft.) and 1.5 m wide (5 ft.). Therefore, excavated Gabion Mat quadrat densities were extrapolated to accommodate those dimensions (Figure 34); only half of mat length used for calculating one meter of linear marsh oyster density (see discussion of Gabion Mats below as to why this was done).

Oyster settlement, survival, growth, and density are influenced by duration of tidal inundation and exposure along a shoreline (Figure 35). In the northern Gulf of Mexico tidal amplitudes, i.e., the range for high tide to low tide, are microtidal when compared to the larger tidal ranges of the east and west coasts of the United States. Louisiana, because of its location in the central northern Gulf has some of the smallest tide ranges in the United States, with an average of about 0.3 meters (1 ft.). The exception to this small tidal range occurs when there are storms such as hurricanes and tropical depressions, when there are steady strong winds moving onshore from the Gulf of Mexico, and when there are winter weather fronts moving in from the northwest. The Gabion mats had by far the greatest period of complete and partial aerial exposure due to tidal activity, followed by ReefBlks and then A-Jacks, at 51%, 23% and 17% respectively, for the period from January 2008 to December 2014 (Figure 35). Almost all of the full exposures occurred in the fall and winter after passage of a northwest cold front.

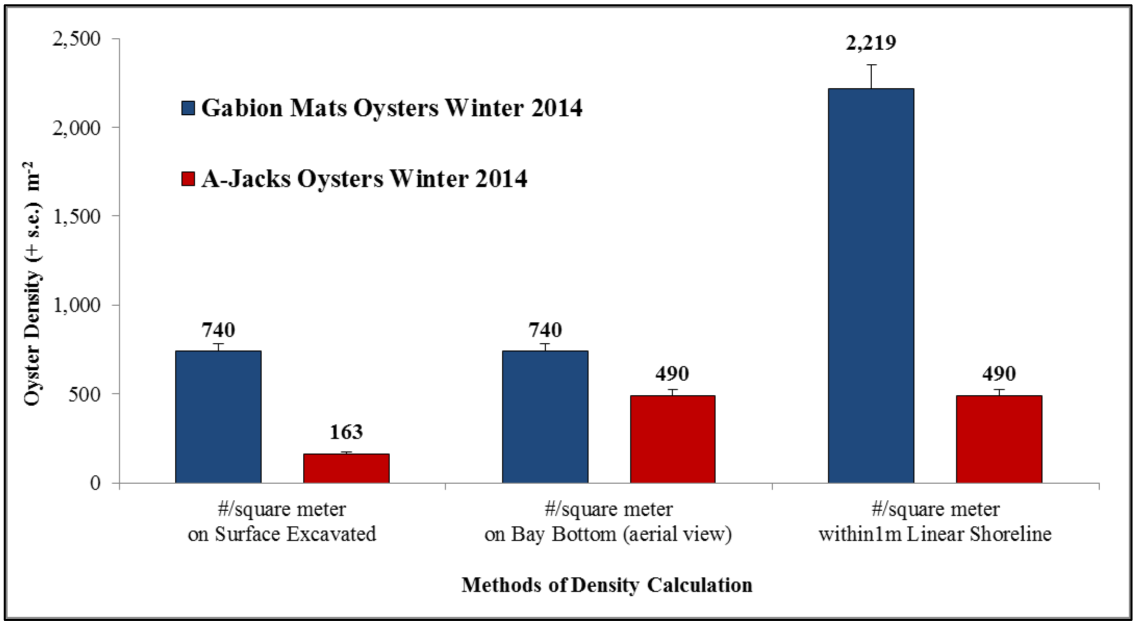


Figure 34. **Oyster densities after 7-years post-construction on Gabion Mats and A-Jacks, pooling data from each of the three Reaches, A, B and E for each structure type. Densities are reported in three different metric methods.**

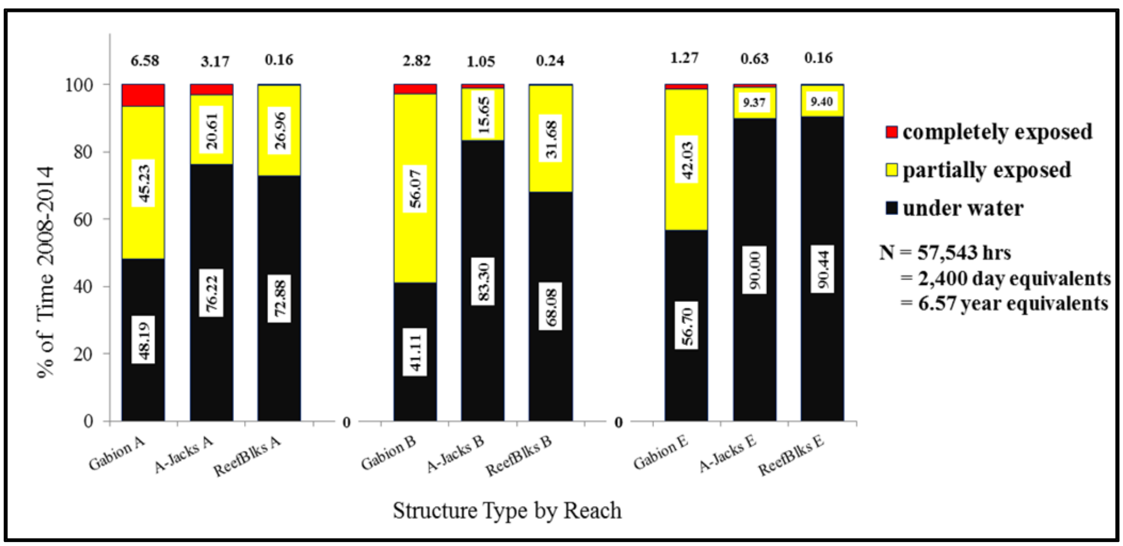


Figure 35. **Percent of time each structure type was inundated and exposed from January 2008 through December 2014. Data based on continuous hourly sonde records when sondes were working.**

Oyster shell heights (Figure 36) show that by seven years post construction in winter 2014, the A-Jacks exhibited a greater size frequency distribution than the Gabion Mats, with some oysters attaining a size of near 150 mm. The Gabion Mats were more skewed to oysters in the 25-75 mm range as compared to the A-Jacks with most in the 50-100 mm range. Oysters in the northern Gulf of Mexico can live for 10 years or longer (Cake 1983), but five years is considered more of an average natural life expectancy. Therefore, oysters by the 7th year have cycled through at least one average life expectancy period, and beyond, and oysters nearing 150 mm in shell height can be expected.

The difference in shell height frequencies between A-Jacks and Gabion Mats is probably a combination of factors that influence growth and survival. Gabions Mats were more aerially exposed (Figure 35) and more subjected to wave activity and the abrasiveness of shell rubble washing up on shore. Unlike A-Jacks with a leeward side positioned away from open bay wave activities, the Gabion Mats are completely exposed to the harshness of waves.

Shell size-frequency distributions provide valuable information about age structure, population growth and spat recruitment through time but may not be considered a primary performance criterion in evaluating a living shoreline (Baggett et al. 2014). However, size-frequency analysis in this project took on a more significant and primary role because of evaluating three very distinct fabricated structure types, each with different shapes and materials available for oyster recruitment and reef building potential.

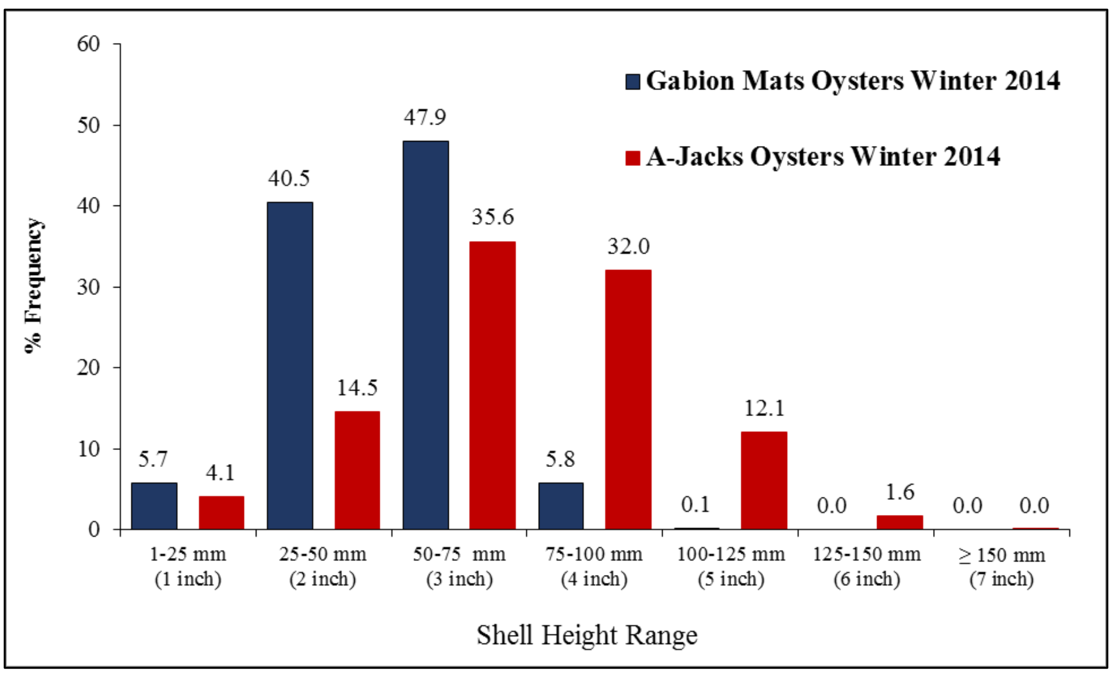


Figure 36. Size frequencies of oysters from Gabion Mats and A-Jacks in winter 2014, seven years post construction. All three Reaches, A, B and E data pooled for respective structure type. Numbers above bars represent the % frequency.

Oyster shell growth by structure type through time progressed steadily from the first year post construction in winter 2008 to the last year of data collection in year seven, winter 2014 (Figure 37). Each of the three unique structures had oyster populations grow at different rates within a winter survey. Differences in shell growth also existed between Reaches for the same fabricated structure type. Gabion Mats had significant l differences ($P < 0.05$) in shell growth between Reaches for each winter survey (Figure 38), as did A-Jacks (Figure 39) and ReefBlks (Figure 40). Such shell growth differences lend itself to an academic discussion on speculations as to why, but from a reef building and oyster population density perspective, the growth differences within a winter for a structure type were not of significant practical consequences, especially by winter 2014, seven-years post construction when large populations with multiple shell size categories existed.

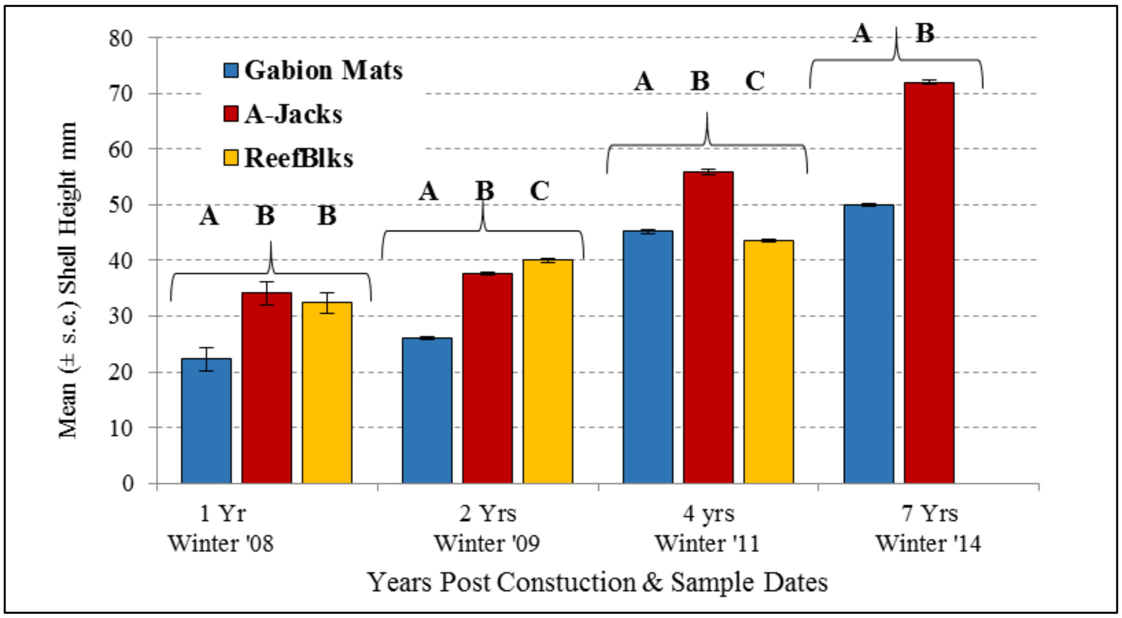


Figure 37. Mean (± s.e.) shell height by structure type within a winter survey year. Letters above structure type within a winter signifies statistically similar to one another or not ($P < 0.05$). In winter 2011 survey only Reaches A and B represents ReefBlk data. In winter 2014 survey all ReefBlks failed at all three Reaches and therefore is not represented. Kruskal-Wallace one-way ANOVA on Ranks; $\log_{10}$ transformations did not normalize shell heights.

A hindrance to oyster reef development on all three of the fabricated structure types was fouling by the hooked mussel, *Ischadium recurvum*. This animal has been found in large numbers throughout every winter survey and year of the project (Figure 41). In the winter of 2014, the numbers were greatest on the A-Jacks when compared to the Gabion Mats (Figure 42). General observations as well as empirical data have shown that this pervasive mollusk is attracted to oysters and generally has the highest densities when there is vertical relief to a fabricated structure. For example, some of the highest densities were found in the winter 2011 survey on

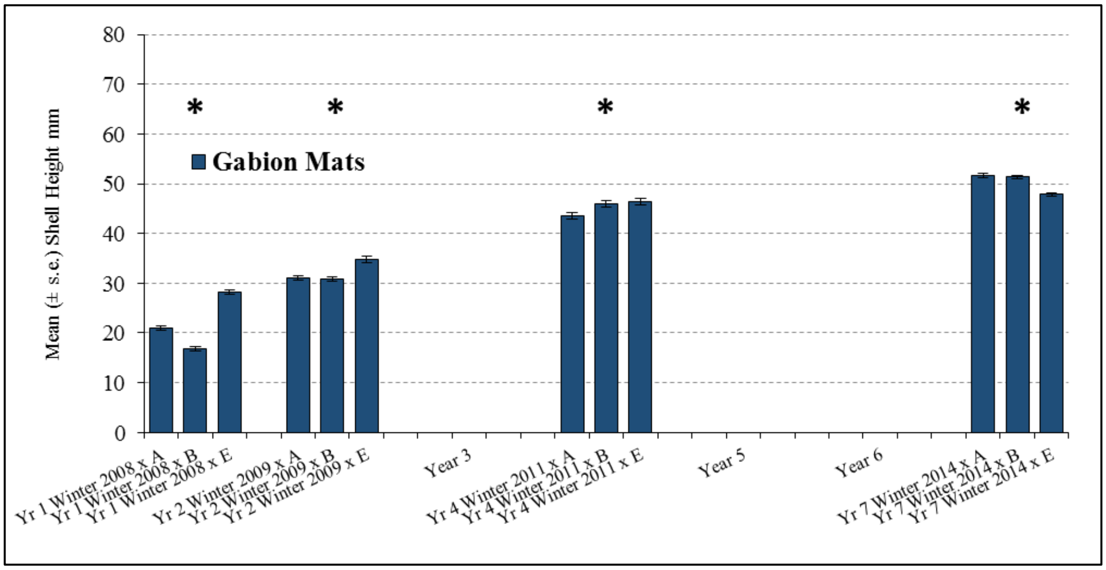


Figure 38. Mean (± s.e.) shell height for Gabion Mats for each Reach within a winter survey. An asterisk above a survey indicates that at least one Reach is statistically different from the others within that specific winter survey ($P < 0.05$). Kruskal-Wallace one-way ANOVA on Ranks; $\log_{10}$ transformations did not normalize shell heights.

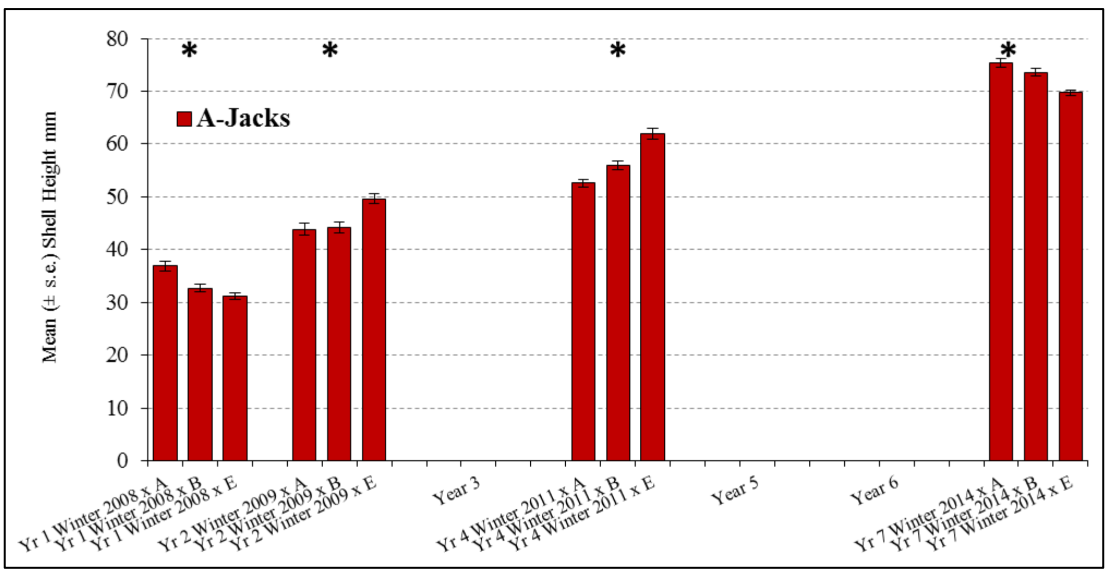


Figure 39. Mean (± s.e.) shell height for A-Jacks for each Reach within a winter survey. An asterisk above a survey indicates that at least one Reach is statistically different from the others within that specific winter survey ($P < 0.05$). Kruskal-Wallace one-way ANOVA on Ranks; $\log_{10}$ transformations did not normalize shell heights.

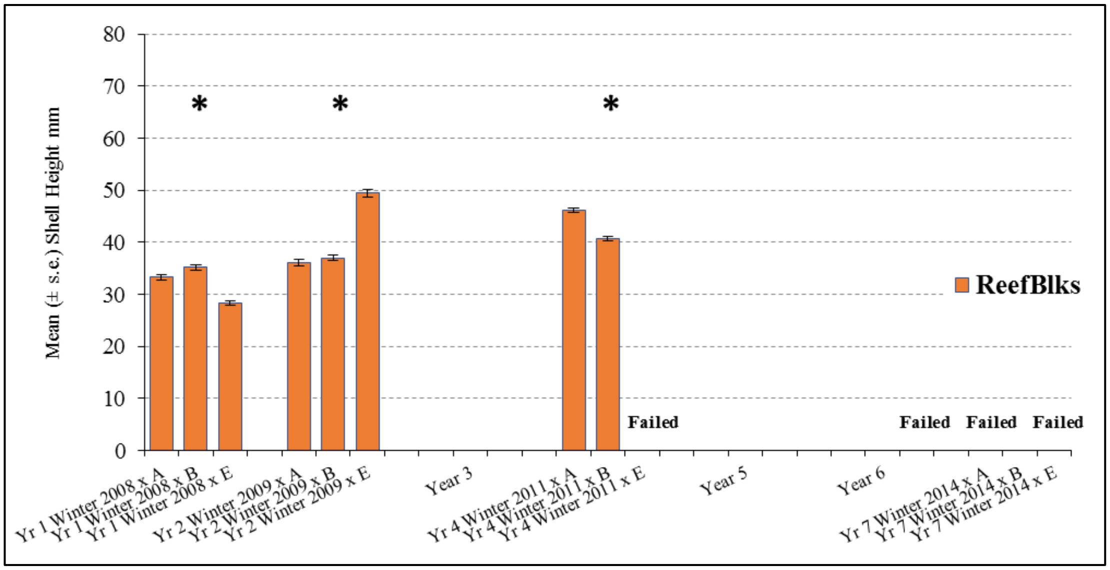


Figure 40. Mean (± s.e.) shell height for ReefBlks for each Reach within a winter survey. An asterisk above a survey indicates that at least one Reach is statistically different from the others within that specific winter survey ($P < 0.05$). Failed indicates loss shell substrate within ReefBlks of that specific Reach. Kruskal-Wallace one-way ANOVA on Ranks; $\log_{10}$ transformations did not normalize shell heights.

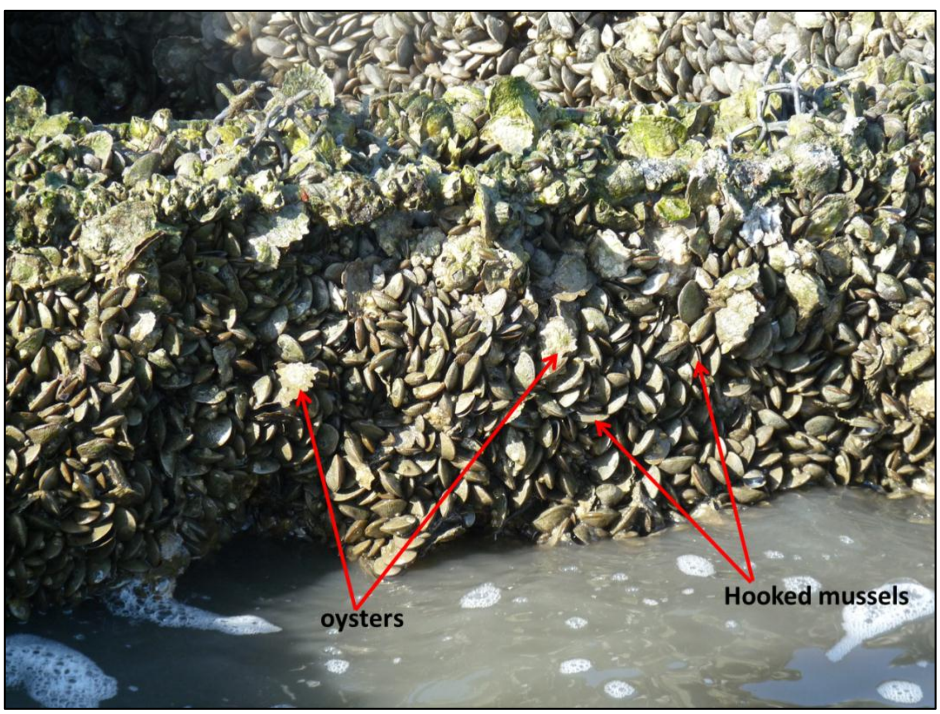


Figure 41. Hooked mussels in large numbers on the vertical side of a Reach B ReefBlk in winter 2011 survey.

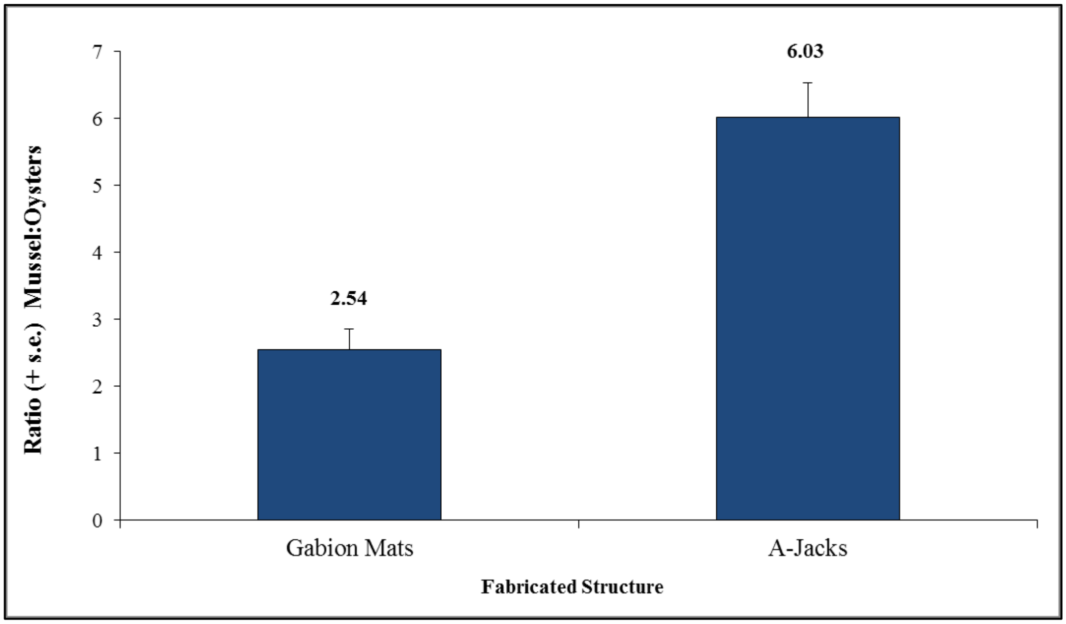


Figure 42. Mussel-to-Oyster ratio comparing Gabion Mats and A-Jacks in winter 2014 survey.

ReefBlks (Melancon et al. 2013). Besides its competition for space and food, it becomes a surface upon which oyster spat will settle. This oyster spat settlement on hooked mussels has been observed numerous times during this study. The mussel attaches to a substrate by byssal threads that are very strong and can easily hold the weight of an oyster and many mussels (Figure 43). Unfortunately, when the mussel dies the byssal threads will eventually decompose and the animal will detach from its substrate. Particularly for fabricated structures with significant vertical relief, such as the A-Jacks and Gabion Mats, this creates a dilemma. Oysters that attach to the hooked mussel have the potential to fall off into the underlying sediments and suffocate or be washed away by wave and currents; this scenario has been observed in this project. The largest hooked mussels were 65 mm in shell height.

The eastern oyster is a protandric hermaphrodite, i.e., when the animal first matures it is generally a male (Thompson et al. 1996). Sex reversal to female usually occurs between spawning events when gonads are not producing gametes. Galtsoff (1964) determined that as oysters grow, and by default become older, the proportion of female oysters in the population becomes greater. That is what was occurring at the TE-45 sites (Figure 44), where the percentage of the female population increased as the oysters, and reef, matured. More than 50% of oysters were females by the time they reached a shell height of 60 mm, and thereby producing a ratio greater than 1:1. By the winter of 2014, the population of ≥ 60 mm oysters on the Gabion Mats were 28.2% while the A-Jacks had a population equal to 68.5%. Therefore, the A-Jacks also had a larger population of female oysters per square meter than the Gabion Mats.

Figure 43. One hooked mussels supporting a large cluster of mussels by its byssal threads. The large mussel below the hooked mussel being held is a ribbed mussel but others are hooked mussels. Greater than 98% of mussels found on the bio-engineered reefs were hooked mussels.

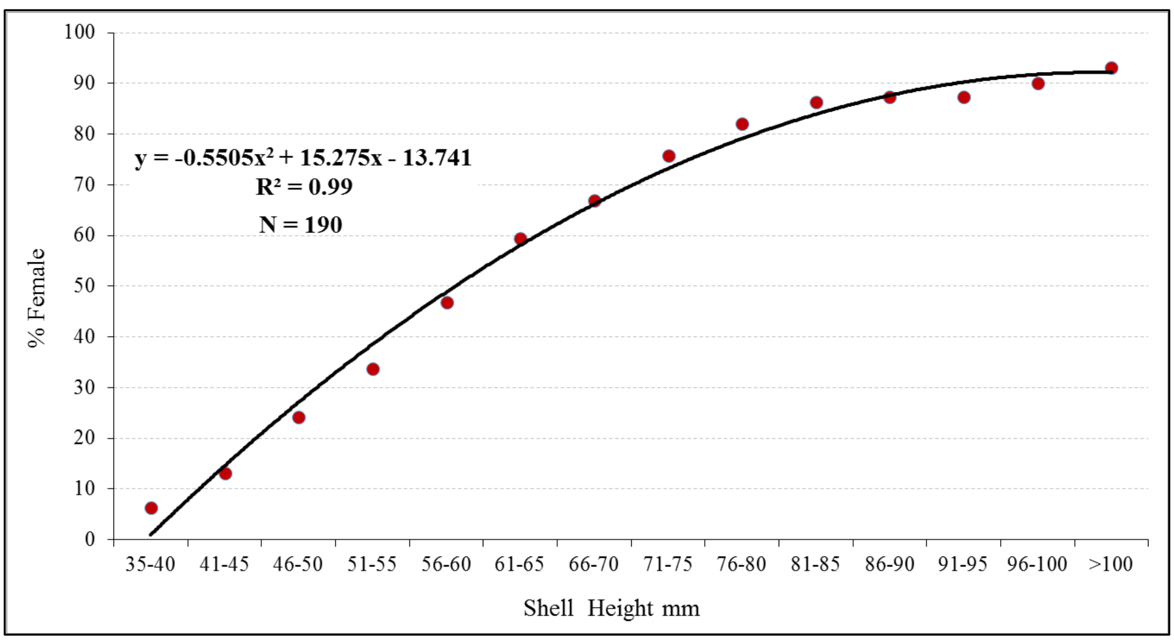


Figure 44. Shell Length at which oysters change sex to become females. Data is composite of a nearby bayou and the TE-45 structures. A Two-Way ANOVA of bayou vs. structures indicated no significant difference between locations, therefore combined for graph.

Gabion Mat Metrics

The distribution of oysters across the lengths of Gabion Mats was not uniformly distributed in any prior winter (Melancon et al. 2010, 2013), and that pattern continued in the winter 2014 assessments (Figure 45). Reaches A and B are represented in Figure 45, but not Reach E because data could not be obtained due to insufficient low tide conditions to expose the mats for visual data collection. This confirms the *a priori* assumption at the onset of monitoring in 2008 that the top of the mats, which are the least inundated and most exposed at low tides, would have the lowest oyster coverage and could develop limited emergent-type reef structure by the 7th year assessment. The data in winter 2014 shows that the greatest oyster and reef density was at mid-mat length, 3 m, with a decline as moved further down the mat (Figure 45). For clarity, the density of oysters in Figure 45 considers this decline when calculating the overall density per length of marsh shoreline; this decline in oyster density from 4 m, 5 m, and 6 m, was 23%, 74%, and 55%, respectively.

A photographic representation of percent oyster overage and reef consolidation can be seen in Figure 46 during the winter 2014 survey. Coverage was greatest at 26.5% and emergent reef at 12.4%. Emergent reef development followed the same pattern as did oyster coverage across the Gabion Mats (Figure 45). Emergent reef offers greater vertical structure and potential wave attenuation. The reasons for less emergent reef are probably the same as for less overall oyster abundance as described in the following paragraph.

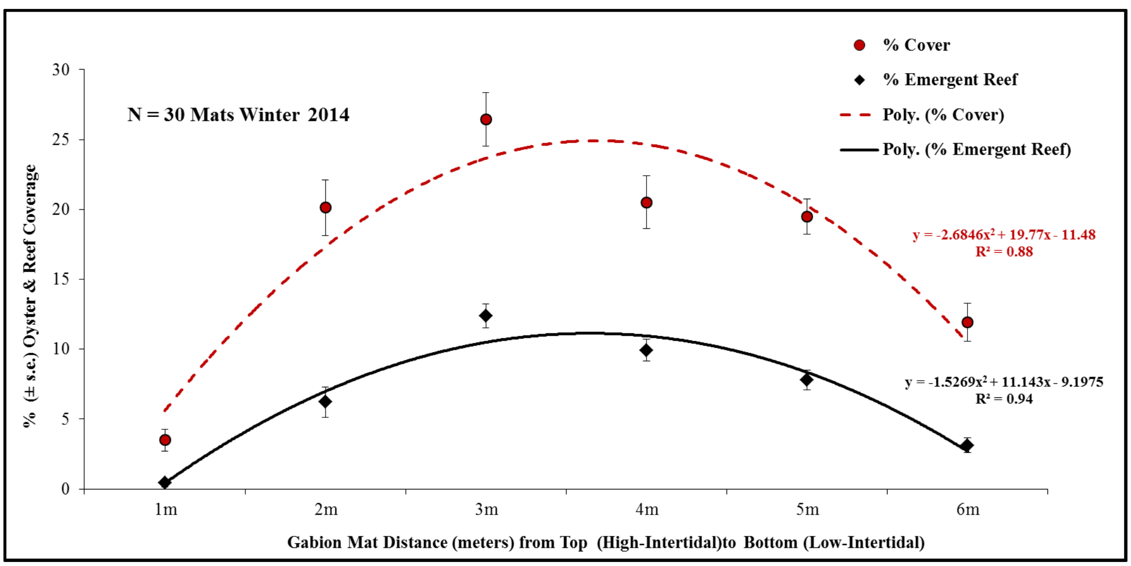


Figure 45. **Mean (± s.e.) percent oyster cover and percent emergent oyster reef across the length of a Gabion Mat in winter 2014. Only Reaches A and B mats represented; could not capture data for Reach E because of high tide conditions.**

Figure 46. **Photo showing the distribution of oysters and emergent reef across Gabion Mats at Reach- B during the winter 2014 survey, seven years post construction**.

There was another *a priori* assumption initially made in 2008 about expectations of oyster recruitment to the Gabion Mats. The assumption was that the lower end of the mats would have the densest concentration of oysters compared to the mid regions because of longer tidal inundation periods, and thus greater opportunities for oyster spat recruitment. However, this did not occur, and as the years of observations progressed, it became apparent that the lower ends of the mats were not going to develop the densest oyster coverage and reef development (Figure 45). The reasons for less oyster coverage on the lower end of the mat compared to mid mat are probably complex. However, observations suggest that major reasons are: (1) the lower end is exposed to the greatest flux in adjacent sediment disturbances from wind and waves, (2) crab abundance and its predation potential was highest because of greater inundation periods, and (3) the abrasive nature of shell and rubble upheaval from the bay and its deposit on the mats by wave activity (Figure 47). All three reasons seemingly work in combination to reduce oyster populations on the lower ends. The influence and interactions of predation and sediment and shell movement abrasiveness were not empirically documented in this project, but should be considered for monitoring in future projects that use Gabion Mats for shoreline stabilization. This second *a priori* assumption was rejected.

During the course of this 8-year project, Gabion mats were assessed four times (Figure 48); winter 2008 (1-year post construction), winter 2009 (2-years post construction), winter 2011 (4-years post construction), and lastly, winter 2014 (7-years post construction). As stated earlier in the Methods Section, the number of density quadrats was reduced during winters 2008 and 2009 because of the necessity to reduce disturbance during the early stage of the

Figure 47. Shell rubble (large inset) and shell hash (small inset) washed onto Gabion Mats at Reach A in winter 2015. Some self-generated but most washed onto mats from wave activity from bay.

project; therefore, winters 2008 and 2009 are more comparable to one another, and winter 2011 to 2014 to one another for the same reason. Therefore, general trends in data between winters (Figure 48) are more appropriate than for comparing absolute numbers. With these density caveats stated, the general overall observed trend was a reduction in numbers in the last two winter surveys as compared to the first two winters.

Gabion Mat's trend of greater densities at mid-mat during the first two winters, 2008 and 2009, (Figure 48) may be due to greater opportunity for space on newly created habitat, and therefore less competition and better survival opportunities. Also noteworthy, there was little old oyster shell and shell hash washed up on the mats from the bay during the first two years, but over time the deposits became more abundant and certainly had more of an effect on abrasive activity that potentially has the ability to reduce survival. Another variable that may have had an effect on oyster density was the spat failure in spring 2010 after the Deep Water Horizon oil spill, and a very low spring spat set in the spring of 2013. The winters of 2011 and 2014 surveys were each 1.5 years after low spring spat sets. By winter 2014, 7-years post construction, oyster densities ranged from a low of 558 m^{-2} ± 102 at Reach B to a high of 883

m^{-2} ± 118 at Reach E (Figure 53). However, all three Reaches had densities in winter that are considered good for continued oyster reef development.

Oyster shell heights appeared to be skewed to lower sizes when represented in 25 mm groupings (refer back to Figure 41), but when expressed at a higher resolution, 5 mm groups, a well-shaped bell curve develops for the Gabion Mats (Figure 49). This does not mean that there were no shell height differences between Reaches for the oyster populations, but even with these differences, well-shaped bell curves were noted at each Reach. Mean shell height differences between Reaches in such a stochastic environment where habitat differences can occur within meters or less of one another were anticipated. The cumulative shell heights of the three Reaches that progressively developed into a bell-shaped curve by winter 2011 (Figure 49) indicates that the oyster populations were not experiencing abrupt die-off of larger or smaller oysters, and therefore a good degree of population stability. The data support the assumption that such an aerially exposed and harsh wave habitat does influence the life expectancy and overall shell growth of the oyster populations.

Hooked mussels are in large numbers on the Gabion Mats. The hooked mussel exhibited a steady increase relative to the number of oysters, especially evident through years on Reaches A and B (Figure 50). Gabion Mats at Reach E did not show as distinctive an upward trend each winter survey as did Reaches A and B, but the rise in numbers at Reach E from winter 2011 to winter 2014 was still substantial, from a mussel-to-oyster ratio of 1.24 to 2.27, respectively, while oyster density did not substantially increase. Hooked mussels are routinely found with oysters along the Gulf and Atlantic coast and are more likely to settle on live oyster substrates than substrates with only shell (Bourgeois 2015).

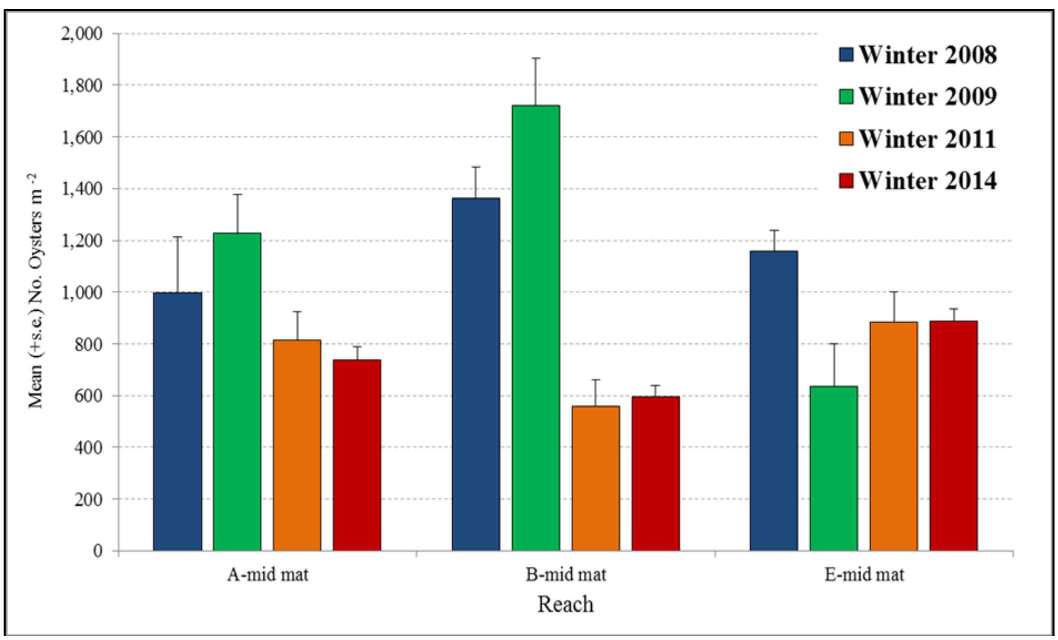


Figure 48. **Mean (+ s.e.) Gabion Mats oyster density for each winter survey. Density represented are mid-mat quadrats.**

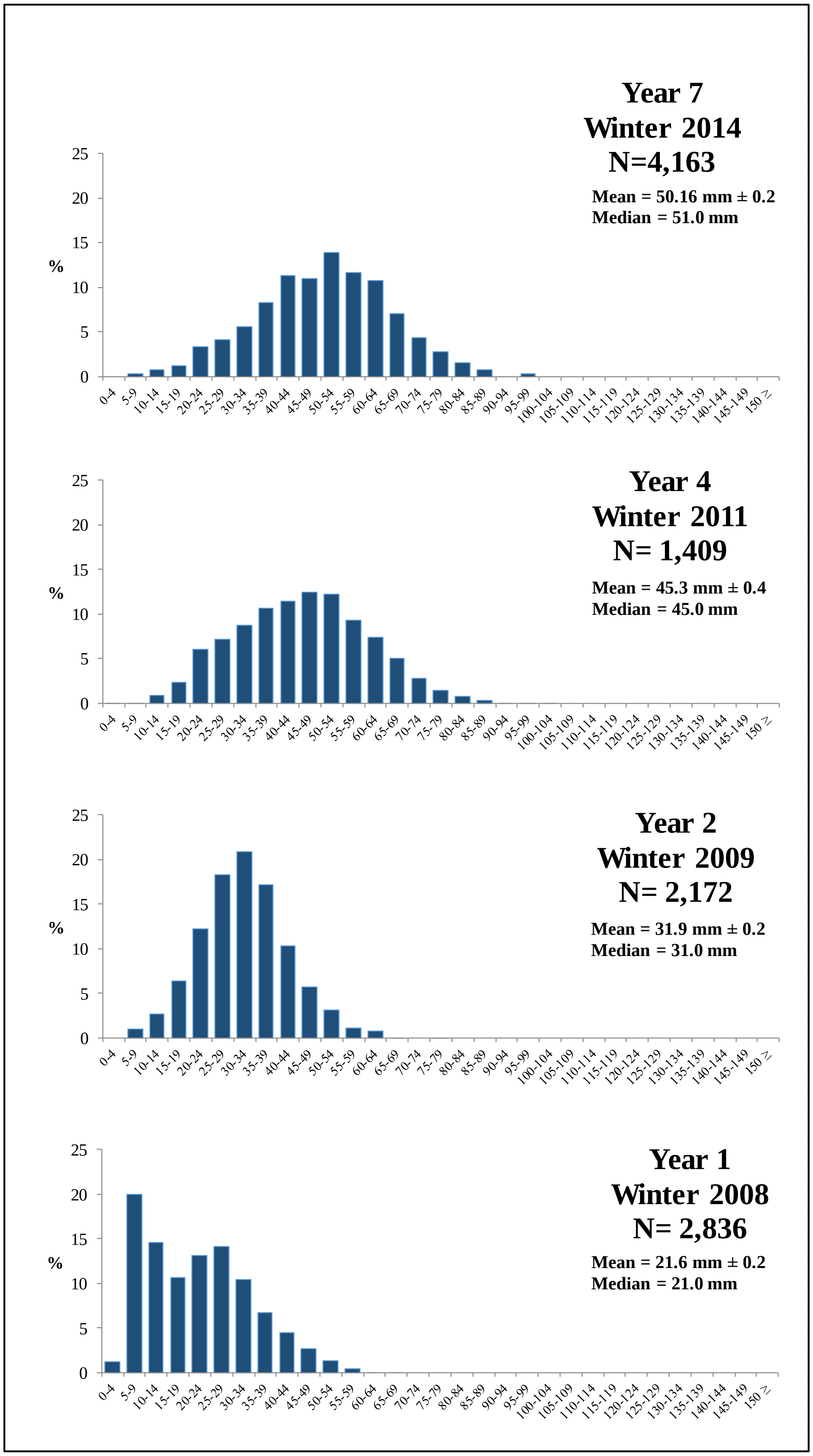


Figure 49. **Oyster Population shell height (5 mm groupings) distributions for Gabion Mats during the winter surveys. Data from all three Reaches, A, B and E combined.**

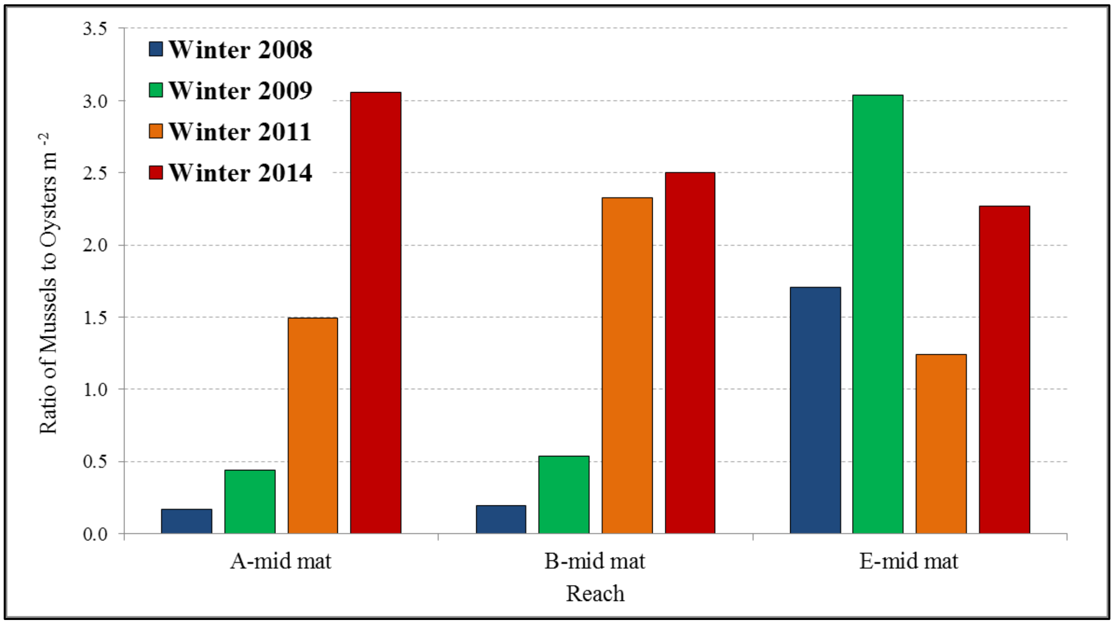


Figure 50. **Ratio of mussels to oysters on Gabion Mats by winter survey. All three Reaches, A, B and E combined.**

A-Jack Metrics

Oyster densities for A-Jacks showed a distinctive decline in numbers within all three Reaches from every preceding winter survey (Figure 51). Such decline for years one and two post construction, winters 2008 and 2009, when compared to winter 2011 was somewhat expected when one considers that the first two years was new substrate with less competition for food and space, and a very robust spring 2008 oyster spat set on quarry tiles. However, the continued significant decrease from winter 2011 to winter 2014 was a surprise, even though there was spring 2010 spat failure and a very low spring 2013 spat set on the quarry tiles. The Gabion Mats did not experience such a decline in oyster density from winter 2011 to winter 2014, but did experience the same spat failures.

Percent oyster coverage on the A-Jacks was closely tied to emergent reef, i.e. oysters showing vertical relief above the substrate. This was anticipated because of the hard flat surface of the A-jacks cement arms. By year seven in winter 2014, it became difficult to separate the two categories so they were combined (Figure 52). There was a distinct difference on the amount of oyster cover/reef from Reach A with the least to Reach E with the most. Reach E has always been considered the more dynamic of the three bay sites because of observed strong tidal currents and its position just south of several bayous that are known to be very

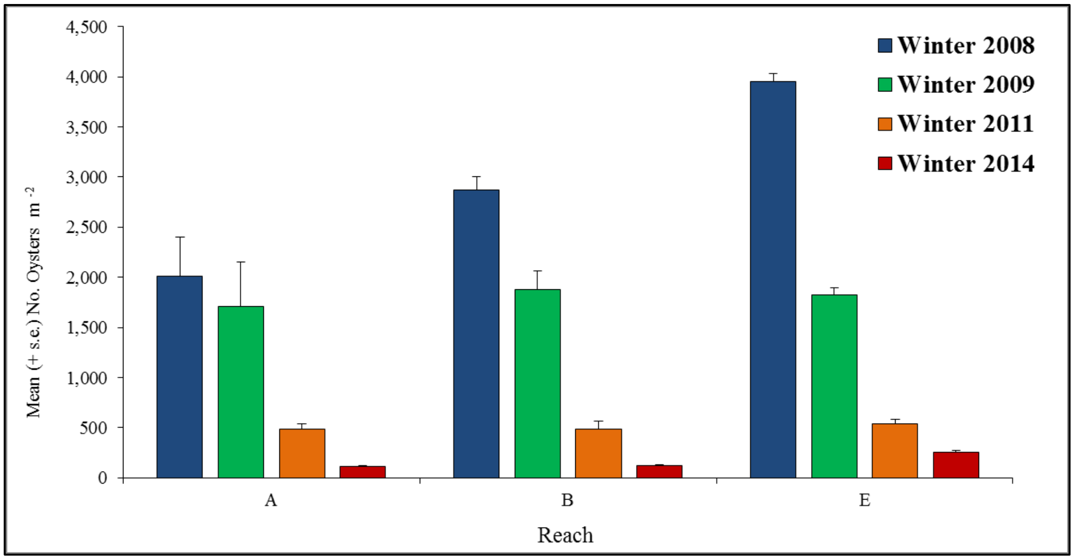


Figure 51. **Mean (+ s.e.) A-Jacks oyster density for each winter survey.**

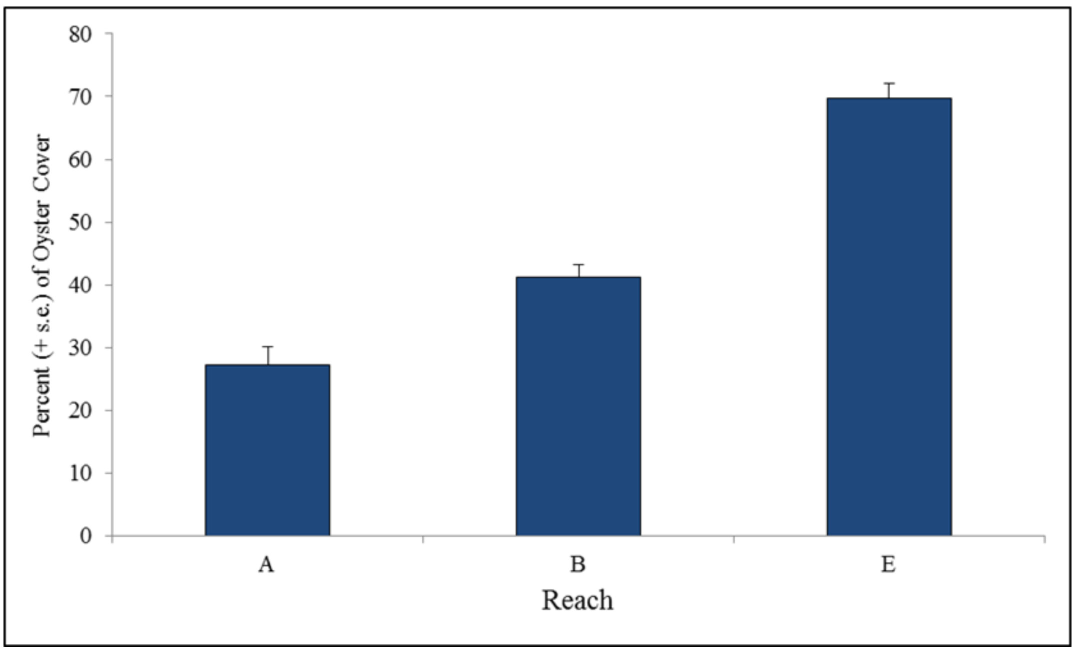


Figure 52. **Percent oyster cover by Reach on A-Jacks' arms in winter 2014.**

productive private oyster leases (personal knowledge E. Melancon), and therefore a ready supply of oyster larvae and potential spat recruits. By winter 2014, the Gabion Mats had also shown Reach E to be the dominant site for oyster density.

Mussels had also become dominant on the A-Jacks through each successive winter survey at Reaches A and B. The mussel-to-oyster ratios expanded considerably at these two reaches during the winter of 2014 (Figure 53). However, for Reach E the ratio remained relatively steady from during the winter surveys. The relative rapid increase in mussel ratio in winter 2014 at Reaches A and B cannot be readily explained, although small oyster densities at those two Reaches (Figure 51) compared to Reach E could explain some. Similarly, the continued decline in oyster density through each winter survey, but not a corresponding decline in mussel abundance could also have influenced the increased in the ratio.

By the third year post-construction there appeared to be a visual difference in the pattern of oyster abundance between the windward (facing the bay) and leeward (facing the shoreline) sides of the A-Jacks at all three Reaches. During the winter 2011 survey, eight A-Jacks were paired for preliminary work and there was a statistical difference between them, but it was not reported in the Melancon et al. (2013) report. However, during the winter 2014 report 36 A-Jacks were paired, 12 per Reach, with the leeward side consisting of the top and leeward arms, and the windward only those arms. The difference in oyster density between leeward and windward was significantly different (P <. 0.05) (Figure 54). The significant

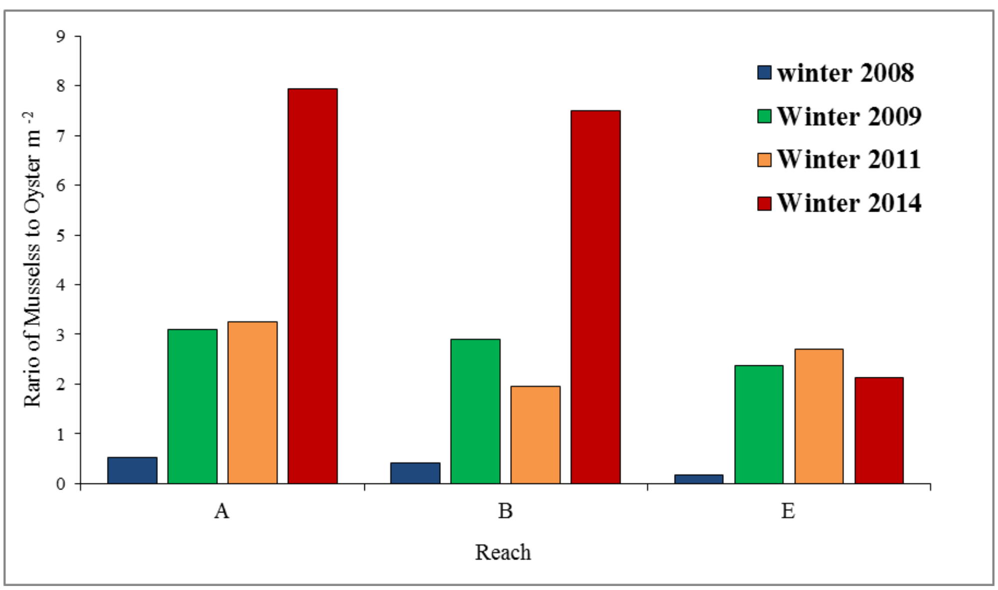


Figure 53. Ratio of mussels to oysters on A-Jacks by winter survey and reach.

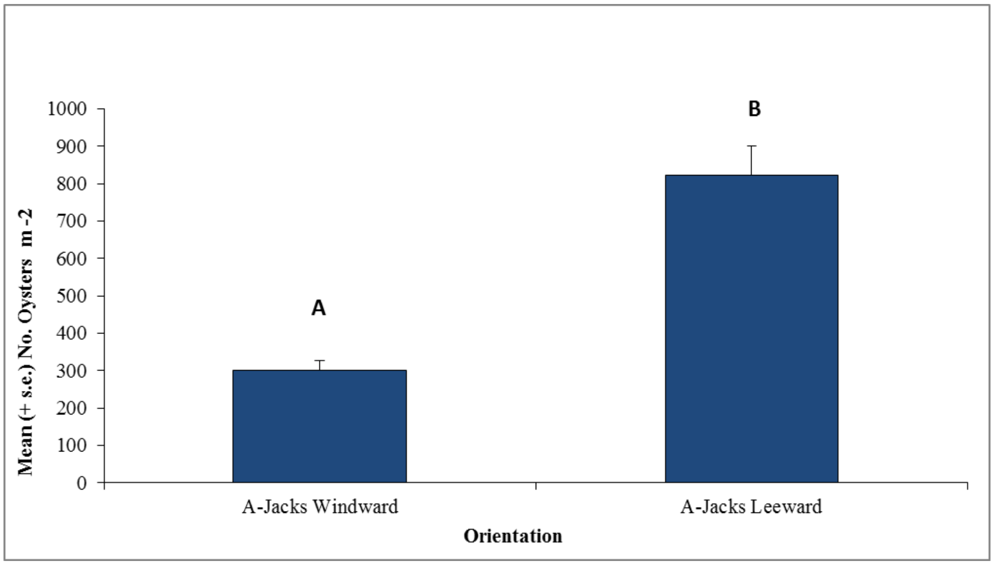


Figure 54. **Mean (+ s.e.) oyster density based on orientation. Different letters above bars represents significant difference (P < 0.05) between orientations (Paired t-test).**

difference suggests it is due to the protected leeward side of the A-Jacks as compared to the unprotected wave-dominated windward. Mussel density also reflected a significant difference (P < 0.05) between windward and leeward (Figure 55), but not as dramatic as in the oyster density difference.

The A-Jacks exhibited fragments of shells deposited by wind and wave activity similar to that of the Gabion Mats (Figure 56). However, unlike the Gabions, the shell fragments washed up from the bay and those self-generated does not appear to impede reef development because of vertical nature of the A-Jacks.

The A-Jacks exhibited a larger shell height distribution pattern than that of the Gabion Mats (Figure 57), and began to develop a more bell-shaped distribution by year two after construction, winter 2009. By year two, a few oysters had attained a shell height of 95 mm and by year four, winter 2011, a shell height of 125 mm and a relatively well-shaped bell curve. However, it is interesting that by year seven, winter 2014, the shape of the frequency distribution had become more skewed with fewer smaller size classes and a shift to larger oysters. This skewness may be due to faster growth of small oysters and the life longevity of larger oysters, especially when compared to the size frequencies of the Gabion Mats. To address the possibility that the difference in shell height frequencies on A-Jacks from that of Gabion Mats may be due to orientation to the bay and shoreline, i.e., windward wave-exposed A-Jack arms and leeward wave-protected arms, the arms were paired and a t-test performed along with size frequency distribution comparing the two (Figure 58). There was a statistically significant (P < 0.05), but from a practical standpoint probably not relevant.

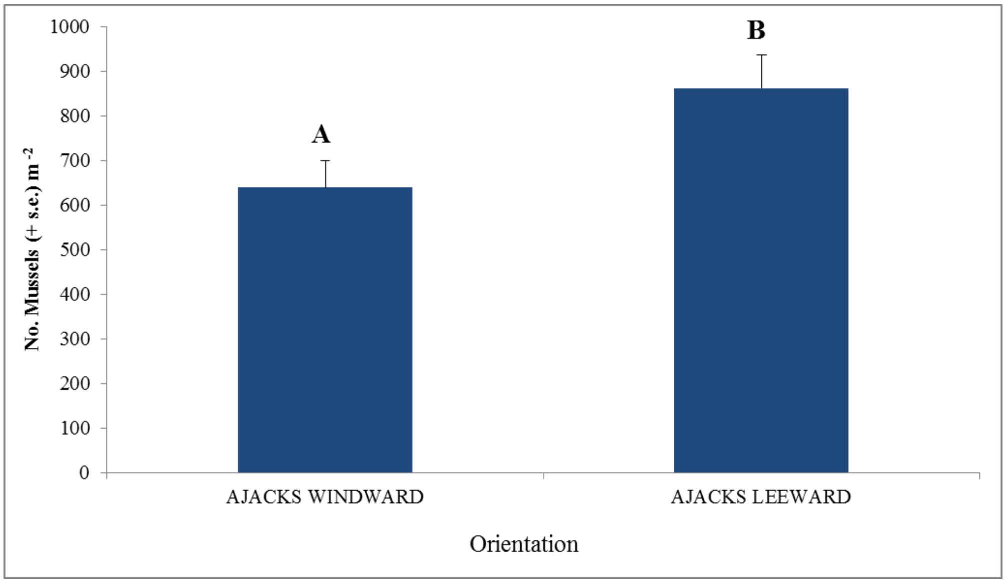


Figure 55. **Mean (+s.e.) mussel density based on orientation. Different letters above bars represents significant difference (P < 0.05) between orientations (Paired t-test).**

Figure 56. **A-Jacks at Reach-B in winter 2014 survey showing underlying geotextile mat with limestone used as a base, and the mixed in pieces of oyster and mussel shells washed up from the bay by waves and from shell chipped off reef populations. Windward (bay side) to the right and leeward (marsh side) to the left.**

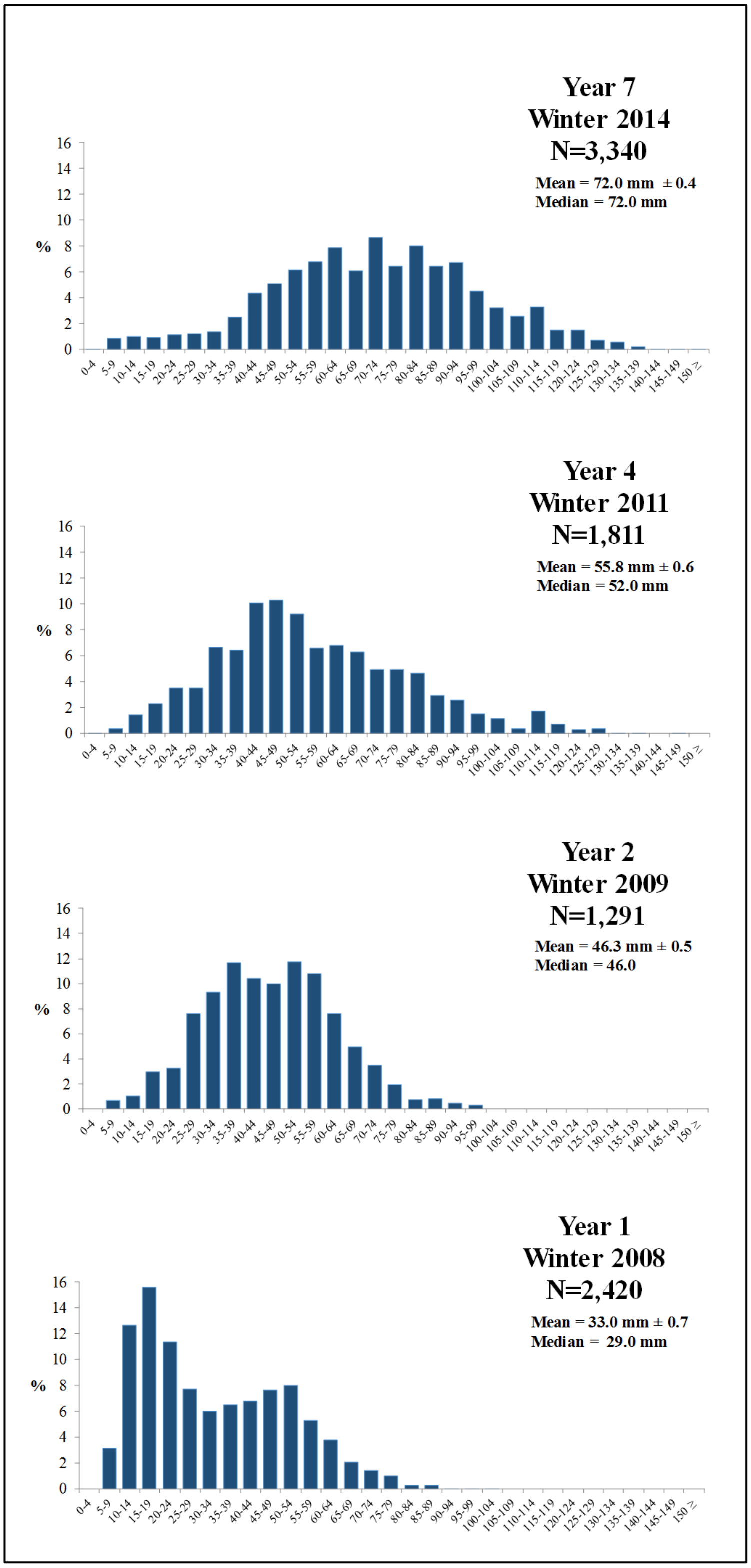


Figure 57. Oyster Population shell height (5 mm groupings) distributions for A-Jacks during the winter surveys. Data from all three Reaches, A, B and E combined.

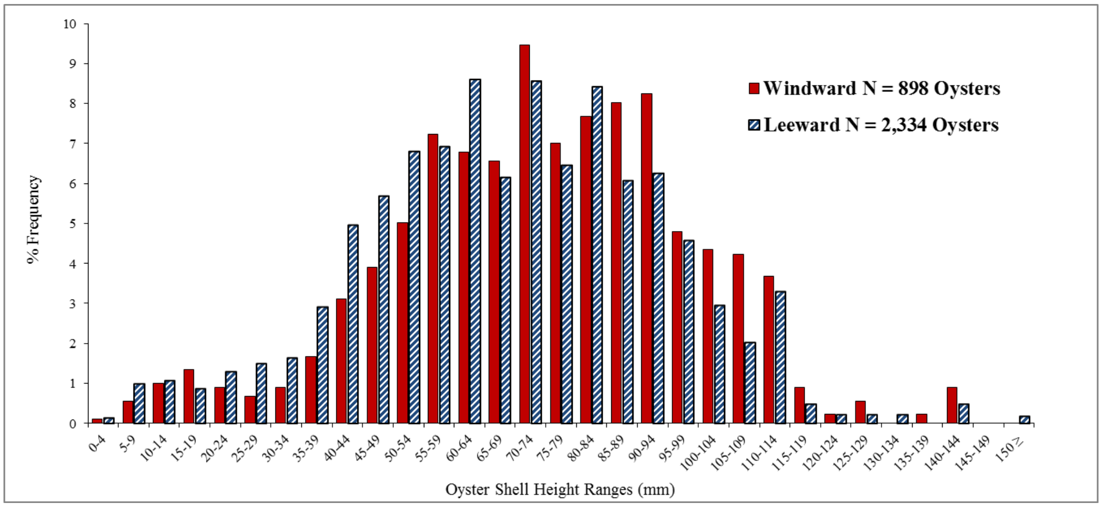


Figure 58. **Live oyster height frequency distribution between windward and leeward sides of A-Jacks from winter 2014 survey. All three Reaches of A-Jacks combined.**

ReefBlk Metrics

In the winter 2009 survey ReefBlks had the highest density of oysters (surficial+internal), 4,467 m^{-2} ± 287, when compared to the other two structure types (Melancon et al. 2010). Although the density of oysters (surficial+internal) decreased by winter 2011 survey, 2,294 m^{-2} ± 160, it was again the best when compared again to A-Jacks and Gabion Mats (Melancon et al. 2013). However, the winter 2011 oyster density data is based ReefBlks only from Reaches A and B, and none from Reach E. By the winter of 2011, there was a dramatic loss of oyster shells from the bags at Reach E.

By the second year (winter 2009) oyster shell loss within the structures was not significantly different between Reaches, suggesting that most of the shell disapearance may have actually been more of shell compaction after transport and placement at sites (Figure 59). However, by year four (winter 2011) there was a definite and significant loss of shell at Reach-E (Melancon et al. 2013) and some loss at the other two Reaches, as seen in the spread of data points (Figure 59). By year seven (winter 2014) there was wholesale loss of oyster shell at all sites (Figure 59). By the 7th year the only concentraion of oysters on ReefBlks was on the top horizontal rebars (Figure 60).

Throughout the eight years of this project the ReefBlks also exhibited a differnce in oyster abundance and shell volumes between leeward-facing and windward-facing, although more subtley than the A-Jacks. The ReefBlks for Reaches A and B exhibited a strong correlation in the direction eached structure faced by winter 2014, seven years post construction (Figure 61) with leeward always a little less shell loss than windward for adjacent blocks. However, by winter 2014 it didn't really matter much which direction the Reefblks were facing since so much shell had already been lost at all sites.

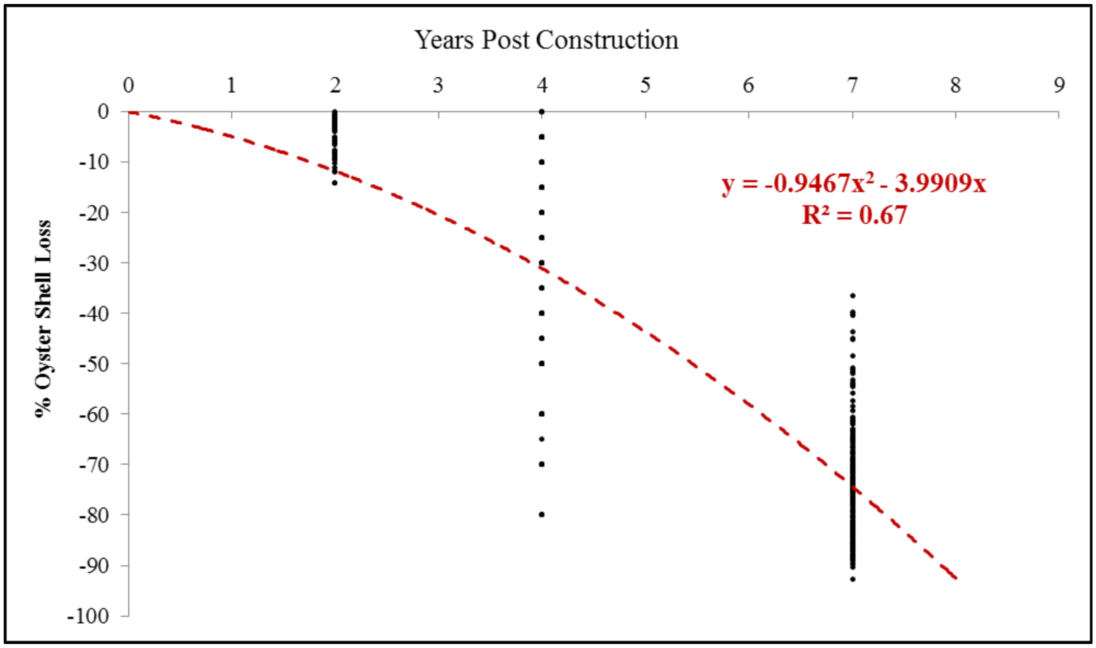


Figure 59. **Regression of percent oyster shell loss in Reefblks by year post construction.**

Figure 60. **Reach B showing tops of ReefBlk with oysters colonized on the iron rebars winter 2014. Note the absence of oyters and shell below the top rebars. The A-Jacks tie-ins are in the foreground, which show how the tops of the bay-facing arms had little recruitment.**

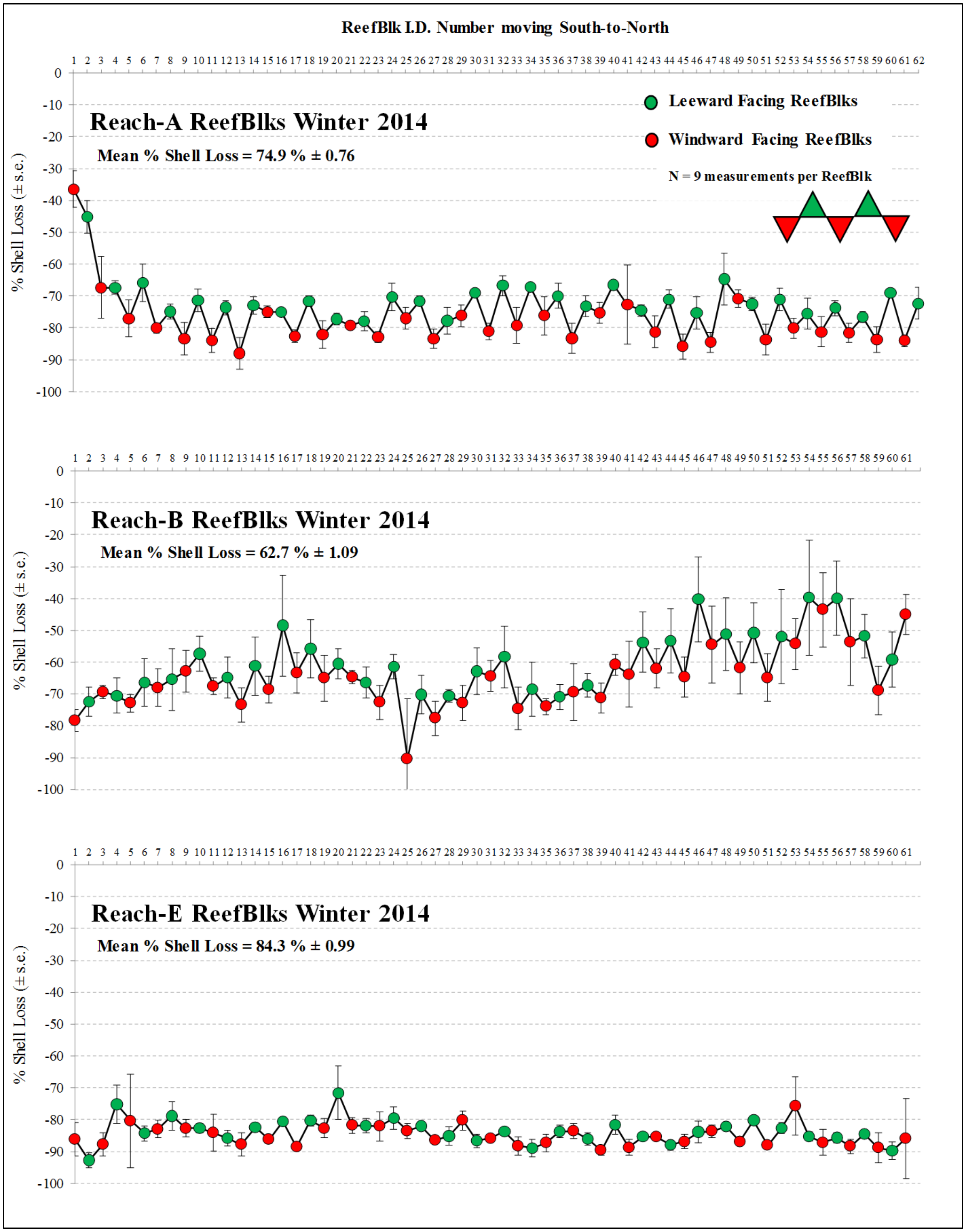


Figure 61. **Shell loss by individual triangular-shaped ReefBlk unit within each Reach by winter 2014, seven years post construction.**

In summary, Melancon et al. (2013) had shown how shell pest such as stone crabs, polycheate worms and boring sponges could make shell brittle and more prone to loss by wave activity. It is very obvious by winter 2014, seven years post-construction, that oyster shell is not a good substrate for use in the ReefBlks in an enviroment where there are shell pest, a mostly subtidal environment conducive to survival of shell pest, and relatively high-energy wave activities. In such an enviroment the Reach E ReefBlks oystershell volume was reduced by 50% or more after only five post-construction years (Figure 59). The only substrate still available for oysters to set, survive and grow were the tops of the iron rebar supports of the ReefBlk frame, which in time will also deteriorate (Figure 60). The inflence of wave energy on the ReefBlks was significant with virtually every ReefBlk facing windward (toward bay) exhibiting greater oyster shell loss than those facing leeward (toward marsh) at Reaches A and B (Figure 61). However, by the winter of 2014 the facing direction (windard or leeward) of the Reach E ReefBlks was of little consequence because these structures incurred a greater than 50% decline in shell volume by the winter of 2011.

Natural Intertidal Reefs as Reference Sites

The open bay shoreline is a very eroding and high-energy hostile habitat for oysters to recruit to and to gain a foothold and form reef. A survey of the adjacent shorelines near the three Reaches did not have any intertidal oyster populations present and other sites had to be found. The three sites used for reference were, by necessity, in more protected areas where there was less erosion and wave energy, and therefore mudflats (Figure 6). Median shell heights for each reference site in the winter of 2014 indicated that each site was significantly different from the other two sites (Figure 62). Site 3 was the most protected site from wind and wave activity with the smallest fetch distance and this may have played a role in greater shell height, whereas site 1 was the most wind/wave exposed.

A shell height frequency composite of all three reference sites by 5 mm groupings in winter 2014 indicated a lot of similarity with the A-Jacks, but not with Gabion Mats (Figure 63). The A-Jacks have a very distinctive advantage over Gabion Mats with significant leeward infrastructure protected from wind and wave activities. Gabion Mat shell height frequencies reflect the harsh reality of total exposure to large fetch distances in the bay and the resulting high-energy wave activities that have the potential to influence population growth. In addition, the Gabions' oyster populations measured were mid-mat and more aerially exposed by ebbing tides than that of the A-Jacks.

The natural intertidal reefs along the northern shore of Terrebonne Bay that are found in the local tidal cuts and inlets do not always form a contiguous reef. It is assumed that this is because of the soft mud soils and the harshness of wave activity on a shallow-sloping microtidal habitat. Therefore, oysters are often more patchy in nature and scattered along the marsh shoreline. This was the type of reference reefs used in this study, and an example can be found in Figure 64.

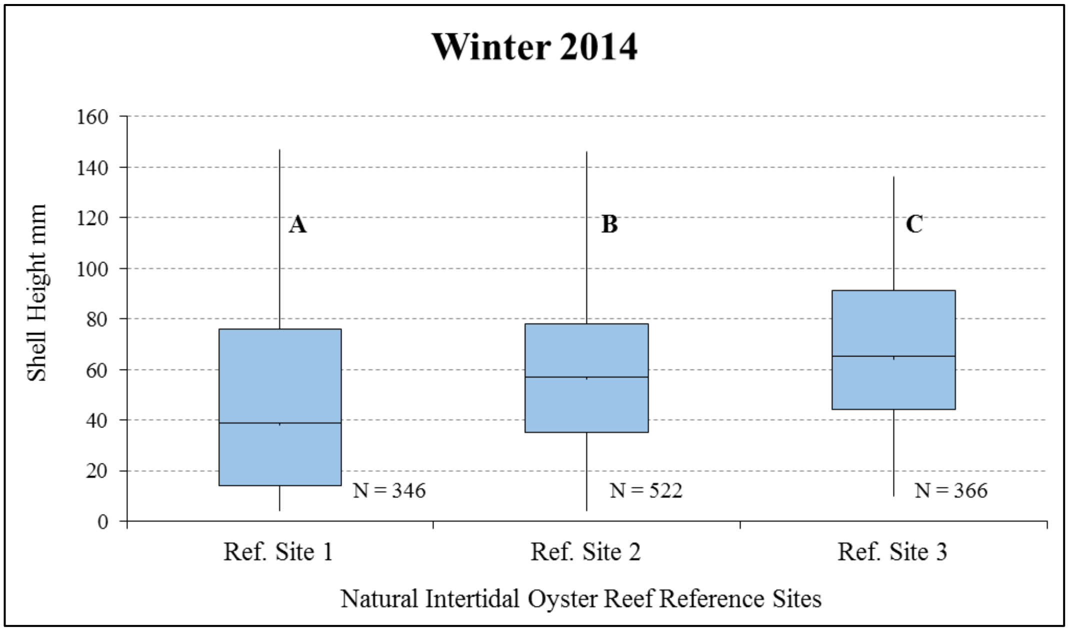


Figure 62. **Median, range and 25% and 75% quartiles oyster heights for the three natural intertidal reference sites. Letters above bar indicate if significant difference exist between sites (P < 0.05).**

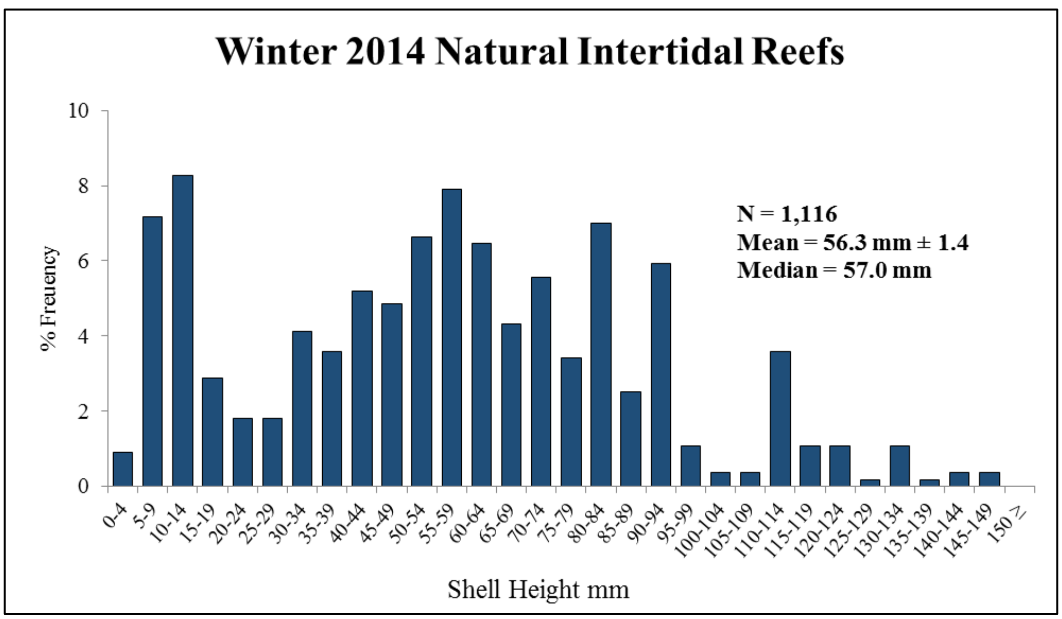


Figure 63. **Shell height frequency of natural intertidal reef populations from the combined three reference sites for winter 2014 survey.**

Figure 64. **Natural intertidal oyster reef reference site #2 exposed at low tide.**

Oyster Populations on Experimental Structures Summary

Table 5 summarizes the oyster and mussel population data collected for the TE-45 project during the winter of 2014. All data in the table are grouped by treatment, i.e., bio-engineered structure type, to evaluate the functioning of each after seven years of oyster reef development. Gabion Mats had the greatest concentrations of oysters per square meter (Tables 5 and 6), and had the lowest mussel-to-oyster ratio, and this formed the primary basis for ranking it best (Table 5). However, the A-Jacks had better overall oyster coverage and percent of population greater than 60 mm in shell length (most oysters female by 60 mm).

Based on oyster coverage, the oyster populations on the Gabion Mats are developing reef slowly compared to the A-Jacks (refer back to Figure 36 and to Tables 5 and 6). Another factor must also be considered in assessing the overall ranking of Gabion Mats versus A-Jacks in terms of oyster reef development. The Gabion Mats with its oyster populations are completely exposed to the harsh environmental conditions of the TE-45 shorelines, e.g., windward exposure to high wave energy generated by significant fetch distances across the bay. The amount of shell rubble deposited on the mats show the results of this harsh habitat (refer back to Figure 47). However, when one compares how A-Jack oyster populations are developing on opposite sides of this structure, it becomes evident that the great majority of these populations are emerging and maturing on the leeward side and therefore significantly protected from the harsh bay (windward) conditions. Are the A-Jacks' oyster population densities biased and inflated because of leeward protection, which will be eventually lost as the structures deteriorate and subside? That question cannot be answered in a short 7 years of assessment, but the possibility cannot be ruled out.

Table 5. **The winter of 2014 (7 years post-construction) oyster population metrics by treatment.**

Treatment	**# Oysters per Linear Meter of Shoreline**	**# Oysters/m² of Bay Bottom (aerial view)**	**# Hooked Mussels/m² of Bay Bottom (aerial view)**	**% Oyster Coverage on Structures**	**% Oyster Pop. ≥ 60 mm (~2.5 in.)**	**Potential for Continued Oyster Reef Development**
Gabion Mats **(1)**	2,219 ± 135	740 ± 45	1,918 ± 273	26.5 ± 1.9	28.2	**Best**
A-Jacks **(2)**	490 ± 36	490 ± 36	2,352 ± 220	46.0 ± 2.5	68.5	**Good**
ReefBlks **(3)**	--	--	--	--	--	**FAILED**

(1) Gabion Mats: only surficial (top-layer of rocks) at the mid-mat sites represented for density per square meter, between 3-4 m distance from top of a mat (refer back to Figure 50). However, the entire bottom half of mat (3 m in length) used for calculating oysters per linear meter of shoreline (refer back to Methods).

(2) A-Jacks: all scraped oysters per site used, and adding together leeward and windward facing arms of structures per site; separately, windward oyster density = 301 m^{-2} ± 25, and leeward oyster density = 823 m^{-2} ± 77.

(3) ReefBlks: failed because greater than 50% of oyster shell lost in structures at all three Reaches.

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 6). 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 during the study period (2007-2014). 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 shoreline erosion occurred behind the Gabion Mat treatment until the 2010-2012 interval, and the minor transgressions that did occur during and after this interval appear to be a result of structure settlement and placement issues. The shorelines behind the ReefBlk and A-Jack treatments eroded at comparable rates (Table 6), and the wind data suggest that these structures are more sensitive to cold front derived shoreline erosion than the Gabion Mats. Therefore, the Gabion Mats functioned at a higher level than the other treatments in reducing the erosion rates.

Table 6. Structure cost-effectiveness variables and rankings at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

Structure	***Structure Cost* $/m ($/ft)**	***Shoreline Change 2007-2014* (m/yr)**	***Oyster Coverage (%)***	***# Oysters per Linear Meter of Shoreline***	***Structure Volume Change* (m3)**	***Structure Settlement* (m)**	***Rank***
Gabion Mat	$1,758 ($536)	-0.28	26.5 ± 1.9	2,219 ± 135	-33.7	-0.21	***1***
A-Jack	$1,510 ($460)	-1.22	46.0 ± 2.5	490 ± 36	-55.3	-0.14	***2***
ReefBlk	$1,310 ($399)	-1.19	Failed	Failed	-12.3	-0.11	***3***

The ReefBlk treatment recorded lowest sediment deficit for the 2008-2015 interval (Table 6) and was the only structure to experience a volume gain in its lee. At Reaches A and B the ReefBlks showed minimal aggradation. The Gabion Mat treatment documented the second lowest leeward sedimentation deficit, and the A-Jack treatment had the largest mean volume loss (Table 6). These differences in sedimentation were not significant ($P > 0.05$). The variation in sedimentation was relatively high for all structure types. Reach E had smallest sediment deficit and considerably lower variation than the other reaches. Therefore, the ReefBlk treatment was more proficient than the other treatments in retaining sediment in its lee.

The weighting of the structures appears to be driving settlement rates. The Gabion Mat (heaviest structure) treatment recorded the highest settlement rate. The A-Jack (median weighted structure) treatment had the second highest settlement rate and the ReefBlk (lightest structure) had the lowest (Table 6). However, the differences in settlement were not significant ($P > 0.05$). The variation in structure settlement was similar for all structure types. Structures at Reach E had higher settlement rates and lower variation than Reaches A and B due to poorer soil bearing values (Eustis 2002).

The cost-effective ranking of the TE-45 treatments are as follows - Gabion Mats (1), A-Jacks (2), and ReefBlks (3) (Table 6). 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. While the A-Jack and ReefBlk treatments reduced shoreline erosion rates, these rates were significantly higher than the Gabion Mat rate. In addition, these treatments seem to be vulnerable to cold front initiated shoreline erosion. The Gabion Mats had the greatest concentrations of oysters per square meter and had the lowest mussel-to-oyster ratio. Though the A-Jacks had better overall oyster coverage and higher shell heights than the Gabion Mats, this structure also had a protected side (leeward) that enhanced oyster growth and maturation. 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.

Additional Investigative Efforts

During the eight years, six (6) Master of Science theses were successfully completed by students working on the TE-45 project. The focus of the research included:

- Assessment of oyster recruitment and reef development on bio-engineered structures two-year post-construction (Linson 2010),
- Influence of a high-energy habitat and degree of tidal immersion time on oyster population development (O'Malley 2012),
- Abundance of populations of associated fish and invertebrate species on and near the fabricated structures (Bacheler 2013),
- Fabricated structures' influence on fauna immigration and emigration along the fringing marsh (Bacheler 2013),
- Diet of fish species associated with the fabricated structures (Bruce 2013),
- Predation rate on structures' oyster and hooked mussel populations (Bourgeois 2015),
- The attraction of hooked mussels to live oysters versus oyster cultch (Bourgeois 2015), and,
- The filtration rate of a fabricated reef dominated by oysters and mussels (Buter 2015).

The following excerpts are the Abstracts from the theses. Each thesis is included as Supplements 1-6 with this report.

Thesis Supplement #1
Initial Oyster Reef Development on Bio-engineered Living Shorelines Structures used for Erosion Control in a Louisiana Salt Marsh by Mark Linson (2010)

This study documents the first two years of an on-going eight year project to document oyster recruitment and reef development on three different bio-engineered structure types used to armor the northern shoreline of Lake Barre located within the Terrebonne estuary system. The structures are Triton Gabion Mats®, ReefBlks®, and A-Jacks®. The study objective was to determine which structure type, if any, initially recruits oysters the best and begins the process of reef development. In conjunction with Nicholls State University's eight-year study, the Louisiana Office of Coastal Protection and Restoration (OCPR) is investigating which structure may best reduce the marsh shoreline erosion rate.

Results of the initial two-year assessment indicate that sufficient oyster spat were available in the bay for potential recruitment to the structures and to an intertidal reef nearby that was used as a reference site. Thus, all three structures had opportunity for oyster recruitment, and all did exhibit the development of oyster populations. This indicates that survival and growth is occurring sufficiently to potentially establish reef.

In the two years since construction, oyster densities (surficial + interior) for all of three structure types have exceeded the oyster density found at a natural intertidal reef site, 1,936/ m^2 ± 944, and with less variability. Gabion mats, 6.1 m long by 1.5 m wide by 0.3 m deep, were subdivided into three intertidal zones based on distance from top of mat, which had the least time of tidal inundation. Sufficient oyster densities on the gabion mats occurred at mid-intertidal, 3,300/m^2 (±483) and low-intertidal, 2,194/m^2 (± 294), mid-intertidal. The A-Jacks and ReefBlk structures, both placed foreshore and rising to a maximum of 0.6 m in height above bay floor, exhibited no significant difference in oyster recruitment densities ($p<.05$) between leeward and windward sides. A-Jacks oyster density averaged 4,629/m^2 (± 346), while ReefBlks averaged 4,466.60/m^2 (± 245).

The interior oysters for all three bio-engineered structure types, confined to crowded interstitial spaces, realistically have little to no chance of growing to a size that will contribute to emergent reef and protect a shoreline. It is the surface (surficial) layer of oysters that will recruit new generations that can potentially develop consolidated reef. Focusing only on the surficial oysters, densities by winter 2009 were for Gabion Mats, upper mat 401/m^2 ±108 oysters, mid mat 1,196/m^2 ± 148 oysters, and for lower mat 781/m^2 ± 105 oysters. Surficial density for A-Jacks was 542/m^2 ± 67 oysters, and for ReefBlks 1,167/m^2 ± 129 oysters.

All three structure types exhibited oyster size frequency (shell height) was used as an index to describe population complexity. All three structures exhibit good size distributions indicating the survival and growth necessary to establish a reef. After two years, oysters exhibited growth on all structure types comparable to a natural intertidal reef. The A-Jacks structures had the largest oysters at an average of 46.3 mm (± 4.0) shell height, followed by ReefBlks had an average oyster shell height of 40.2 mm (± 4.2), and then Gabion Mats with a low-intertidal average shell height of 33.9 mm (±3.4), which was comparable to the natural intertidal lengths of 32.4 mm (± 1.1).

Surficial barnacle and hooked mussel populations increased significantly from 2008 to 2009, this could pose a threat to oyster reef development in the future because of increased competition for food and space.

Thesis Supplement #2

The Effects of Wave Energy and Emersion Regime on Initial Oyster Community Development on Constructed Oyster Reefs by Daniel Anthony O'Malley (2012)

Oyster reefs, *Crassostrea virginica*, provide ecosystem services including provision of essential fish habitat, water filtration, carbon sequestration, and wave energy attenuation. Wave energy attenuation is an important ecosystem service in Louisiana, which is losing coastal wetlands, in part due to erosion, at an alarming rate. Several projects are currently being planned or implemented in the Northern Gulf of Mexico to establish oyster reefs along the shoreline for the purpose of attenuating wave energy and slowing the rate of shoreline erosion. One such project is TE-45, located in Lake Barre, on the Northern shore of Terrebonne Bay, Louisiana. TE-45 is a demonstration project that includes three different breakwater structures designed to develop oyster reefs. The structure types used are; Triton gabion mats, A-Jacks, and Reefblks.

The goal of this study was to determine the effects of wave energy and tidal inundation regime on initial oyster reef development. Objectives included determining spatial and temporal recruitment patterns of oysters and barnacles, *Balanus sps*., determining the amount of water motion at different areas, determining percent of time sites were exposed to air, and determining differences in oyster reef community parameters, including the presence of mussels within the Mytilidae family.

Plastic mesh bags filled with one layer of oyster shell were placed on structures throughout the TE-45 project site and in a nearby natural intertidal reef. The percent of time these bags were exposed to air was determined using Hydrolab™ MS-5 minisondes, which recorded the water depth at two locations within the study site every hour for the duration of the study. Wave energy regime was determined by the dissolution rate of plaster of paris clod cards placed throughout the study sites relative to fetch distance. Shell bags were deployed on 10-11 May 2010 and retrieved on 30 June 2011. Shell bags were analyzed in the lab to determine live oyster, mussel, and barnacle densities, oyster and barnacle percent mortality, mean oyster and mussel length, mussel:oyster ratio, total sessile community biomass, and live oyster 10 mm size-class length frequency.

Bimodal recruitment peaks in the spring and fall were documented for oysters and barnacles. The natural intertidal reef was exposed to the air more frequently than the oyster reef breakwater structures. Wave energy was also less at the natural reef than at two of the three reaches of breakwater structures. Community biomass and oyster density were both greater at the natural reef than at the breakwater structures. Mean mussel length and mussel density did not differ by reach, structure type, emersion (aerial exposure) regime, or wave energy regime. Barnacle density was greatest at Reach E, but did not differ by structure type, emersion regime, or wave energy regime. Percent barnacle mortality varied greatly among reaches and structure types, but trends of greater barnacle mortality at low wave energy sites and at high emersion sites were evident.

The mussel:oyster ratio was greatest at A-Jacks, and within the group of similar structures excluding A-Jacks, was greater at high wave energy sites than at low wave energy sites. Oyster length frequencies differed between windward, high wave energy Reefblks and interior, low wave energy Reefblks at five of six sites. The natural reef site is experiencing better reef development than the breakwater structures.

Given the greater biomass and oyster density at the protected, low wave energy natural intertidal reef site, and the greater mussel:oyster ratio at high wave energy sites, it is concluded that high-intensity wave activity negatively influences the development of oyster reef. This suggests that although all three constructed structures are recruiting oysters, long-term and sustainable reef development in a high-energy habitat may be difficult to achieve the same similarities in reef metrics as a more sheltered natural intertidal reef.

Thesis Supplement #3
Constructed Oyster Reefs Assist in Creation of Habitat for Fish and Macroinvertebrate Assemblages in a Louisiana Estuary by Victoria Bacheler (2013)

Coastal habitats in southern Louisiana are experiencing high rates of land loss, due to shoreline erosion. These habitats, which include highly productive estuaries, are extremely important for numerous nekton populations, especially commercially and recreationally important fish species. Several tactics have been used to reduce the shoreline erosion rate, including placement of constructed reefs in high wind and wave environments, which aid in building oyster reefs. Oyster reefs and the adjacent intertidal marshes are an important aspect of Louisiana coastal wetlands. Many fishes, mollusks, and crustaceans rely on oyster reefs and intertidal marshes for survival, and the eastern oyster (*Crassostrea virginica*) provides services to many species. The oyster creates valuable habitat, which can be used for nursery grounds, feeding areas, and refugia for a variety of mobile fauna. Constructing reefs that utilize a natural element of the ecosystem (oysters) to protect sensitive marshes from erosion seems like an ecologically sound idea. However, it is unknown whether constructed reefs benefit nekton assemblages like natural oyster reefs. The first goal of this study was to describe the nekton assemblages around three types of constructed reefs (A-Jacks, Triton Gabion mats, and ReefBlks) in comparison to natural, intertidal oyster reefs at three sites within Terrebonne Bay, Louisiana. The second goal of this study was to determine whether the constructed reefs negatively affected nekton use of intertidal marshes adjacent to constructed reefs.

Nekton assemblages included a diverse array of fish and macroinvertebrates around constructed and natural reefs based on samples collected from March 2011 through September 2012. Combining all three gear types (minnow traps, gill nets, and crab traps), a total of 8,194 individuals of 53 species were collected during this study.

Few significant differences were found between natural and constructed reefs in means for fish and macroinvertebrate abundance (catch per unit effort: CPUE), blue crab abundance, number of male blue crabs, number of female blue crabs, species richness, species diversity (H´), and fish and macroinvertebrate biomass. Community analyses (nMDS, ANOSIM, and

SIMPER) also showed no differences in nekton assemblages between constructed reefs and natural reefs.

Bottomless lift nets were used to compare the nekton assemblages among intertidal salt marshes with and without adjacent constructed reefs. There were 3,309 individuals (33 species) captured with 80 lift net samples from March 2012 through November 2012. Statistical analyses indicated no differences in means for density (individuals/m2), species richness, species diversity (H´), or total biomass among treatments. Community analyses (nMDS, ANOSIM, and SIMPER) also showed no differences in nekton assemblages among treatments.

The results of this study, suggest the following conclusions: 1) The three constructed reefs (A-Jacks, Triton Gabion mats, and ReefBlks) seem to be comparable to natural oyster reef in providing habitat for a diverse array of nekton and are appropriate for use in protecting coastal environments from erosion, and 2) A-Jacks®, Triton® Gabion Mats, and ReefBlks do not appear to limit nekton use of adjacent, vegetated, intertidal habitats.

Thesis Supplement #4
Diet Comparisons of Fish Associated with Constructed and Natural Reefs of *Crassostrea virginica* by Maggie Bruce (2013)

Reefs of *Crassostrea virginica* are fish-aggregating habitats because the niches reefs create provide shelter for inhabitants from predation, while small bivalves provide a food source for foraging crustaceans and juvenile fish species. The objective of this study was to quantify oyster reef prey species in the stomachs of predatory fish associated with the constructed and nearby natural intertidal oyster reefs. It was hypothesized that diets, fullness index, and percent empty stomachs between constructed and natural oyster reefs would be similar for all captured fish species.

Fish were captured using gill nets, hook-and-line, and crab traps from 14 October 2011 to 3 November 2012. A total of 383 fish were caught and 16 species were used in the diet analysis study. Fish stomachs were excised and contents identified to the lowest possible taxon and categorized as mollusk, crustacean, vegetation, fish, worm, or unidentifiable. An overall similarity in diets, fullness indices, and percent empty stomachs between fish captured at natural and constructed reefs supports the hypothesis that fish are utilizing artificial reef food resources in similar ways as natural reefs. Therefore, it is concluded that the oyster reefs developing on the ReefBlks, A-Jacks, and Gabion Mats of TE-45 provide the same or comparable resources as nearby natural intertidal oyster reefs. No distinction is made between the three constructed reef types.

Thesis Supplement #5
Predation, Recruitment, and Reef Development of Hooked Mussels, Ischadium recurvum, and Eastern Oysters, Crassostrea virginica, On Fabricated and Natural Oyster Reefs by Caleb Paul Bourgeois (2015)

Oyster reefs provide valuable ecosystem services including shoreline protection in intertidal areas. We tested the effectiveness to perpetuate natural oyster reef function of three fabricated reef structures (Gabion Mats, A-Jacks, and ReefBlks), part of the CWPPRA Terrebonne Bay Shore Protection Demonstration (TE-45) project, as well as nearby natural intertidal reefs located in Terrebonne Bay, Louisiana. We measured the ecosystem functions of recruitment and predation of hooked mussels, *Ischadium recurvum*, and reef development of eastern oysters, *Crassostrea virginica*, associated with natural and fabricated oyster reefs.

We tested if percent mortality of hooked mussels was different between the three fabricated structures and natural intertidal oyster reefs. In four two-week, and one four-week experimental trial during the spring through fall of 2013 we measured the percent mortality of hooked mussels using three predator exclusion cages: open, partially closed, and closed. Cages were fastened to the fabricated reefs along their major axis of orientation (horizontal, vertical, and inclined), and concurrently placed on the flat to gently sloping bottom sediments at the natural reefs. There were no statistically significant differences in mussel percent mortality between the four reef structure types. However, as expected, percent mortality was significantly higher ($P < 0.05$) in open and partially closed cages than in closed cages. Previous studies at TE-45 have found that blue crab abundance, a major bivalve predator also observed in abundance in our study, were similar between all three fabricated reef structure types and natural intertidal reefs. Our data concludes that because multiple predators are present and actively feeding along fabricated reefs, that those predator-prey interactions on hooked mussels are not limited by physical characteristics of the reef, e.g. shape, size, vertical relief, and composition.

In another study, from 31 July to 3 November, of 2013, in one continuous experimental trial, we measured oyster reef development along fabricated reefs and natural intertidal reefs. Hatchery raised oysters attached to ceramic quarry tiles were placed in similar predator exclusion cages as the mussel experiment, and then deployed at the TE-45 fabricated structures and at natural reefs. After a 95-day period, predator exclusion cages were collected and the number of oysters per tile, original plus recruited spat, was enumerated. The mean number of oysters per tile was significantly higher ($P < 0.05$) at natural reef sites for all three cage types than at the fabricated reef types. Overall, the mean number of oysters per tile was significantly higher ($P < 0.05$) in closed cages than in open cages. When exclusively assessing the three fabricated reef types, there were no significant differences in the mean number of oysters per tile by cage type ($P=0.541$) and by structure type ($P=0.913$). Our data concludes that although reef development was dominated by the natural reef sites, the ability of the three fabricated structures were equally able to allow oyster reef development based on their structural differences, albeit significantly less than natural reefs. Additionally, the natural reefs used in this study were located in more protected bays with much smaller fetch distances compared to the fabricated reefs. As a result, natural reefs were often exposed to less wave energy, therefore potentially increasing oyster reef development.

We also tested the effect of live adult oysters on the recruitment of hooked mussels and oysters from March to October of 2014. Paired experimental mesh recruitment bags, one containing oyster halfshell and the other containing oyster halfshell with live oysters, were placed in triplicate samples along fabricated and natural reefs. The paired experimental bags were collected and replaced monthly, and the mean number of individual mussels and oysters that recruited per bag was enumerated. Hooked mussels recruited every month from March to October with a peak in March, while oysters recruited in mass during June and few in the other months. This early-summer oyster recruitment pattern is typical in the northern Gulf of Mexico. Overall, for all fabricated and natural reef types, hooked mussels recruited significantly more to mesh bags containing live oysters ($P < 0.001$) than mesh bags containing halfshell only. Oyster recruitment density was overwhelmingly greater at the natural reefs. However, we found no significant differences for oyster recruitment between the paired substrate types (halfshell vs. live + halfshell) except at Gabion Mats ($P < 0.05$).

Results from the recruitment experiments indicate that hooked mussels settle consistently throughout the spring, summer, and fall, and that there is an obvious preference to settle on established oyster, most likely due to chemotaxis attraction. Oyster spat had no significant preference for live oysters, which could indicate a preference for any firm substrate in the estuary. The greater number of spat collected at the natural reef sites could be a result of the exposure to high-energy wave events experienced at TE-45.

Thesis Supplement #6

Seston Clearance Rates of Bivalves on Living Shoreline Oyster Reefs from a Northern Gulf of Mexico Estuary by Kristin Nicole Buter (2015)

Oyster reefs have been associated with the potential for high filtering capacities, which can significantly influence and regulate primary production and water quality. Oyster reefs have also become an international central focus as a potential perpetual living resource for coastal shoreline wetlands erosion protection. However, few field experiments exist that have documented *in situ* data to support the assumption of great water filtering capacity that is often cited as an important ecological benefit to these living-shoreline erosion-control habitats. Additionally, there are no known studies from oyster reefs from Louisiana and other Gulf states. Therefore, an *in situ* experiment was designed and implemented to quantify changes in seston, primarily chlorophyll-a, associated with a seven-year old living-shoreline oyster reef that has become established on fabricated A-Jack structures along the northern shore of Terrebonne Bay, Louisiana. The living reef and A-Jacks complex is part of a larger federal-state funded project documenting oyster reef development and shoreline erosion control.

We sampled A-Jack structures that were placed in different locations along the northern shores of Terrebonne Bay, Louisiana, with all placed adjacent and parallel to the marsh shoreline. Tidal flow around the structures and along the open-bay shorelines is very dynamic and always in flux. Therefore, to facilitate upstream and downstream flow measurements, a portable inexpensive Visqueen sheathing flume was designed and used to direct water flow across the reefs. The flume design was ideal for sampling in a shallow and dynamic bay environment, and could be set up and taken down in one hour or less. The flume easily sealed along the bay bottom to allow for accurate calculations of water volume tidal exchange across the studied reef, while also tall enough to reduce gentle breezes that could interfere with the direction of tidal flow currents over the reef. Initial i*n situ* measurements for chlorophyll-a, turbidity (NTU), dissolved oxygen (LDO) and water temperature across the reefs were begun in June 2013 through October 2013, and again the following spring through fall from May 2014 to August 2014.

Fourteen sampling days resulted in sufficient data from each A-Jacks Reach to calculate individual clearance rates. Nine of the fourteen sampling dates resulted in a significant decrease of chlorophyll-a, the representative parameter for seston. The nine sampling days where there was a significant reduction of chlorophyll-a were analyzed separately, along with analysis of the fourteen days overall, because they were believed to best represent seston clearance. Nine of the fourteen sampling days resulted in a significant decrease of dissolved oxygen, but not necessarily on the nine days where there was a significant decrease in chlorophyll-a. Only three sampling days resulted in a significant decrease in turbidity.

The dominant benthic filter feeders at all three Reaches of the A-Jack structures are oysters (*Crassostrea virginica*) and hooked mussels (*Ischadium recurvum*). The average number of bivalves per square meter was highest at Reach B, lowest at Reach E, and Reach A was intermediate. Oyster densities per square meter among Reaches were significantly different ($P < 0.05$) with Reach E having the greatest density and Reach A having the smallest, while Reach B was intermediate. By contrast, hooked mussel density was the smallest at Reach E and the largest at Reach B, with Reach A intermediate.

The average percent removal of chlorophyll-a (Chl-*a*) over fourteen sampling days was 8.47% ± 3.92, with a range of -14.71% to 37.78%. Percent Chl-*a* removal ranged from 2.94% to 37.78%, with an average of 16.74% ± 3.62 across the nine best sampling days. The average clearance rate per individual bivalve over fourteen sampling days was 0.83 l hr^{-1} ± 0.43, with a range of -2.79 l hr^{-1} to 3.2 l hr^{-1}. Clearance rates per individual bivalve ranged from 0.37 l hr^{-1} to 3.20 l hr^{-1}, with an average clearance rate of 1.71 l hr^{-1} ± 0.34 across the nine best sampling days. The five days that did not result in a significant decrease in chlorophyll-a had negative percent chlorophyll-a removal and clearance rate values. Therefore, the higher values for the nine-day averages over the overall averages resulted from the removal of negative percent chlorophyll-a removal and clearance rates from the calculated nine day averages.

The results of this experiment compare well with other field experimental results obtained from east coast oyster reefs. Our results provide for the first time seston clearance rates for bivalves for a living-shoreline oyster reef within Louisiana and the Northern Gulf of Mexico. The design of the flume also provides a portable and relatively easy mechanism to quantify clearance rates in a high-energy bay environment and on fabricated oyster reefs.

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 and leeward of the ReefBlk structures at Reach E, the adjacent Reach E reference area also experienced scouring signifying that the structures are 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. Moreover, these structures both appear to be susceptible to cold front derived erosion. The Gabion Mat treatment is maintaining its shorelines and seems to show the greatest promise as a shoreline protection structure.

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 oyster coverages by 2-years post construction. However, by 4-years post-construction the ReefBlks began to lose oyster shell dramatically at Reach E, and by 7-years post-construction all three Reaches had lost well over 50% of their oyster shells used as substrate for oysters to build reef. A-Jacks oyster population densities remain good by 7-years post-construction, and have the better shell height (surrogate for age of oyster) distribution than the Gabion Mats. However, much of the A-Jacks density and shell height are due to oysters on the leeward side of the structures, and it is not known if this population can be maintained in the future as the structures break apart and continue to subside. As a result, the Gabion Mat is clearly the most effective shoreline protection structure at the TE-45 Reaches based on the above two goals.

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, but failed, 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. 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 elevation surveys conducted in 2011 and 2015 as shown in Tables 3 and 4. All of the structures have settled since construction, with the most extreme area being Reach E. In particular, the Gabion Mat 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.

There are no recommended improvements to the Gabion Mats and A-Jacks structures for the development of oyster populations. However, it is recommended that oyster shell not be used in Reefblks in habitats where there is shell pests' recruitment and survival, and where structures are partially or totally submerged by tidal activity during most of a year.

c. Lessons Learned

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 develop adequately a sampling regime that fulfills biological assessment objectives, while also attempting to reduce oyster reef disturbances that may influence shoreline erosion assessments. For example, for future work the surface layer of rocks and shells are the only layer of substrate that needs to be removed to assess oyster reef development; inner oysters on the three structures assessed will never attain enough size and complexity to develop reef.

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 in 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.

Elevation Summary

- All shoreline Reaches recorded volume losses during both pre- and post-construction intervals.
- The Reach A, B, 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, Gabion Mats, and Reefblks experienced shoreface scouring.
- The TE-45 structures and reference areas sustained post-construction sedimentation deficits in both the windward and leeward positions.
- 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 B structures and the Reach A ReefBlks have the highest vertical profile while the Reach E structures and the Reach A Gabion Mats 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.
- Erosion behind the Gabion Mat treatment is likely derived from structure settlement and placement issues.
- Flanking erosion is impacting the shorelines behind the Reach E Gabion Mats due to the offset position of the fringing shore and the exposure of these marshes to wave energy.
- The post-construction shoreline transgressions behind the ReefBlk and A-Jack treatments were temporally similar.
- ReefBlk and A-Jack treatments appear to be susceptible to cold front derived erosion.
- The post-construction reference area Reaches have continued to erode at differential rates.
- The Reach A and E reference areas are eroding at very high 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 or partially exposed at low tide, followed by the A-Jacks, and then the ReefBlks with the greatest amount time submerged.

- Salinities remained within the desired range for subtidal and intertidal oyster recruitment, growth, and reef development. However, salinity was on the high end of the desired range and stimulated the colonization of boring sponges and Polychaete worms, along with a relatively good population of stone crabs. The sponges, worms, and crabs eroded oyster shell in ReefBlks used as substrate.
- Winters, after a cold front with winds pushing bay waters out was the only time of year when structures were adequately exposed for extended periods to allow visual and quantitative assessments. Winters also allowed for better assessments of oyster survival, density, and reef building potential because larvae and spat recruitment are at minimum, and after the typical spring and fall bimodal peaks.

Oyster Spat Availability Summary

- Variability in oyster recruitment density by tidal height, year, month, and Reach was evident, but typical and did not vary more than expected.
- Oyster spat recruitment available to all structures were favorable and considered to be more than sufficient for all years, except perhaps in 2010 when there was a spring spat failure that corresponded to the simultaneous presence of oil and dispersant in Terrebonne Bay from the DWH oil spill.
- Seventy-five percent (75%) of all oyster spat recruited to quarry tiles, used to document monthly availability of larvae, occurred at Reach E. However, spat recruitment remained good for reef development at Reaches A and B indicating an abundance of larvae throughout the study area.

Oyster Populations Shell Height Frequency Summary

- All three experimental structures (treatments) exhibited relatively good oyster population size distributions the first two years indicating initial good recruitment and survival. ReefBlk oyster populations eventually crashed because of loss of oyster shell substrate within each block.
- A-Jacks shell height frequency distribution was much greater than that of Gabion Mats due to having a protected leeward-facing side as compared to the windward-facing mats.
- Oyster populations on A-Jacks and Gabion Mats developed relatively good populations of female oysters that should help contribute to spawning bay larvae populations.
- 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 have relatively good densities of oysters and are forming reef.
- Gabion Mat density peaks at mid-mat length and tapers off to bottom of mat. Top of mats are more tidally influenced (greater aerial exposure) than rest of mat so oysters are small and will never develop reef under current tidal regime.

- A-Jacks exhibit significant difference in oyster density between leeward and windward sides with leeward having an average of 2.7 more oysters per square meter.
- Consolidated reef on all the structures is a veneer-type development with living oysters more concentrated on the surface where larger-sized oysters concentrate and begin to form reef.
- ReefBlks had some of the greatest oyster densities by winter 2009 survey. However, by 4-years post-construction (winter 2011 survey) they began to fail because of significant (> 50 %) oyster shell substrate loss, and by 7-years post-construction (winter 2014 survey) all had failed.
- Hooked mussels attach to oysters in great numbers. Unfortunately, oyster spat recruitment onto hooked mussels has been observed numerous times during this study. The mussel attaches to a substrate by byssal threads and when the mussel dies, the byssal threads decompose and the animal will detach from its substrate. Larval oysters that recruit and grow on the mussels have the potential to fall off into the underlying sediments and suffocate or be washed away by wave and currents, especially on vertical structures such as the ReefBlks. This scenario of oysters falling into the bottom substrate has been observed numerous times in this project.

Supplemental Research Summary (from M.S. Theses)

- After two years post-construction, oysters exhibited growth on all structure types comparable to the natural intertidal reefs in the study area (Linson 20120).
- The interior oysters for all three bio-engineered structure types, confined to crowded interstitial spaces, realistically have little to no chance of growing to a size that will contribute to emergent reef and protect a shoreline. It is the surface (surficial) layer of oysters that will recruit new generations that can potentially develop consolidated reef (Linson 2010).
- Given the greater biomass and oyster density at the protected, low wave energy natural intertidal reef site, and the greater mussel:oyster ratio at high wave energy sites, it is concluded that high-intensity wave activity negatively influences the development of oyster reef. This suggests that although all three constructed structures are recruiting oysters, long-term and sustainable reef development in a high-energy habitat may be difficult to achieve the same similarities in reef metrics as a more sheltered natural intertidal reef (O'Malley 2012).
- The three constructed reefs (A-Jacks, Gabion Mats, and ReefBlks) are comparable to natural intertidal oyster reefs in the study area for providing habitat for a diverse array of nekton; No significant differences (Bacheler 2013).
- A-Jacks, Triton® Gabion Mats, and ReefBlks do not appear to limit nekton use of adjacent, vegetated, intertidal habitats, i.e., ingress and egress, (Bacheler 2013).
- Oyster reefs developing on the ReefBlks, A-Jacks, and Gabion Mats provide the same or comparable prey resources as nearby natural intertidal oyster reefs in fish diets (Bruce 2013).
- Multiple predators are present and actively feeding along constructed reefs, and the predator-prey interactions on hooked mussels are not limited by the physical characteristics of the bio-engineered reefs, e.g. shape, size, vertical relief, and material composition (Bourgeois 2015).
- Hooked mussels recruit consistently throughout the spring, summer, and fall, and there is an obvious preference to settle on live oysters, most likely due to chemotaxis attraction. Oyster

spat had no significant preference for live oysters or clean aged oyster shells (Bourgeois 2015).

- Our study provides for the first known (published) actual (not theoretically derived) seston clearance rates for bivalves (oysters + hooked mussels) on a living-shoreline oyster reef within Louisiana and the Northern Gulf of Mexico. The results of this experiment compare well with other field experimental results obtained from east coast oyster reefs. The average percent removal of chlorophyll-a (Chl-a) over fourteen sampling days was 8.47% ± 3.92, with a range of -14.71% to 37.78%. Percent Chl-a removal ranged from 2.94% to 37.78%, with an average of 16.74% ± 3.62 across the nine best sampling days. The average clearance rate per individual bivalve over fourteen sampling days was 0.83 L hr^{-1} ± 0.43, with a range of -2.79 L hr^{-1} to 3.2 L hr^{-1}. Clearance rates per individual bivalve ranged from 0.37 L hr^{-1} to 3.20 L hr^{-1}, with an average clearance rate of 1.71 L hr^{-1} ± 0.34 across the nine best sampling days (Buter 2015).

VI. References

Bacheler, V. 2013. Constructed Oyster Reefs Assist in Creation of Habitat for Fish and Macroinvertebrate Assemblages in a Louisiana Estuary. MS Thesis, Nicholls State University 138 pp.

Baggett, L. P., S. P. Powers, R. Brumbaugh, L. D. Coen, B. DeAngelis, J. Greene, B. Hancock, and S. Morlock. 2014. Oyster Habitat Restoration Monitoring and Assessment Handbook. The Nature Conservancy, Arlington, VA, USA. 96pp.

Bahr, L. M. and W. P. Lanier. 1981. The Ecology of Intertidal Oyster Reefs of the South Atlantic Coast: A Community Profile. U.S. Fish and Wildlife Service, Office of Biological Services, Washington D.C. FWS/OBS-81/15, 105pp.

Barber, A. L. 2007. Restoration of Intertidal Oyster Reefs Affected by Recreational Boating Activity in Mosquito Lagoon, Florida. MS Thesis, University of Central Florida 111 pp.

Barras, J. A., P. E. Bourgeois, and L. R. Handley. 1994. Land Loss in Coastal Louisiana 156-90. National Biological Survey, National Wetlands Research Center Open File Report 94-01. 4 pp. 10 color plates.

Bartol, I. K., R. Mann and M. Luckenbach. 1999. Growth and Mortality of Oysters (Crassostrea virginica) on Constructed Intertidal Reefs: Effects of Tidal Height and Substrate Level. Journal of Experimental Marine Biology and Ecology 237:157-184.

Boyd, C. E. 1979. Water Quality in Warm Water Fishponds. Auburn University Agricultural Experiment Station, 359 pp.

Bourgeois, C. P. 2015. Predation, Recruitment, and Reef Development of Hooked Mussels, *Ischadium recurvum*, and Eastern Oysters, *Crassostrea virginica*, on Fabricated and Natural Oyster Reefs. MS Thesis, Nicholls State University 98 pp.

Brown, S. D and T. M. Bert. 1993. The Effect of Temperature and Salinity on Molting and Survival Menippe adina and Menippe mercenaria Post Settlement Juveniles. Marine Ecology Progressive Series 99: 41-49.

Brown, S. W. 2012. Salinity Tolerance of the Oyster Mudworm Polydora websteri. Thesis. University of Maine, 41pp.

Bruce, M. 2013. Diet Comparisons of Fish Associated with Constructed and Natural Reefs of *Crassostrea virginica.* MS Thesis, Nicholls State University 60 pp.

Buter, K. N. 2015. Seston Clearance Rates of Bivalves on Living Shoreline Oyster Reefs from a Northern Gulf of Mexico Estuary. MS Thesis, Nicholls State University, 102 pp.

Butler, P. A. 1954. Summary of Our Knowledge of the Oyster in the Gulf of Mexico. U.S. Fish and Wildlife Service Bulletin No. 89.

Cake, E. W., Jr. 1983. Habitat Suitability Index Models: Gulf of Mexico American Oyster. U.S. Department of the Interior Fish and Wildlife Service, FWS/OBS-82/10.57, 37pp.

Carver, C. E., I. Theriault and A. Mallet. 2010. Infection of Cultured Eastern Oysters *Crassostrea virginica* by the Boring Sponge *Cliona celata*, with Emphasis on Sponge Life History and Mitigation Strategies. Journal of Shellfish Research, Vol. 29, 4:905–915.

Casas S. M., J. F. LaPeyre, and M. K. LaPeyre. 2015. Restoration of Oyster Reefs in an Estuarine Lake: Population Dynamics and Shell Accretion. Marine Ecology Progress Series. 524, 171-184.

Coastal Protection and Restoration Authority of Louisiana (CPRA). 2010. Operation, Maintenance, and Rehabilitation Plan: Terrebonne Bay Shore Protection and Demonstration (TE-45) project. Baton Rouge, LA 6 pp.

Coen, L. 2015. Oyster Ecology and Restoration Bibliography. http://www.oyster-restoration.org/wp- content/uploads/2015/07/Oyster-BiologyRestorationremotewakes-11_24_15-web.pdf.

Coen, L. D., M. W. Luckenback, D. L. Breitburg. 1999. The Role of Oyster Reefs as Essential Fish Habitat: a Review of Current Knowledge and Some New Perspectives. American Fisheries Society. Symposium 22:438-454.

Couvillion B. R., J. A. Barras, G. D. Steyer, W. Sleavin, M. Fischer, H. Beck, N. Trahan, B. Griffin and D. Heckman. 2011. Land Area Change in Coastal Louisiana from 1932 to 2010: US Geological Survey Scientific Investigations Map 3164. Pamphlet, Scale 1:265,000, 12 pp.

Day, J. W., W. G. Smith, P. R. Wagner and W. C. Stowe. 1973. Community Structure and Carbon Budget of a Salt Marsh and Shallow Bay Estuarine System in Louisiana. Center for Wetland Resources, LSU, Publication No. LSU-SG-72-04, 80 pp.

Dekshenieks, M. M., E. E. Hofmann and E. N. Powell. 1993. Environmental Effects on the Growth and Development of Eastern Oyster, Crassostrea virginica (Gmelin 1791) Larvae: a Modeling Study. Journal Shellfish Research. 12(2):241-254.

Dekshenieks, M. M., E. E. Hofmann and E. N. Powell. 2000. Quantifying the Effects of Environmental Changes on an Oyster Population: A model study. Estuaries 23(5):593-610.

Dunbar, J. B., L. D. Britsch, and E. B. Kemp III. 1992. Land Loss Rates Report 3: Louisiana Coastal Plain. Technical Report GL-90-2. U.S. Army Engineer District, New Orleans. New Orleans, Louisiana

Eustis Engineering Company, Inc. 2002. Geotechnical Investigation State of Louisiana, Terrebonne Bay Shore Protection Demonstration Project, Terrebonne Parish, Louisiana. Eustis Engineering Project No. 17474. 27 pp. plus appendices.

Feng, Z. 2009. Hydrodynamic Response to Cold Fronts Along the Louisiana Coast. MS Thesis, Louisiana State University 111 pp.

Folse, T. M., L. A. Sharp, J. L. West, M. K. Hymel, J. P. Troutman, T. E. McGinnis, D. Weifenbach, L. B. Rodrigue, W. M. Boshart, D. C. Richardi, W. B. Wood, and C. M. Miller. 2008, revised 2014. A Standard Operating Procedures Manual for the Coastwide Reference Monitoring System-Wetlands: Methods for Site Establishment, Data Collection, and Quality Assurance/Quality Control. Louisiana Coastal Protection and Restoration Authority. Baton Rouge, LA. 228 pp.

Gagliano, M. H., S. M. Gagliano and P. J. Moses. 1997. Bay Rambo Oyster Reef: An artificial oyster reef in the deltaic estuarine area of Louisiana. Coastal Environments, Inc. Baton Rouge, LA., 30 pp.

Galtsoff, P. S. 1964. The American Oyster Crassostrea virginica Gmelin. U.S. Fish and Wildlife Service Bulletin. No. 64.

Gauthier, J. D and T. M. Soniat. 1989. Changes in the Gonadal State of Louisiana Oysters During Their Autumn Spawning Season. Journal of Shellfish Research 8(1):83-86.

Gedan, K. B., L. Kellogg and D. L. Breitburg. 2014. Accounting for Multiple Foundation Species in Oyster Reef Restoration Benefits. Restoration Ecology. 22(4):517-524.

Grabowski J. H., R. D. Brumbaugh, R. F. Conrad, A. G. Keeler, J. J. Opaluch, C. H. Peterson, M. F. Piehler, S. P. Powers, and A. R. Smyth. 2012. Economic Valuation of Ecosystem Services Provided by Oyster Reefs. BioScience. 62(10):900-909.

Hardaway, Jr. C. S., D. A. Milligan, and K. Duhring. 2010. Living Shoreline Design Guidelines for Shore Protection in Virginia's Estuarine Environments. Virginia Institute of Marine Science, College of William & Mary, Gloucester Point, Virginia. 84 pp.

Hopkins, S. H. 1962. Distribution of species of *Cliona* (boring sponge) on the Eastern Shore of Virginia. Science. 3, 121-124.

Ingle, R. M., A. E. Joyce, J. A. Quick and S. W. Morey. 1971. Basic Considerations in the Evaluation of Thermal Effluents in Florida. A Preliminary Investigation: The Effect of Elevated Temperature on the American Oyster, Crassostrea virginica (Gmelin). Florida Dept. Nat. Res. Prof. Paper Series. 157-159.

Kennedy, V. S., R. I. E. Newell and A. F. Eble (eds.). 1996. The Eastern Oyster Crassostrea virginica. University of Maryland Press 1,089 pp.

Kennedy, V. S. 1966. Biology of larvae and spat. In: V. S. Kennedy, R. I. E. Newell and A. F. Eble (eds.). The Eastern Oyster *Crassostrea virginica*. Maryland Sea Grant. 371-421 pp.

Krimsky, L. S. and C. E. Epifanio. 2008. Multiple Cues from Multiple Habitats: Effect on Metamorphosis of the Florida Stone Crab, *Menippe mercenaria*. Journal of Experimental Marine Biology and Ecology 358: 178-184.

Langdon, C. J. and R. I. E. Newell. 1996. Digestion and Nutrition in Larvae and Adults. In: V. S. Kennedy, R. I. E. Newell and A. F. Eble (eds.). The Eastern Oyster *Crassostrea virginica*. 231-269 pp.

LaPeyre M. K., L. Schwarting and S. Miller. 2013. Preliminary Assessment of Bioengineered Fringing Shoreline Reefs in Grand Isle and Breton Sound, Louisiana. U.S. Geological Survey Open-File Report 2013–1040, 34 pp.

LaPeyre M. K., A. T. Humphries, S. M. Casas, and J. F. LaPeyre. 2014. Temporal Variation in Development of Ecosystem Services from Oyster Reef Restoration. Ecological Engineering. 63:34-44.

La Peyre, M., L. Schwarting-Miller, S. Miller and E. Melancon. In review. Chapter 20. Comparison of Oyster Populations, Shoreline Protection Service and Site Characteristics at Seven Created Fringing Reefs in Louisiana: Key Parameters and Responses to Consider. In: Living Shorelines: The Science and Management of Nature-based Coastal Protection, CRC Press.

Lear, E., B. Babin, G. Curole, and T. Folse. 2011. 2011 Closeout Report for Mandalay Bank Protection Demonstration (TE-41) Project, Coastal Protection and Restoration Authority of Louisiana, Office of Coastal Protection and Restoration, Thibodaux, Louisiana. 46 pp.

Leonard, L. A. and M. E. Luther. 1995. Flow Hydrodynamics in Tidal Marsh Canopies. Limnology and Oceanography, 40 (8): 1474-1484.

Lenihan, H. S. 1999. Physical-biological Coupling on Oyster Reefs: How Habitat Structure Influences Individual Performance. Ecological Monographs 69:251-275.

Lenihan, H. S. and C. H. Peterson. 1998. How Habitat Degradation Through Fishery Disturbance Enhances Impacts of Hypoxia on Oyster Reefs. Ecological Applications 8:128-140.

Linson, M. A. 2010. Initial Oyster Reef Development on Bio-engineered Living Shorelines Structures used for Erosion Control in a Louisiana Salt Marsh. MS Thesis, Nicholls State University, 102 pp.

Livingston, R. J. 1987. Field Sampling in Estuaries: the Relationship of Scale to Variability. Estuaries 10(3): 194-207.

Lowery, J. and K. T. Paynter. 2002. The importance of molluscan shell substrate. National Marine Fisheries Service, Unpub. Report, 17pp.

May, J. R. and L. D. Britsch. 1987. Geological Investigation of the Mississippi River Deltaic Plain: Land Loss and Land Accretion. Techical Report GL-87-13. U.S. Army Engineer District, New Orleans. New Orleans, Louisiana.

Melancon, E. J. Jr., G. P. Curole, A. M. Ledet, and Q. C. Fontenot. 2013. 2013 Operations, Maintenance, and Monitoring Report for Terrebonne Bay Shore Protection Demonstration (TE-45), Coastal Protection and Restoration Authority of Louisiana, Thibodaux, Louisiana. 75 pp.

Melancon, E. J. Jr., M. A. Linson, G. P. Curole, D. A. Dearmond, and Q. C. Fontenot. 2010. 2010 Operations, Maintenance, and Monitoring Report for Terrebonne Bay Shore Protection Demonstration (TE-45), Coastal Protection and Restoration Authority of Louisiana, Office of Coastal Protection and Restoration, Thibodaux, Louisiana. 51 pp.

Melancon, E. J, T. M. Soniat, V. Cheramie, R. J. Dugas, J. Barras and M. LaGarde. 1998. Oyster Resource Zones of the Barataria and Terrebonne Estuaries of Louisiana. Journal of Shellfish Research 17(4):1143-1148.

Meyer, D. L., E.C. Townsend, G.W. Thayer. 1997. Stabilization and Erosion Control Value of Oyster Cultch for Intertidal Marsh. Restoration Ecology 5: 93-99.

Menzel, R.W. 1951. Early Sexual Development and Growth of the American Oyster in Louisiana Waters. Science. 113:719-720.

Minello, T.J. 1999. Nekton Densities in Shallow Estuarine Habitats of Texas and Louisiana and the Identification of Essential Fish Habitat. P. 43-75 *in* Benaka, L.R. ed. Fish Habitat: Essential Fish Habitat and Rehabilitation. American Fisheries Society, Bethesda, Maryland, 459 pp.

Morris P. Hebert (MPH), Inc. 2003. Terrebonne Bay Shore Protection Demonstration Project Design Report. LDNR Contract No's 2503-00-28 and 2503-03-16. 25 pp.

Morton, R. A. and J. A. Barras. 2010. Hurricane Impacts on Coastal Wetlands: A Half-Century Record of Storm-Generated Features from Southern Louisiana. Journal of Coastal Research 27: 27-43.

Morton, R. A., G. Tiling, and N. F. Ferina. 2003. Primary Causes of Wetland Loss at Madison Bay, Terrebonne Parish, Louisiana. United States Geological Survey, Center for Coastal and Watershed Studies Open File Report 03-60. 22 pp.

O'Malley, D.A. 2012. The Effects of Wave Energy and Emersion Regime on Initial Oyster Community Development on Constructed Oyster Reefs. MS Thesis, Nicholls State University 107 pp.

Piazza, B. P., P. D. Banks, M. K. LaPeyre. 2005. The potential for Created Oyster Shell Reefs as a Sustainable Shoreline Protection Strategy in Louisiana. Restoration Ecology 13: 499-506.

Pollard, J.F. 1973. Experiments to Re-establish Historical Oyster Seed Grounds and to Control the Southern Oyster Drill. Louisiana Wildlife Fisheries Commission, Tech. Bull. 6:1-82.

Powell, E. N., E. E. Hofmann, J. M. Klinck and S. M. Ray. 1994. Modeling Oyster Populations IV: Rates of Mortality, Population Crashes and Management. Fisheries Bulletin 92:347-373.

Reed, D. J. 1989. Patterns of Sediment Deposition in Subsiding Coastal Salt Marshes, Terrebonne Bay, Louisiana: The Role of Winter Storms. Estuaries 12(4): 222-227.

Roberts, H. H, A. Bailey, and G. J. Kuecher. 1994. Subsidence in the Mississippi River Delta-Important Influences of Valley Filling by Cyclic Deposition, Primary Consolidation Phenomena, and Early Diagenesis. Transactions of the Gulf Coast Association of GeologicalSocieties. 44: 619-629.

Roegner, G. C. and R. Mann. 1995. Early Recruitment and Growth of the American Oysters with Respect to Tidal Zonation and Season. Marine Ecology Progress Series. 117:91-101.

Shumway, S. E. 1996. Natural Environmental Factors. In V. S. Kennedy, R. I. E. Newell and A. F. Eble (eds.), The Eastern Oyster Crassostrea virginica, p.467-513.

Steyer, G. D., R. C. Raynie, D. L. Stellar, D. Fuller, and E. Swenson. 1995. Quality Management Plan for Coastal Wetlands Planning, Protection, and Restoration Act

Monitoring Program. Open-file series no. 95-01 (Revised June 2000). Baton Rouge: Louisiana Department of Natural Resources, Coastal Restoration Division. 97 pp.

Stone, G. W., J. M. Grymes III, J. R. Dingler, and D. A. Pepper. 1997. Overview and Significance of Hurricanes on the Louisiana Coast, U.S.A. Journal of Coastal Research. 13: 656-669.

T. Baker Smith, Inc. (TBS). 2008. Terrebonne Bay Shore Protection Demonstration (TE-45) Project Competition Report. Houma, LA 9pp.

Thieler, E. R., and D. Martin, and A. Ergul 2003. The Digital Shoreline Analysis System, Version 2.0: Shoreline Change Measurement Software Extension for ArcView: USGS U.S. Geological Survey Open-File Report 03-076.

Thompson, R. J., R. I. E. Newell, V. S. Kennedy and R. Mann. 1996. Reproductive Processes and Early Development. In: V. S. Kennedy, R. I. E. Newell and A. F. Eble (eds.). The Eastern Oyster *Crassostrea virginica*. 335-370 pp.

Thompson, T. L. and E. P. Glenn. 1994. Plaster Standards to Measure Water Motion. Limnology and Oceanography 39(7): 1768-1779.

Trosclair, K. J. 2013. Wave Transformation at a Saltmarsh Edge and Resulting Marsh Edge Erosion: Observations and Modeling. MS Thesis, University of New Orleans 73 pp.

United States Army Corps of Engineers (USACE) 2004. Low Cost Shore Protection: A Guide for Engineers and Contractors. University Press of the Pacific, Honolulu, Hawaii. 180 pp.

United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS). 2007. Soil Survey of Terrebonne Parish, Louisiana. 318 pp.

Wall, L.M. 2004. Recruitment and Restoration of the Oyster *Crassostrea virginica* in Areas with Intense Boating Activity in Mosquito Lagoon, Florida. Master's Thesis. University of Central Florida. 74 pp.

Watzke, D. A. 2004. Short-term Evolution of a Marsh Island System and the Importance of Cold Front Forcing, Terrebonne Bay, Louisiana. MS Thesis, Louisiana State University 42 pp.

Widdows, J., R.I.E. Newell & R. Mann. 1989. Effects of Hypoxia and Anoxia on Survival, Energy Metabolism, and Feeding of Oyster Larvae (*Crassostrea virginica*, Gmelin). Biological Bulletin. 177: 154–166.

Zimmerman, R., Minello, T.J., Baumer T. and M. Castiglione. 1989. Oyster Reef as Habitat for Estuarine Macrofauna. NOAA Technical Memorandum NMFS-SEFC-249.

Appendix A
(TE-45 Structure Designs)

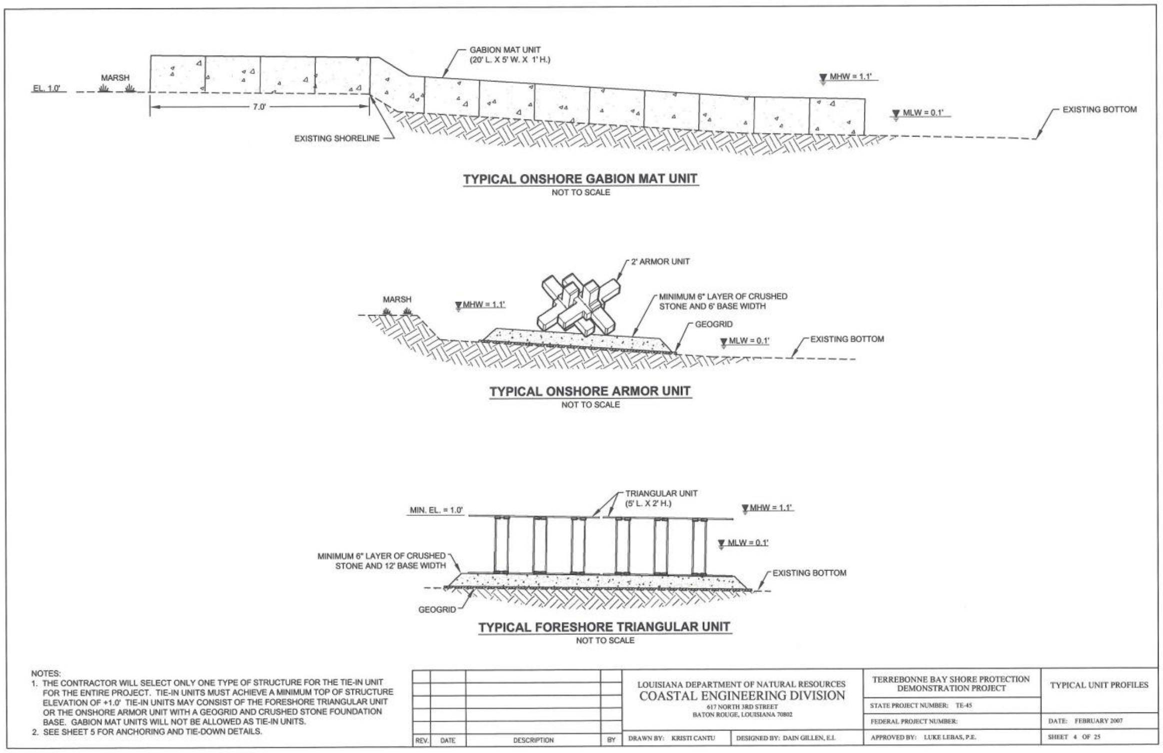


Figure A-1. **Typical cross sections showing the Terrebonne Bay Shore Protection Demonstration (TE-45) project's shoreline protection structures.**

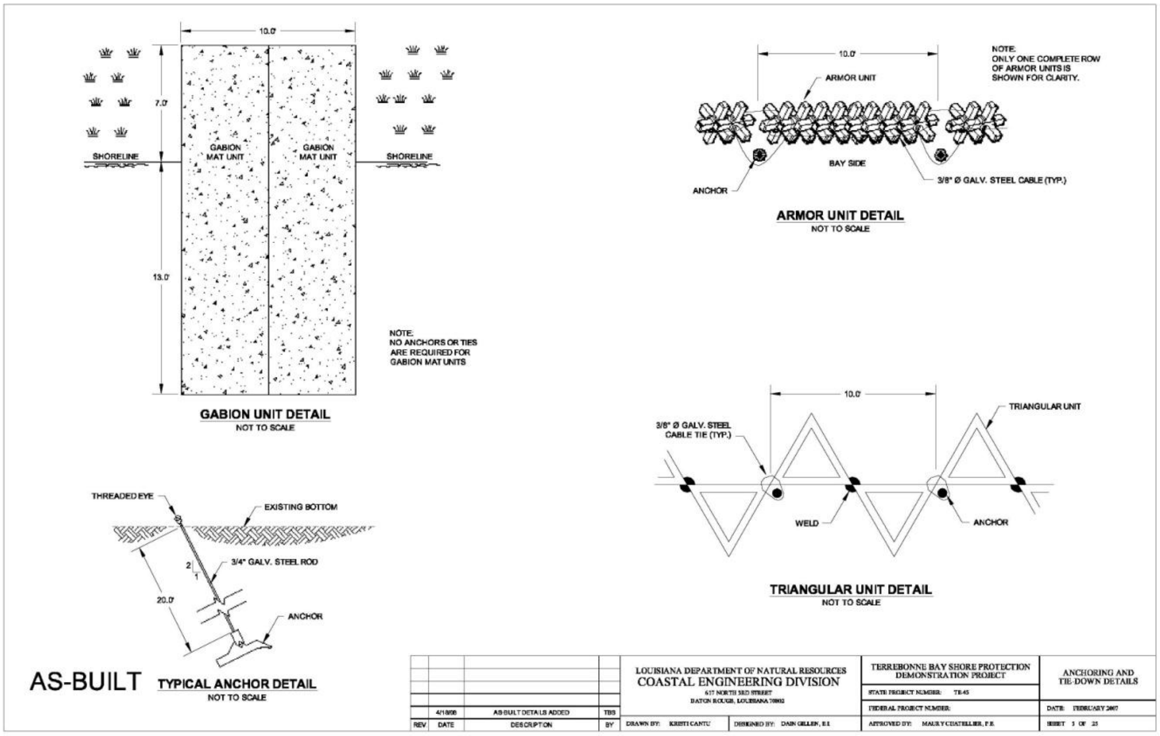


Figure A-2. **Aerial view depicting the typical layout and anchoring details for the Terrebonne Bay Shore Protection Demonstration (TE-45) project's Gabion Mat, A-Jack, and ReefBlk structures.**

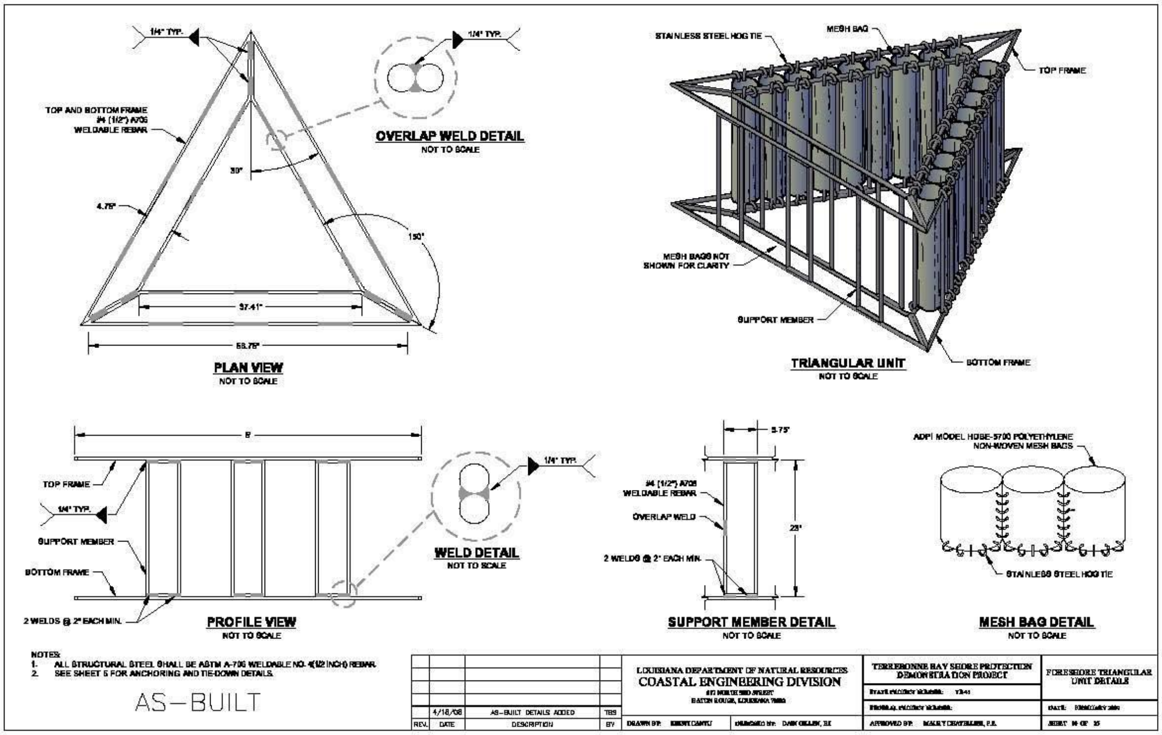


Figure A-3. Design drawings showing the Terrebonne Bay Shore Protection Demonstration (TE-45) project's ReefBlk structure.

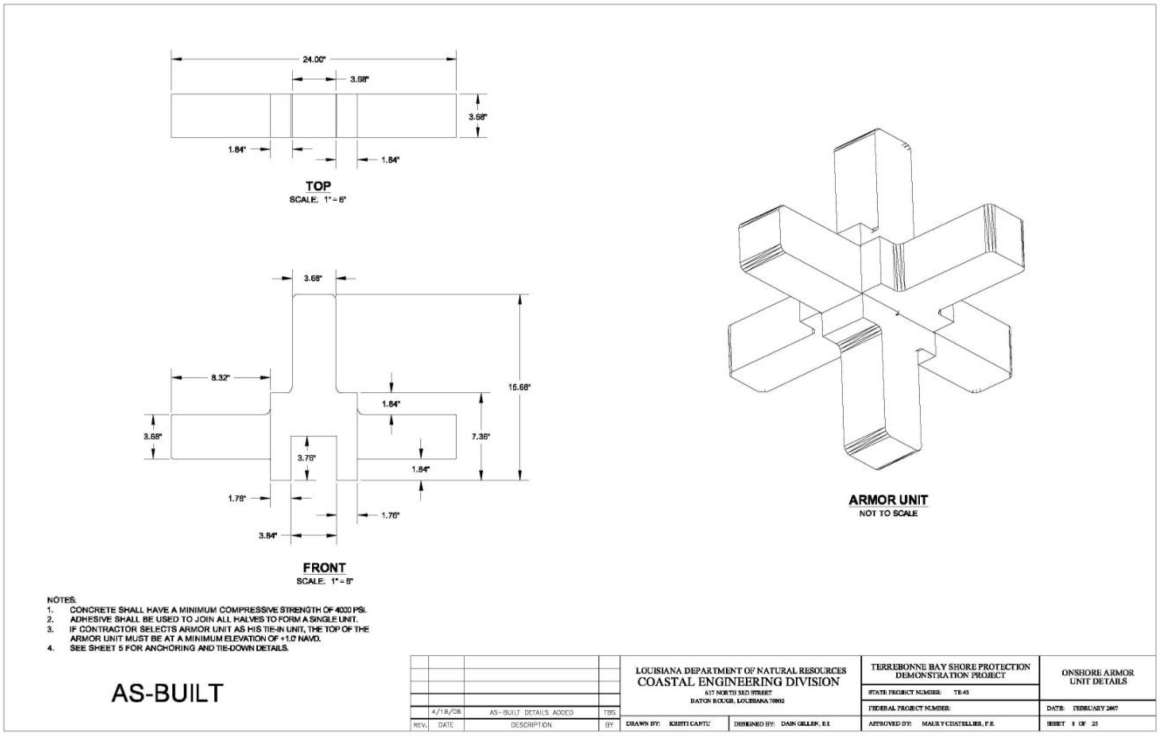


Figure A-4. **Design drawings showing the Terrebonne Bay Shore Protection Demonstration (TE-45) project's A-Jack structure.**

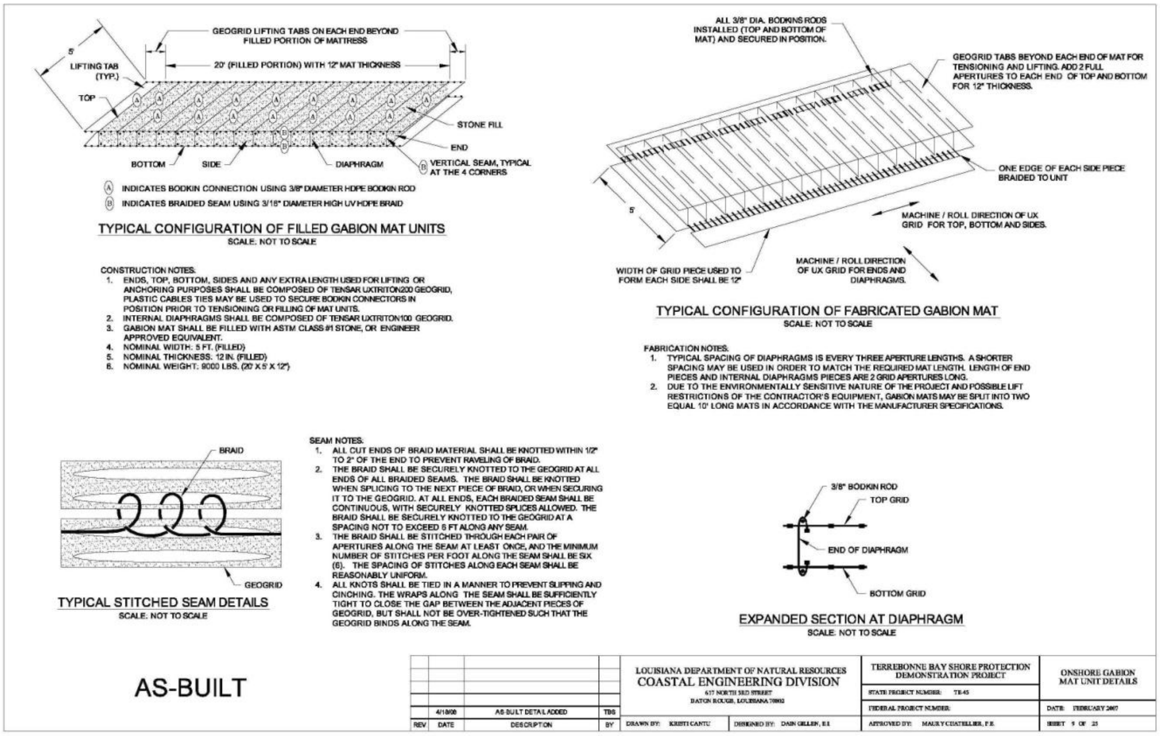


Figure A-5. **Design drawings showing the Terrebonne Bay Shore Protection Demonstration (TE-45) project's Gabion Mat structure.**

Appendix B
(Inspection Photographs)

Photo B-1. **NSU collecting oyster samples along Reach A of the Gabion Mats.**

Photo B-2. **Southern end of Gabion Mats along Reach A.**

Photo B-3. **Southern end of Gabion Mats along Reach Close-up view of the gabion mats and fill material at Reach A.**

Photo B-4: **View of the northern end of the Gabion Mats on Reach A.**

Photo B-5: **Gabion Mats intersect with A-Jacks along Reach A.**

Photo B-6: **View of A-Jacks along shoreline at Reach A.**

Photo B-7: **View of intersection of A-Jacks and ReefBlks along Segment A.**

Photo B-8: **View of off-shore ReefBlks on southern end of Reach A.**

Photo B-9: **Close-up view of ReefBlks along Segment A.**

Photo B-10: **View of Gabion Mats on the northern end of Segment B.**

Photo B-11: View of A-Jacks and shoreline along Segment B.

Photo 12: View of damaged warning sign offshore along Segment B.

Photo B-13: View of ReefBlks along Segment B.

Photo B-14: View of ReefBlks and A-Jack tie-in to shoreline along Segment B.

Photo B-15: View of damaged warning sign offshore along Segment B.

Photo B-16: View of A-Jacks connecting shoreline to ReefBlks along north side of Segment E.

Photo B-17:   View of damaged warning sign offshore from A-Jacks on Reach E.

Photo B-18:   View of offshore ReefBlk units along Reach E.

Photo B-19: Close-up view of offshore ReefBlk units along Reach E.

Photo B-20: View of offshore ReefBlk Units along Segment E.

Photo B-21: View of Gabion mats along the shoreline of Segment E.

Photo B-22: View of Gabion mats at the southern end of Segment E.

Appendix C
(Three Year Budget Projection)

Terrebonne Bay Shore Protection Demonstration / TE45 / PPL10

Three-Year Operations & Maintenance Budgets 07/01/2015 - 06/30/2018

Project Manager	O & M Manager	Federal Sponsor	Prepared By
	Babin	USFWS	Babin

	2015/2016	2016/2017	2017/2018
Maintenance Inspection	$ 20,217.00	$ -	$ -
Structure Operation	$ -	$ -	$ -
Administration	$ -		$ -
USACE Administration	$ -	$ -	$ -

Maintenance/Rehabilitation

15/16 Description: the 2015/2016 inspection will be the final scheduled inspection for this demonstration project.

	2015/2016
E&D	$ -
Construction	$ -
Construction Oversight	$ -
Sub Total - Maint. And Rehab.	$ -

16/17 Description

	2016/2017
E&D	
Construction	
Construction Oversight	
Sub Total - Maint. And Rehab.	$ -

17/18 Description:

	2017/2018
E&D	$ -
Construction	$ -
Construction Oversight	$ -
Sub Total - Maint. And Rehab.	$ -

	2015/2016	2016/2017	2017/2018
Total O&M Budgets	$ 20,217.00	$ -	$ -

O&M Budget (3 yr Total)	**$ 20,217.00**
Unexpended O&M Funds	**$ 39,418.95**
Remaining O&M Budget (Projected)	**$ 19,201.95**

OPERATIONS & MAINTENANCE BUDGET WORKSHEET

Project: <u>TE-45 Terrebonne Bay Shoreline Protection Demonstration Project</u>

FY 15/16 – will be the final inspection of the TE-45 project.

Administration		$ 0
O&M Inspection & Report		$ 20,217
Operation/Navigational Aid:		$ 0
Maintenance:		$ 0
E&D:	$ 0	
Construction:	$ 0	
Construction Oversight:	$ 0	

Operation and Maintenance Assumptions:

<u>CPRA Direct Costs</u>

<u>Inspection:</u>	
CPRA Engineer 3 – 12 hrs@ $60/hr.:	$ 720
CPRA Engineer 6 – 12 hrs @ $73/hr.	$ 876
CPRA Scientist 4 – 10 hrs @ $50/hr.	$ 500
	$ 2,096
<u>Report:</u>	
CPRA Engineer 6 – 60 hrs. @ $73/hr.	$ 4,380
Total Direct CPRA Costs:	**$ 6,476**

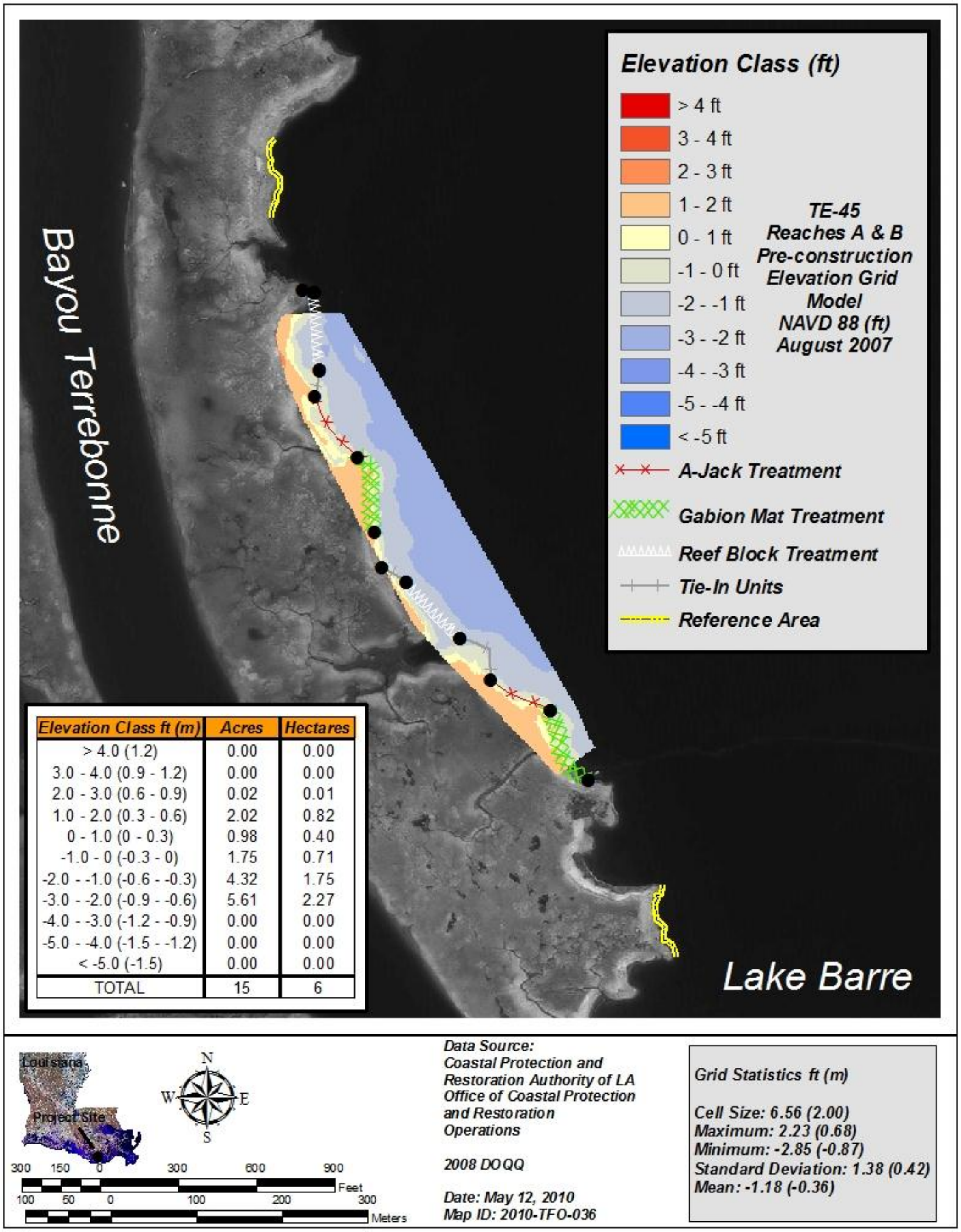
<u>CPRA Indirect Costs</u>

<u>Inspection:</u>	
CPRA Engineer 3 – 12 hrs@ $127.30/hr.:	$ 1,528
CPRA Engineer 6 – 12 hrs @ $154.88/hr.	$ 1,859
CPRA Scientist 4 – 10 hrs @ $106.08/hr.	$ 1,061
	$ 4,448
<u>Report:</u>	
CPRA Engineer 6 – 60 hrs. @ $154.88/hr.	$ 9,293
Total Indirect CPRA Costs:	**$13,741**

2015-2018 Accounting

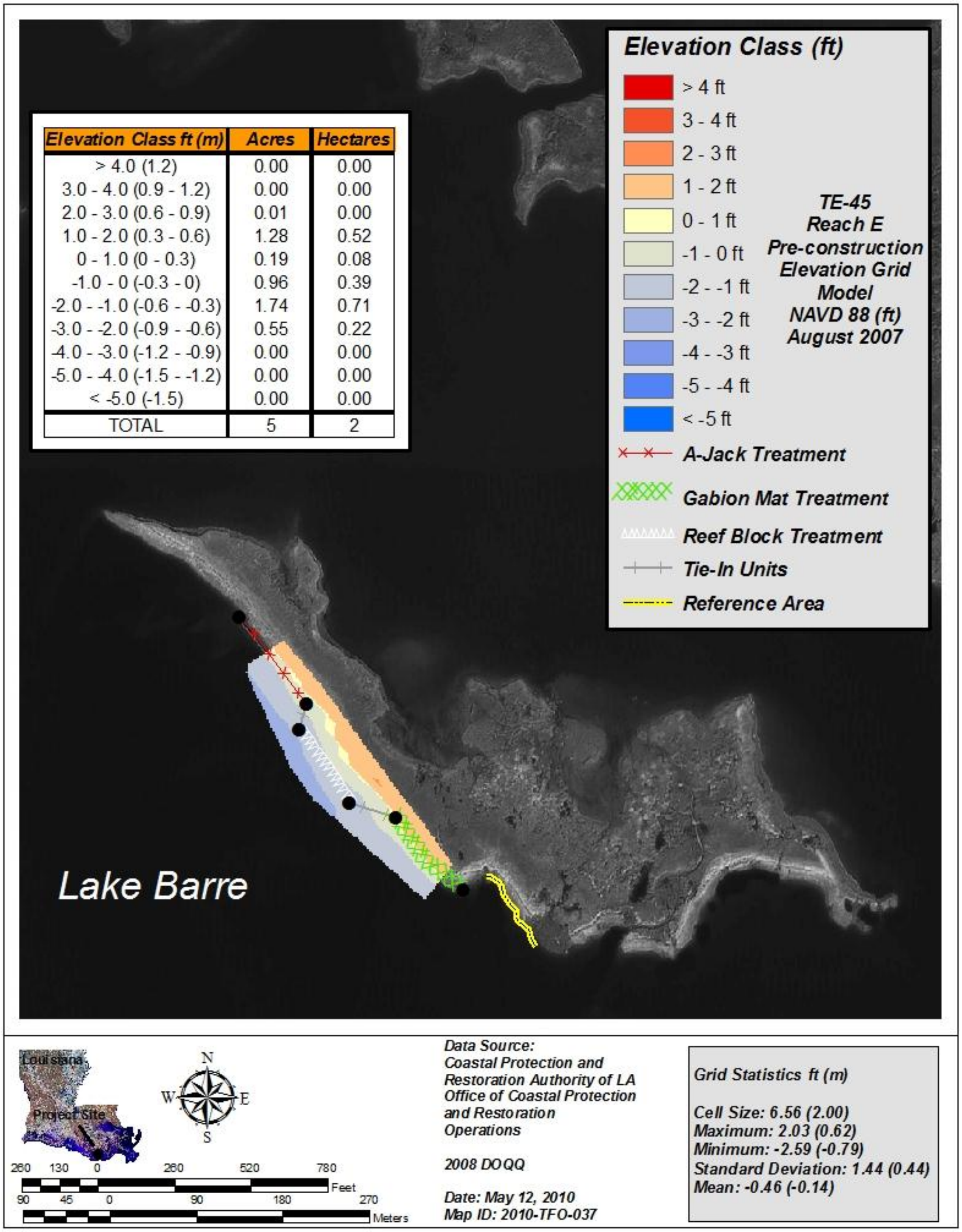
Approved CWPPRA Budget (Lana Report):	$	55,243.00
Expenditures (LaGov)	$	15,825.05
Current Unexpended O&M Funds:	**$**	**39,417.95**

Appendix D
(Elevation Grid Models)



Elevation Class ft (m)	Acres	Hectares
> 4.0 (1.2)	0.00	0.00
3.0 - 4.0 (0.9 - 1.2)	0.00	0.00
2.0 - 3.0 (0.6 - 0.9)	0.02	0.01
1.0 - 2.0 (0.3 - 0.6)	2.02	0.82
0 - 1.0 (0 - 0.3)	0.98	0.40
-1.0 - 0 (-0.3 - 0)	1.75	0.71
-2.0 - -1.0 (-0.6 - -0.3)	4.32	1.75
-3.0 - -2.0 (-0.9 - -0.6)	5.61	2.27
-4.0 - -3.0 (-1.2 - -0.9)	0.00	0.00
-5.0 - -4.0 (-1.5 - -1.2)	0.00	0.00
< -5.0 (-1.5)	0.00	0.00
TOTAL	15	6

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



Elevation Class ft (m)	Acres	Hectares
> 4.0 (1.2)	0.00	0.00
3.0 - 4.0 (0.9 - 1.2)	0.00	0.00
2.0 - 3.0 (0.6 - 0.9)	0.01	0.00
1.0 - 2.0 (0.3 - 0.6)	1.28	0.52
0 - 1.0 (0 - 0.3)	0.19	0.08
-1.0 - 0 (-0.3 - 0)	0.96	0.39
-2.0 - -1.0 (-0.6 - -0.3)	1.74	0.71
-3.0 - -2.0 (-0.9 - -0.6)	0.55	0.22
-4.0 - -3.0 (-1.2 - -0.9)	0.00	0.00
-5.0 - -4.0 (-1.5 - -1.2)	0.00	0.00
< -5.0 (-1.5)	0.00	0.00
TOTAL	5	2

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

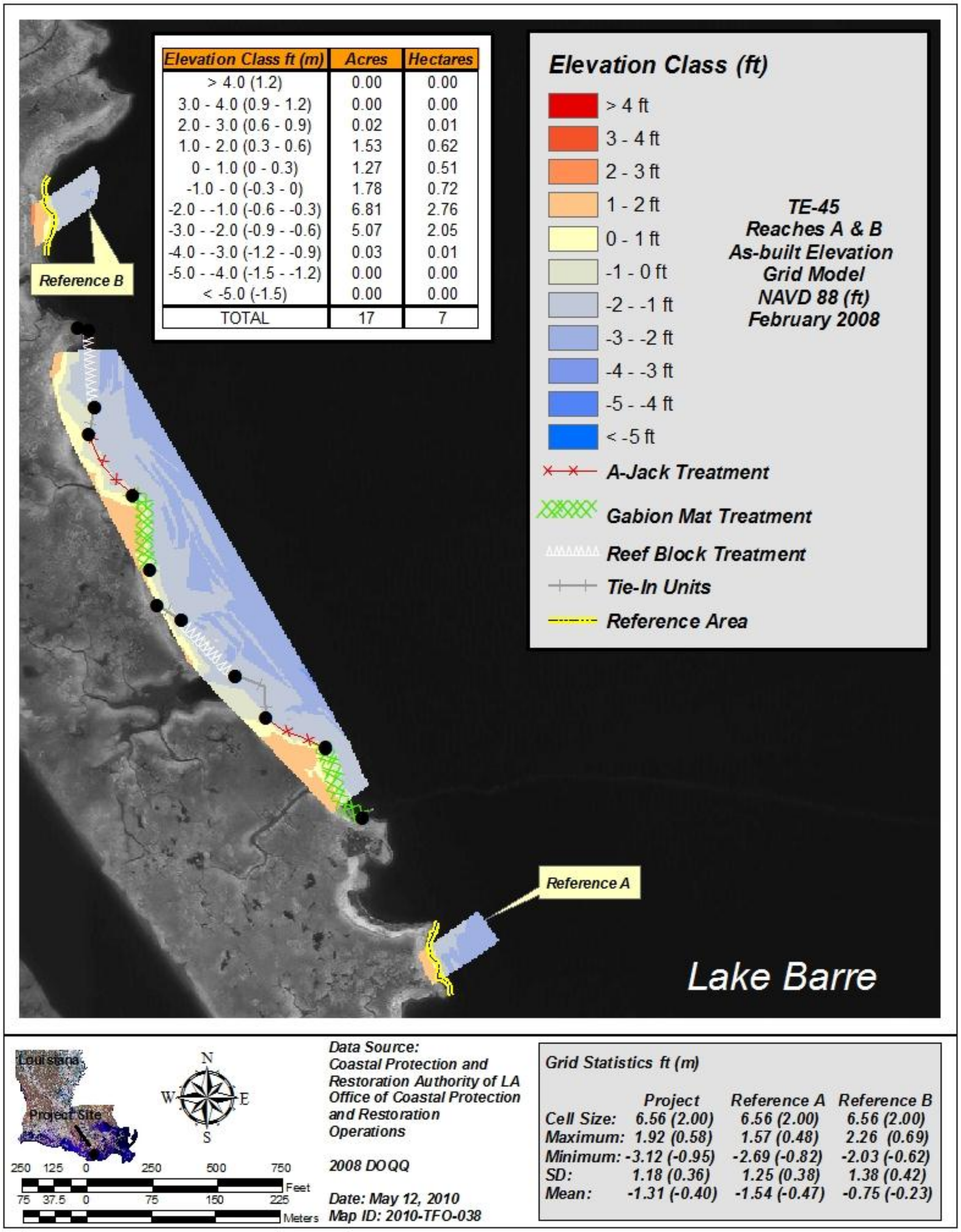
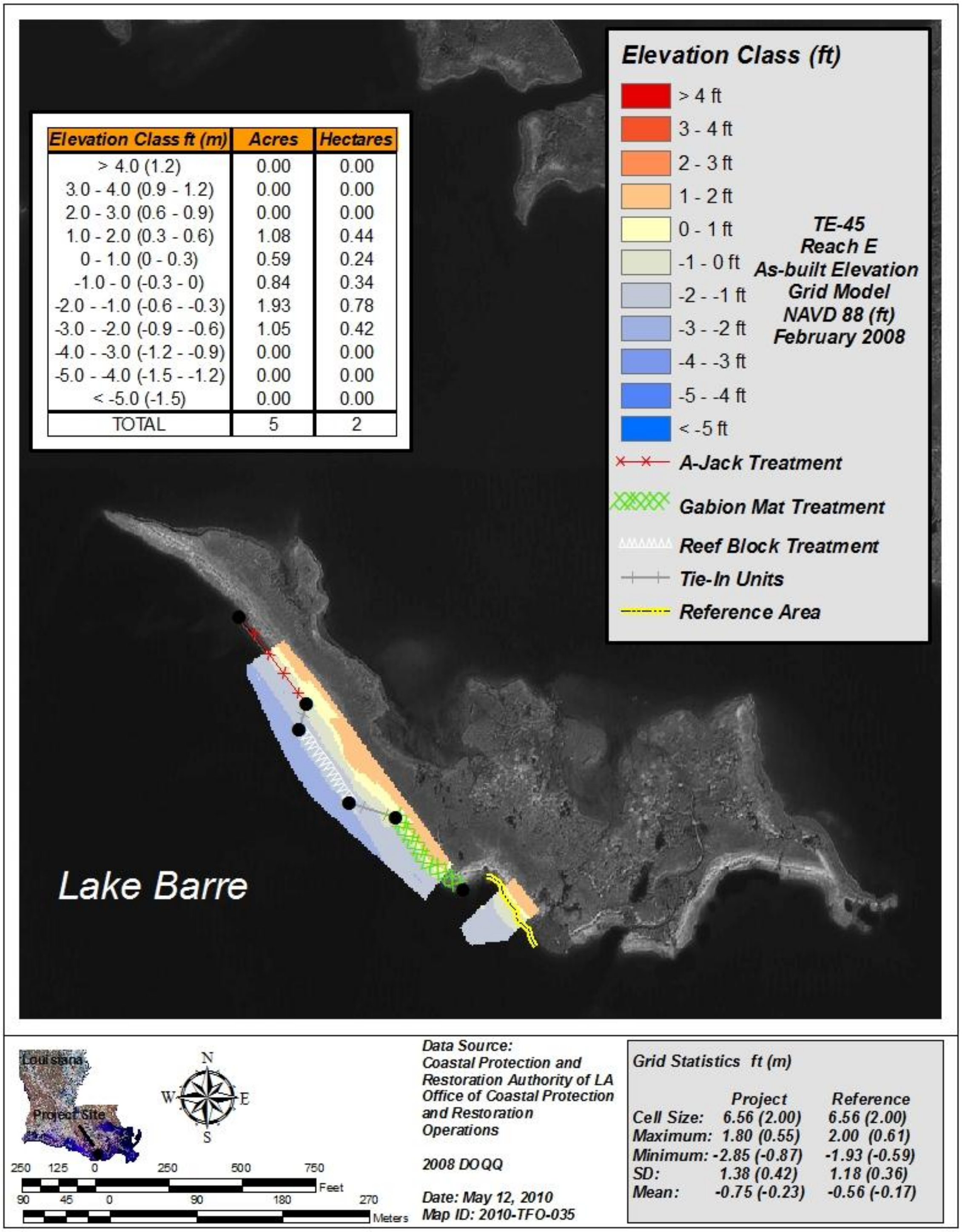


Figure D-3. As-built (Feb 2008) elevation grid model for Reaches A and B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.



Elevation Class ft (m)	Acres	Hectares
> 4.0 (1.2)	0.00	0.00
3.0 - 4.0 (0.9 - 1.2)	0.00	0.00
2.0 - 3.0 (0.6 - 0.9)	0.00	0.00
1.0 - 2.0 (0.3 - 0.6)	1.08	0.44
0 - 1.0 (0 - 0.3)	0.59	0.24
-1.0 - 0 (-0.3 - 0)	0.84	0.34
-2.0 - -1.0 (-0.6 - -0.3)	1.93	0.78
-3.0 - -2.0 (-0.9 - -0.6)	1.05	0.42
-4.0 - -3.0 (-1.2 - -0.9)	0.00	0.00
-5.0 - -4.0 (-1.5 - -1.2)	0.00	0.00
< -5.0 (-1.5)	0.00	0.00
TOTAL	5	2

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

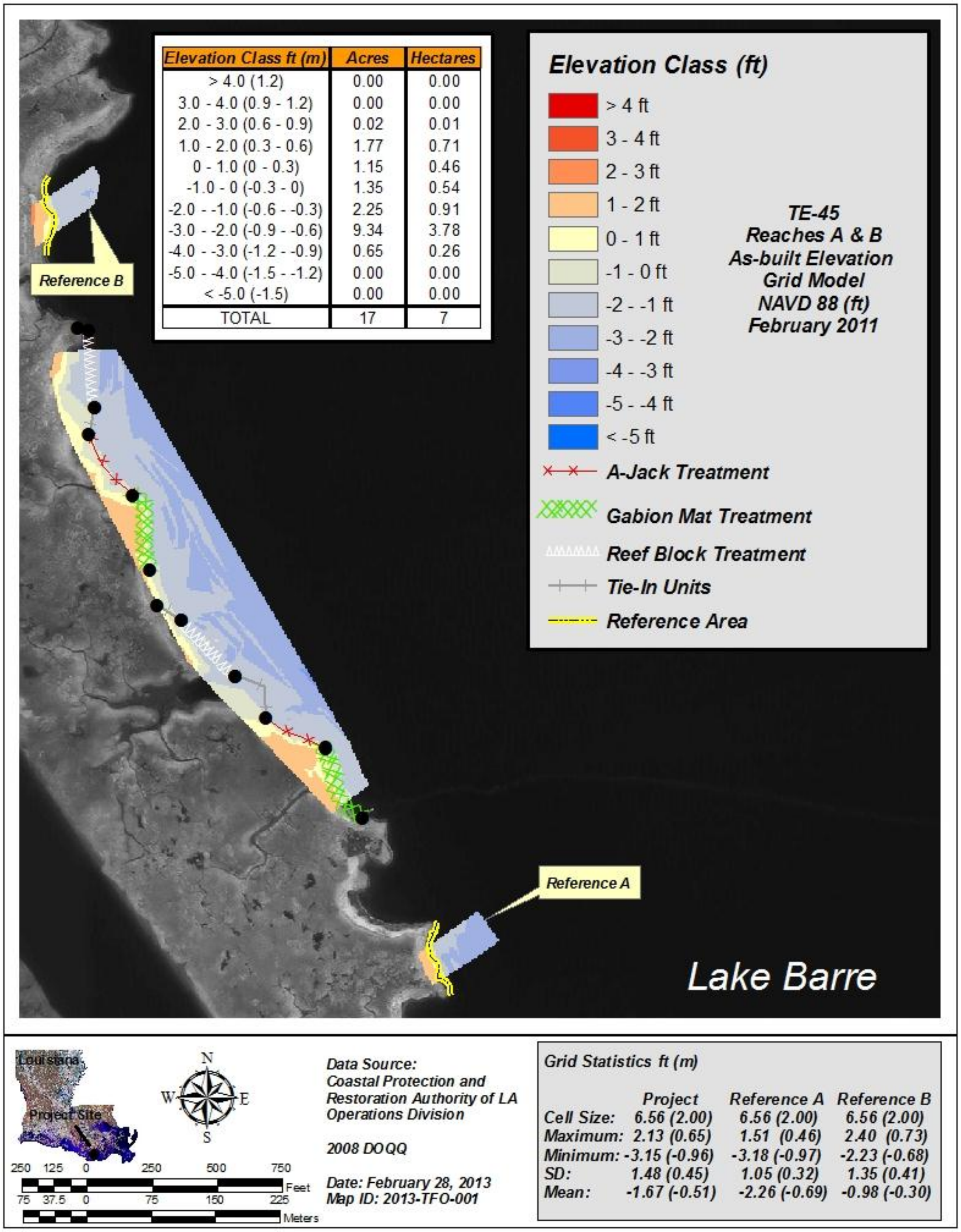


Figure D-5. Post-construction (Feb 2011) elevation grid model for Reaches A and B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

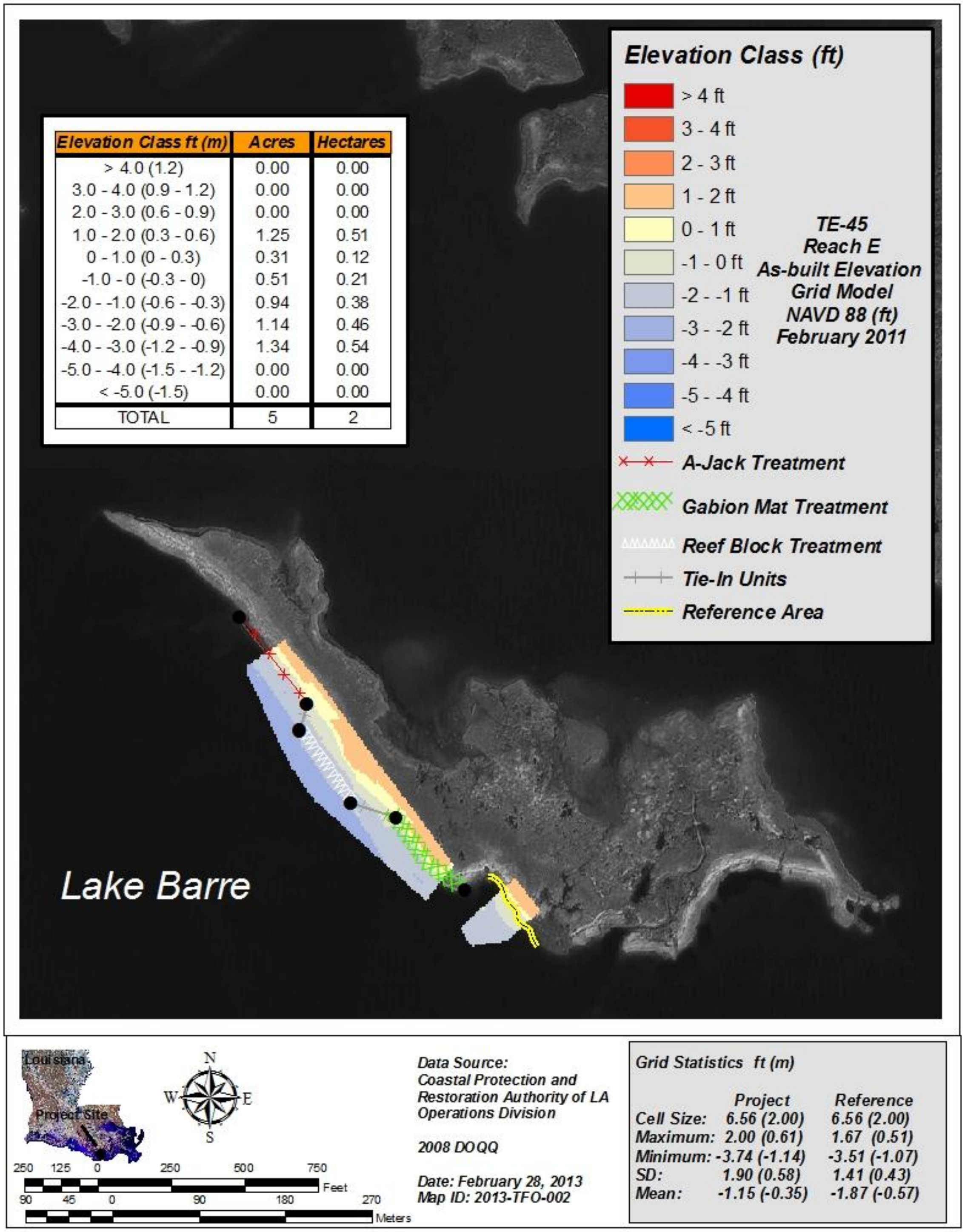


Figure D-6. **Post-construction (Feb 2011) elevation grid model for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

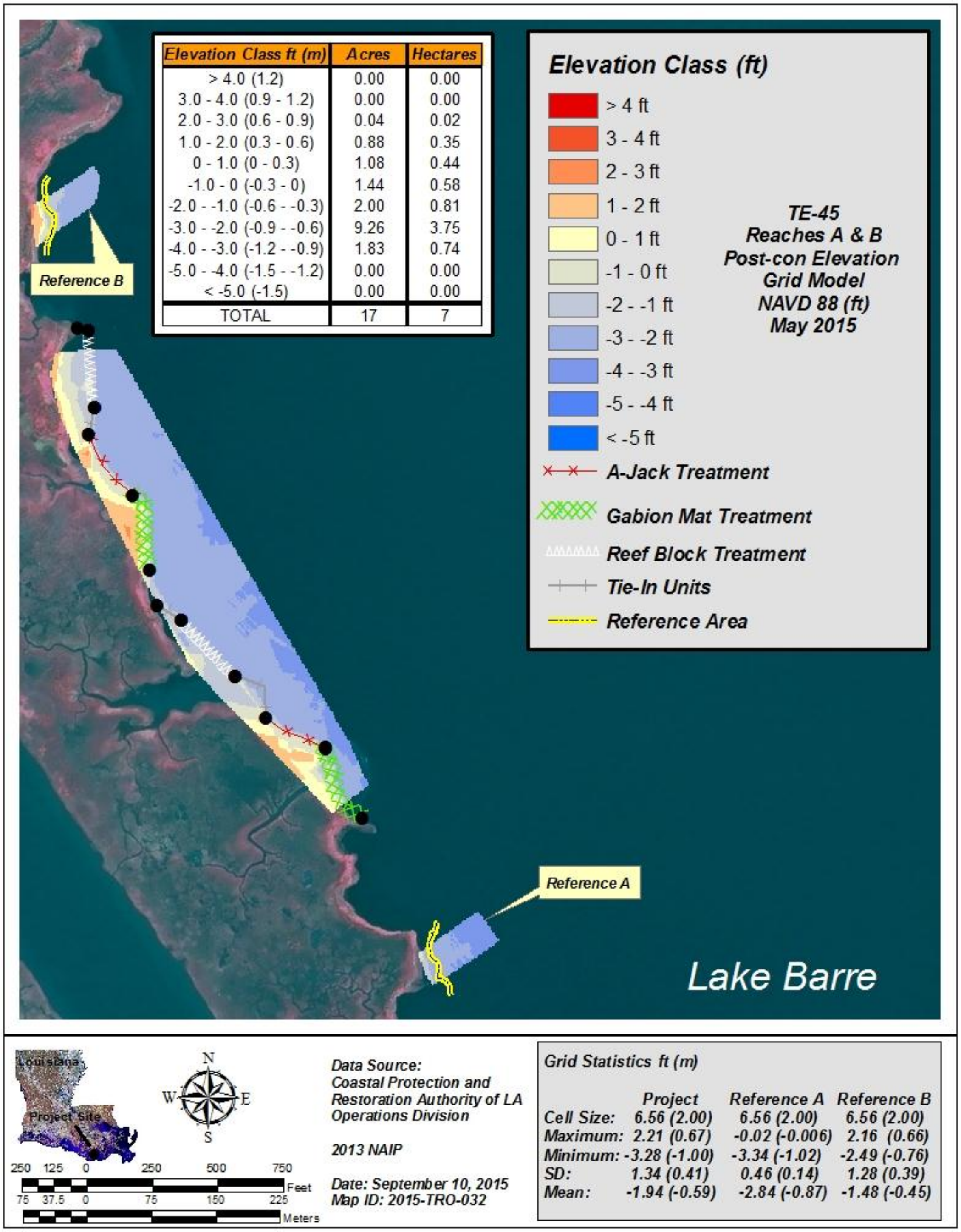


Figure D-7. Post-construction (May 2015) elevation grid model for Reaches A and B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

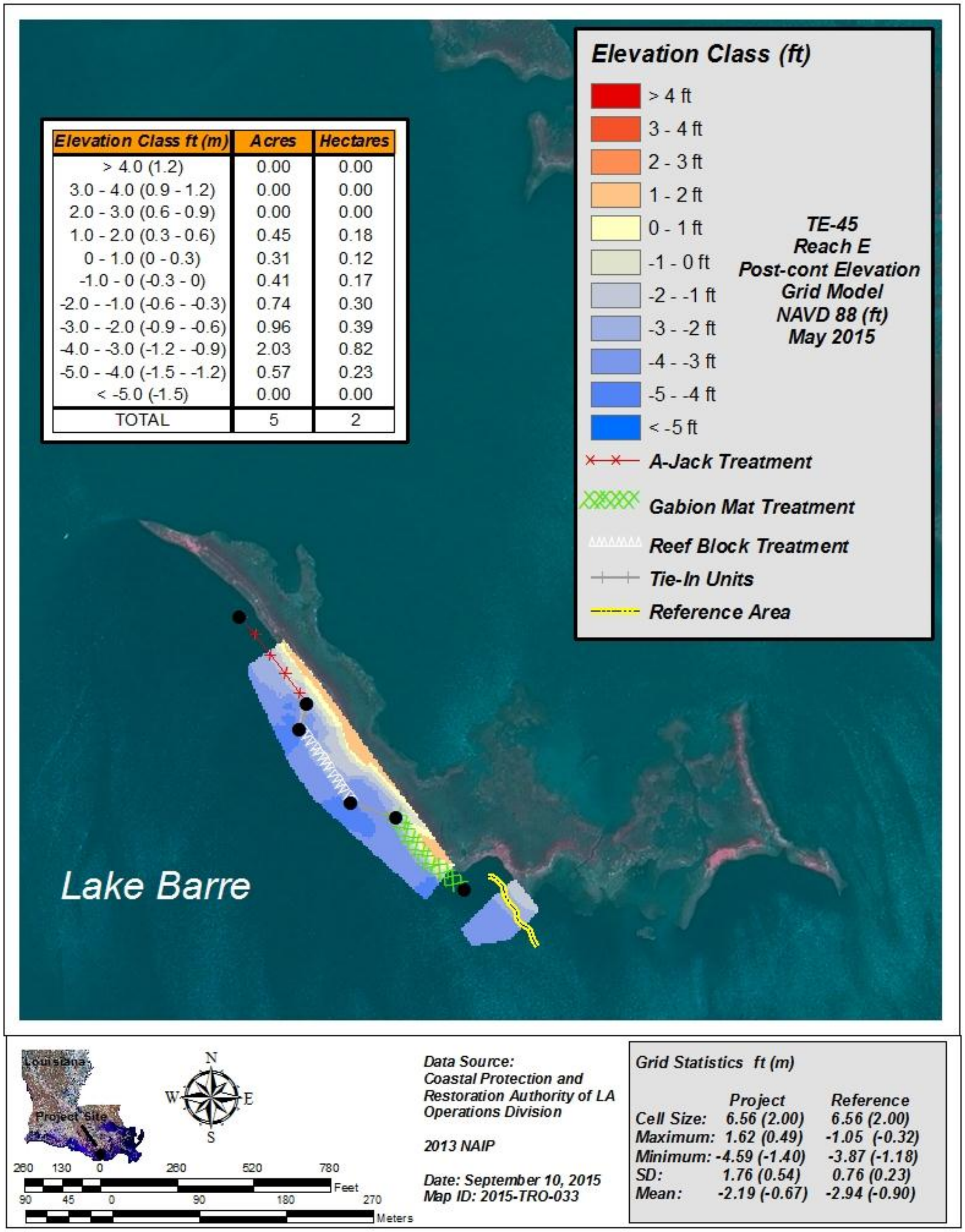


Figure D-8. **Post-construction (May 2015) elevation grid model for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

Appendix E
(Shoreline Change Graphics)

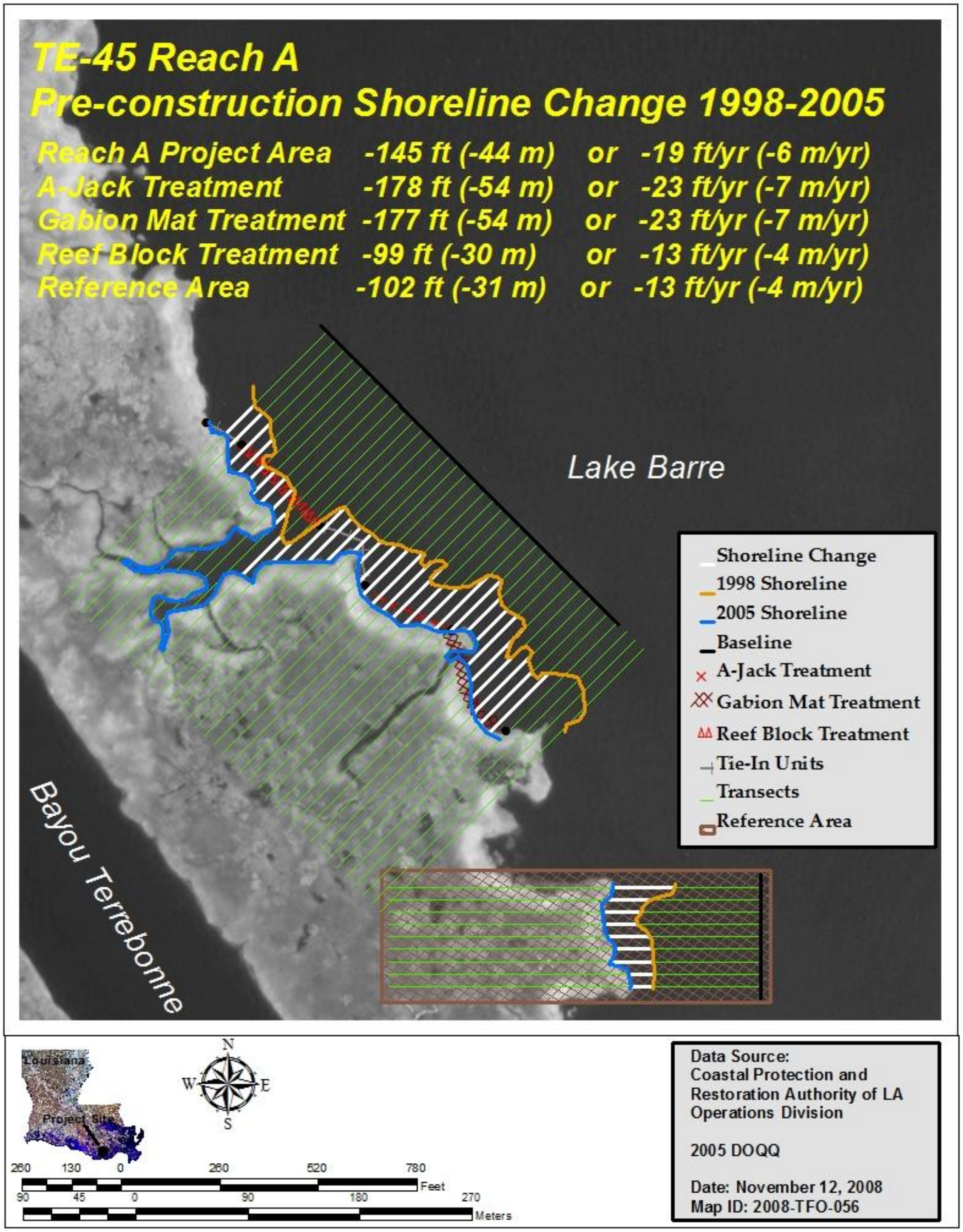


Figure E-1. **Pre-construction (1998-2005) shoreline change for Reach A at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

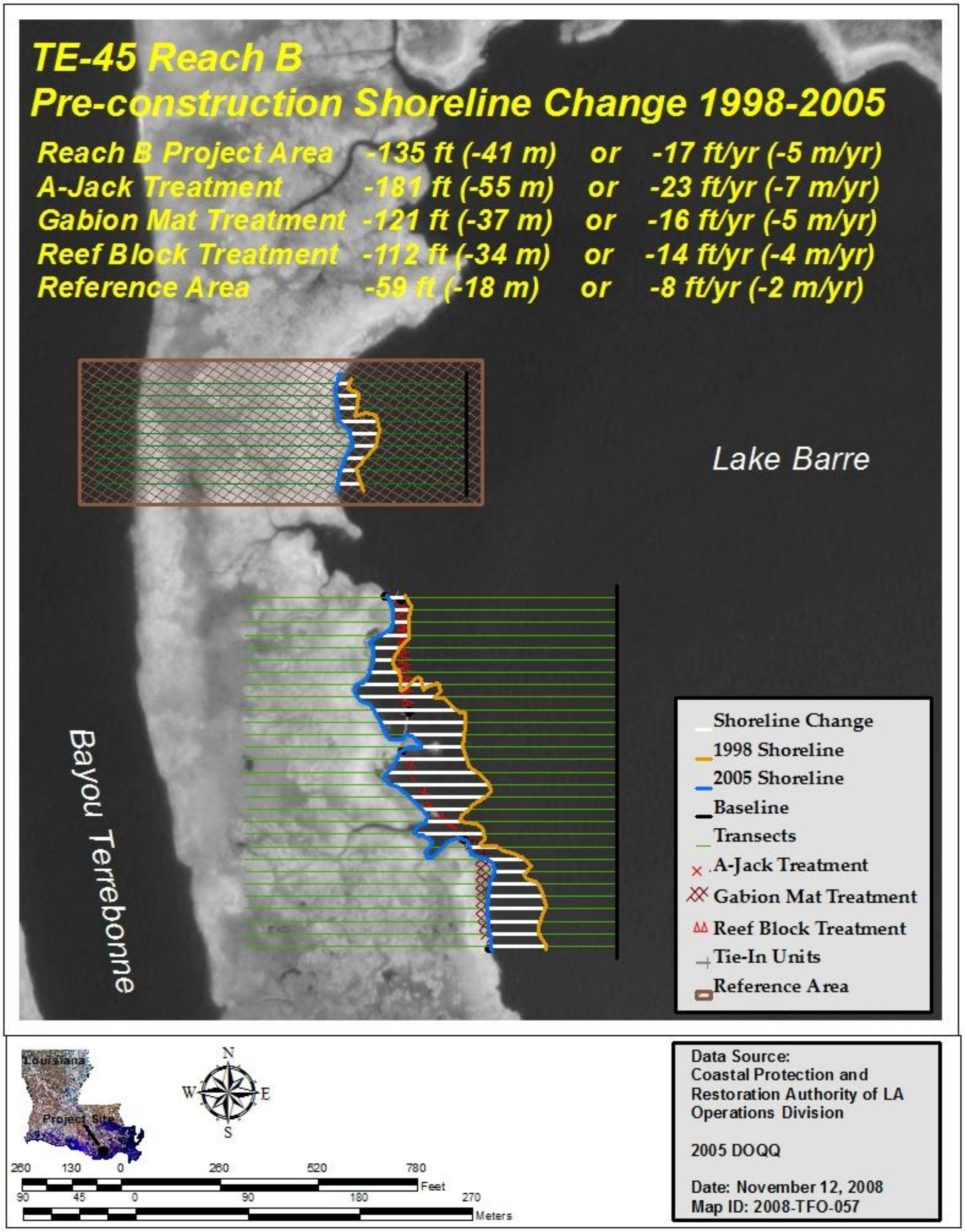


Figure E-2. Pre-construction (1998-2005) shoreline change for Reach B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

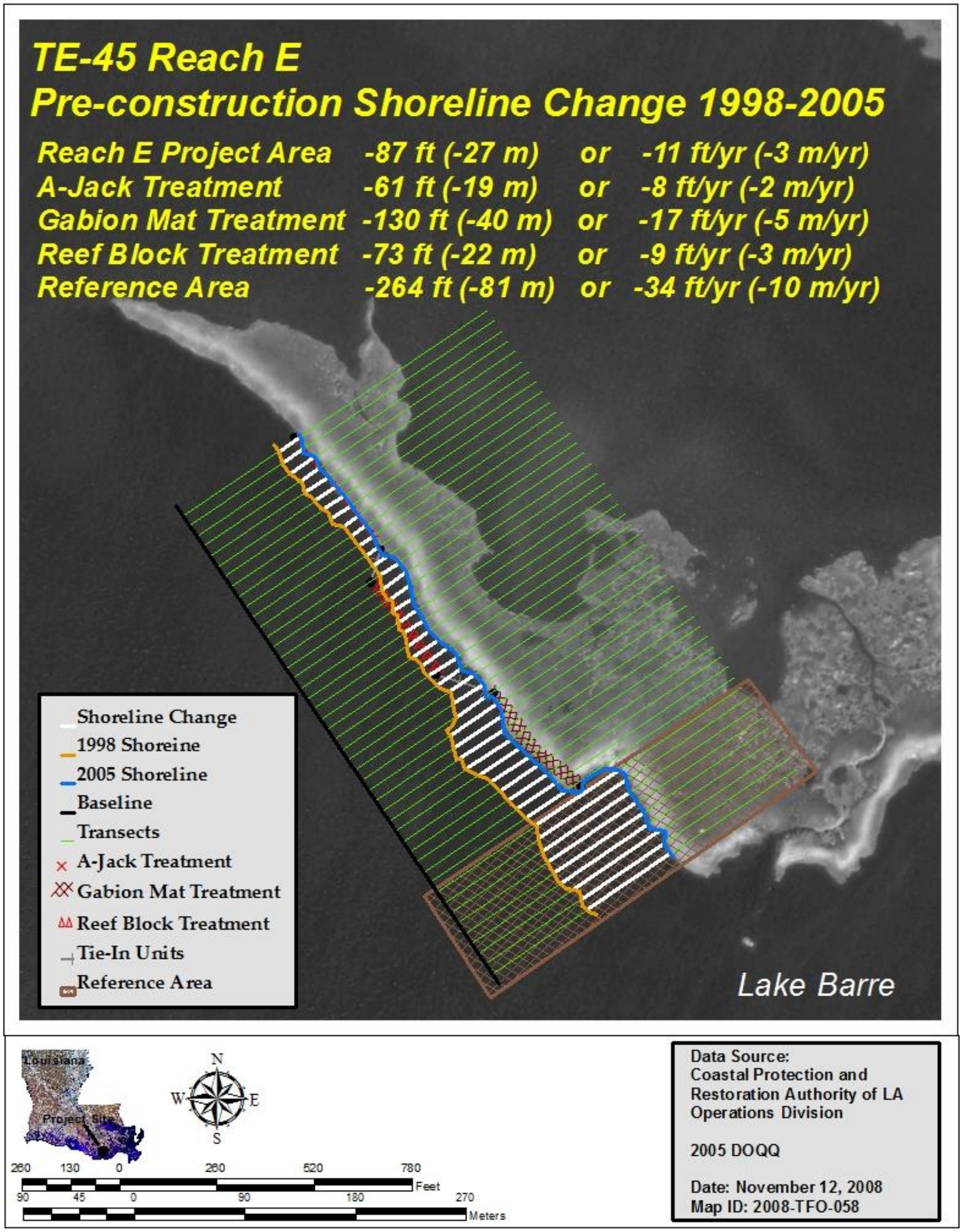


Figure E-3. **Pre-construction (1998-2005) shoreline change for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

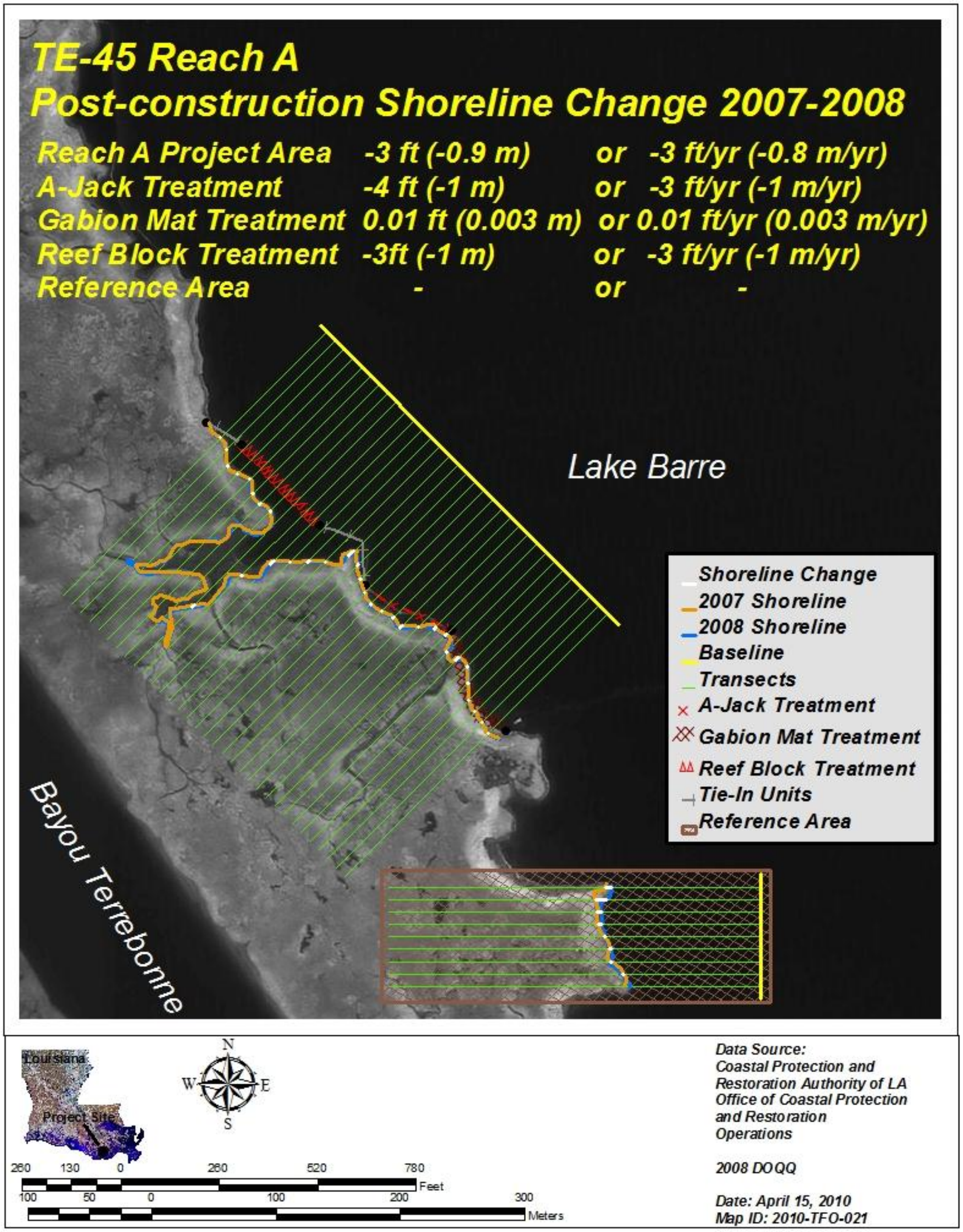


Figure E-4. **Post-construction (2007-2008) shoreline change for Reach A at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

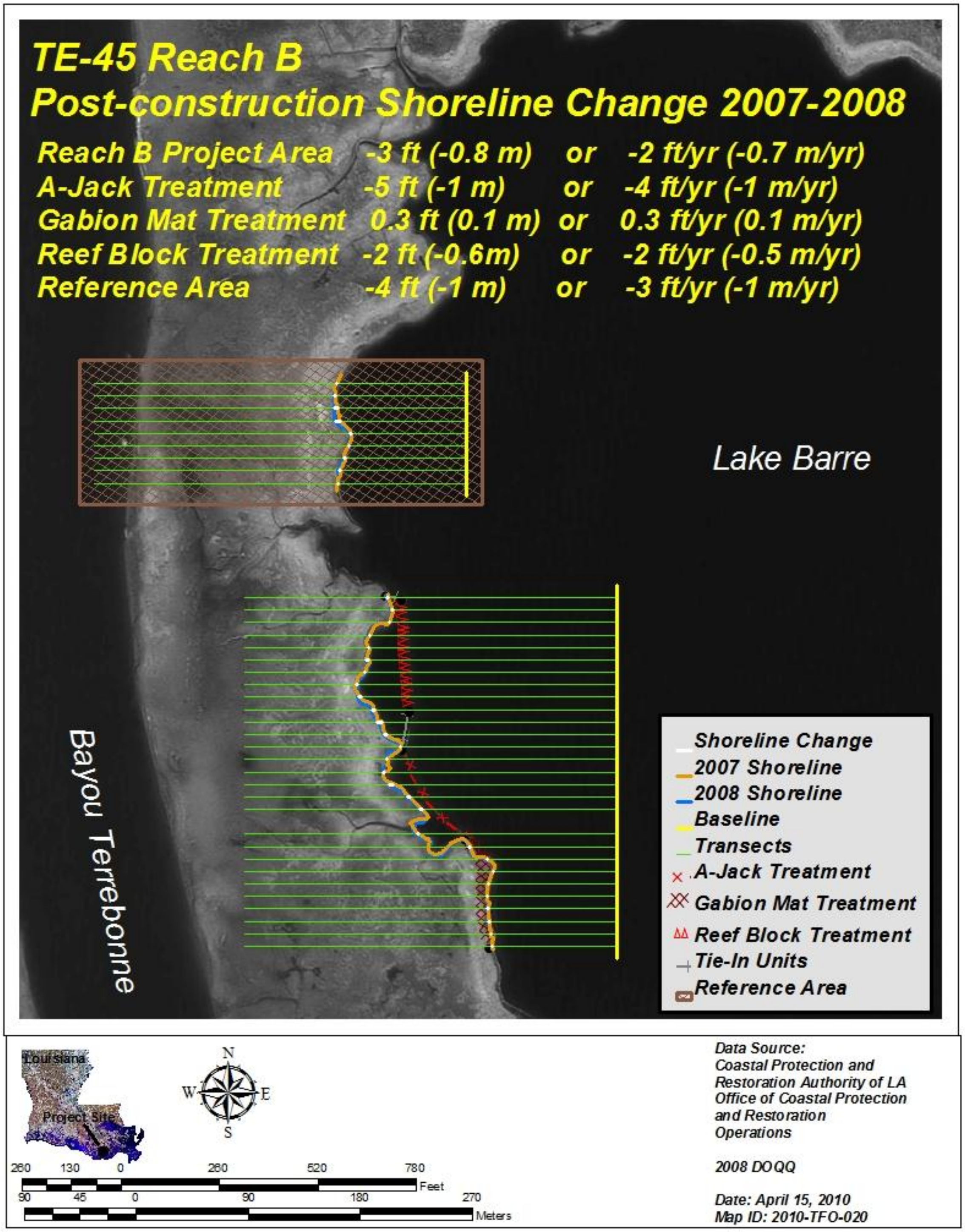


Figure E-5. Post-construction (2007-2008) shoreline change for Reach B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

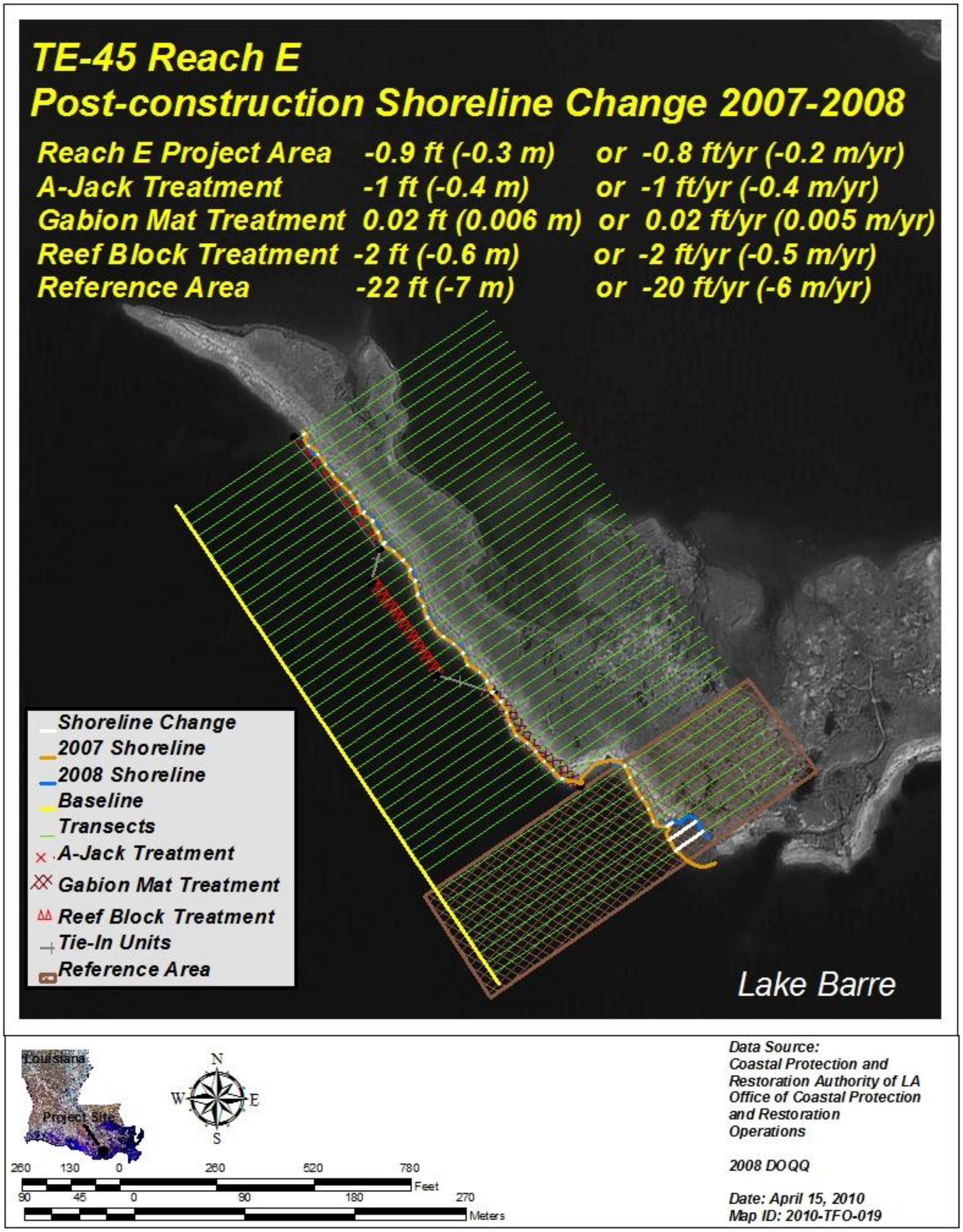


Figure E-6. **Post-construction (2007-2008) shoreline change for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.**

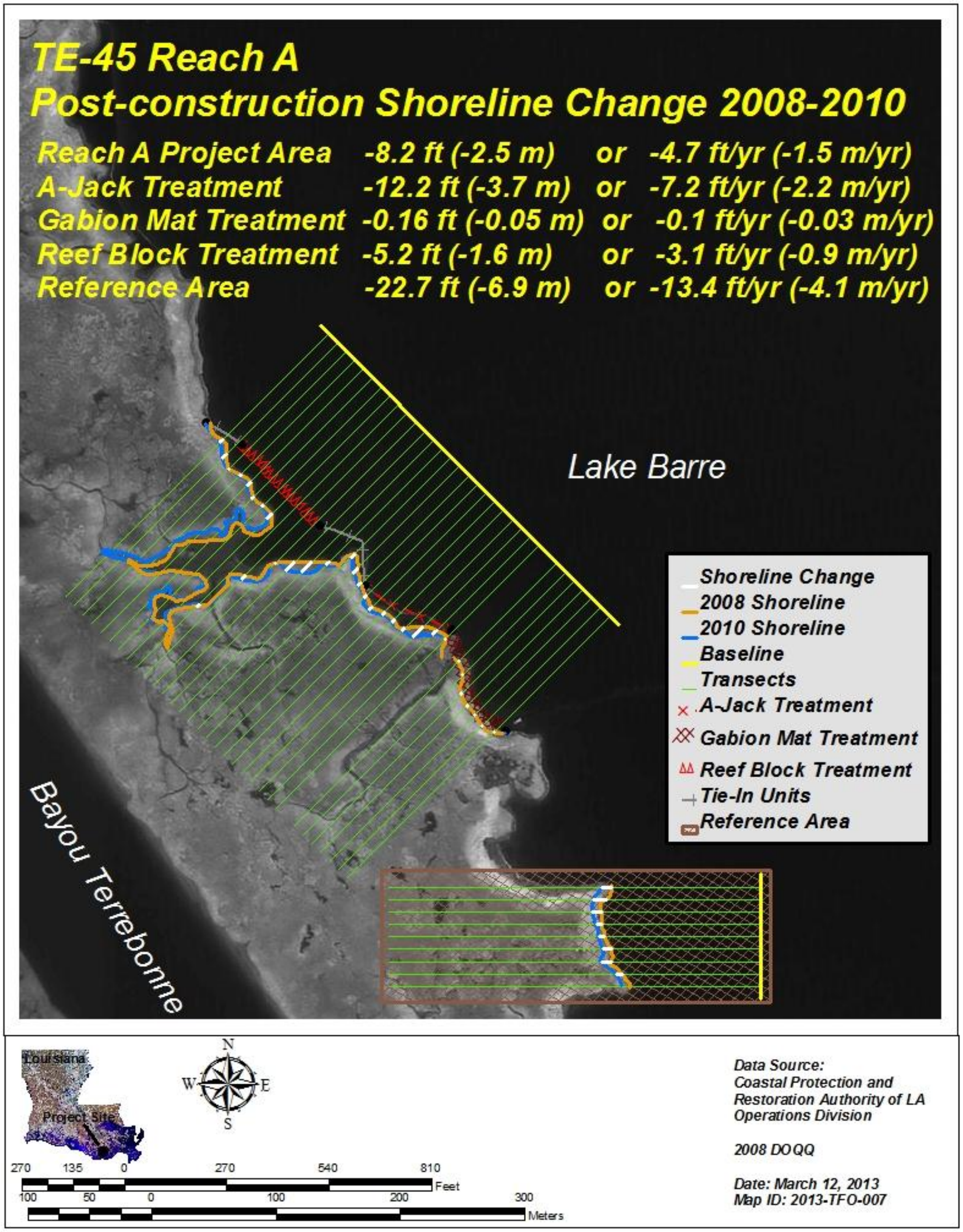


Figure E-7. Post-construction (2008-2010) shoreline change for Reach A at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

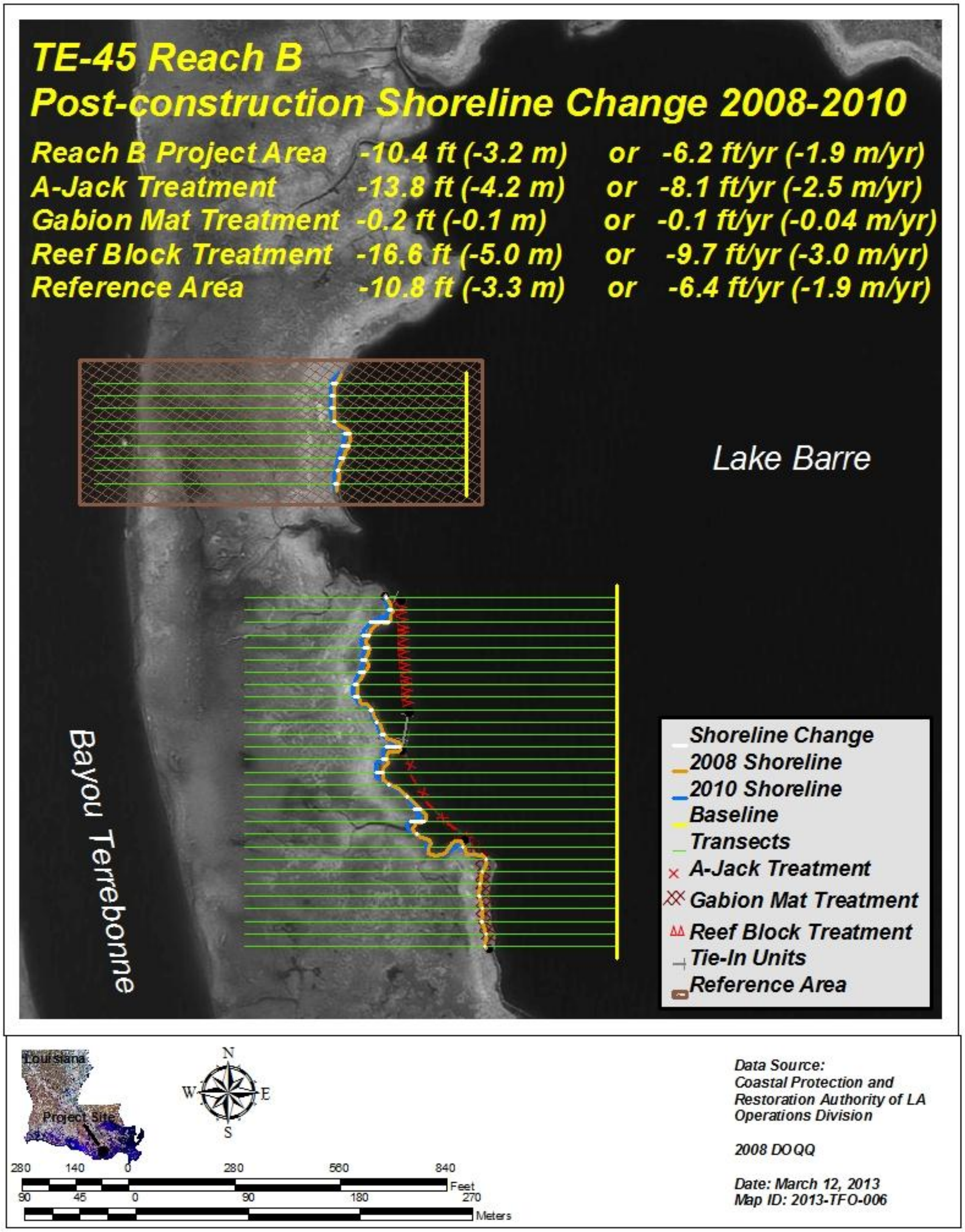


Figure E-8. Post-construction (2008-2010) shoreline change for Reach B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

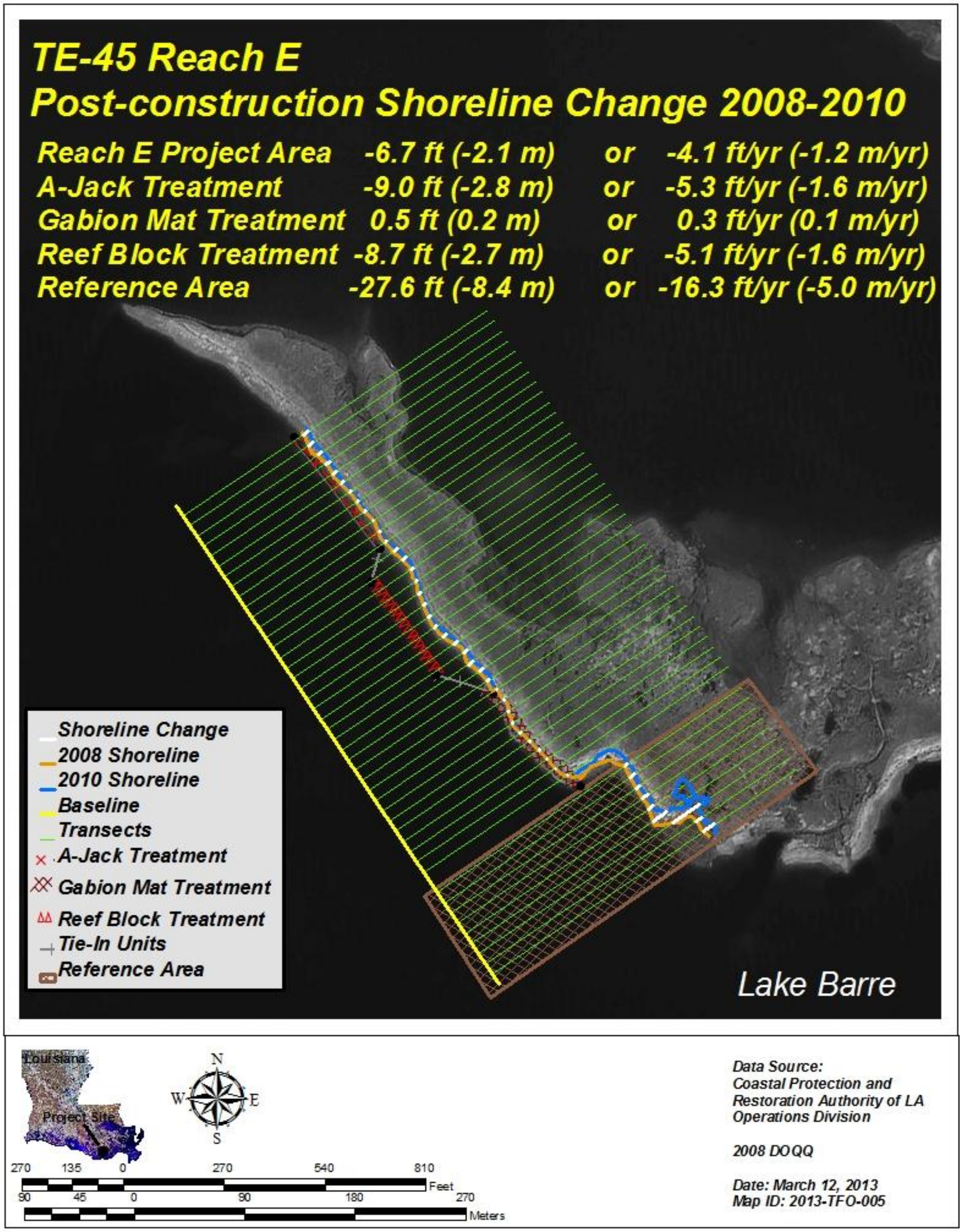


Figure E-9. Post-construction (2008-2010) shoreline change for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

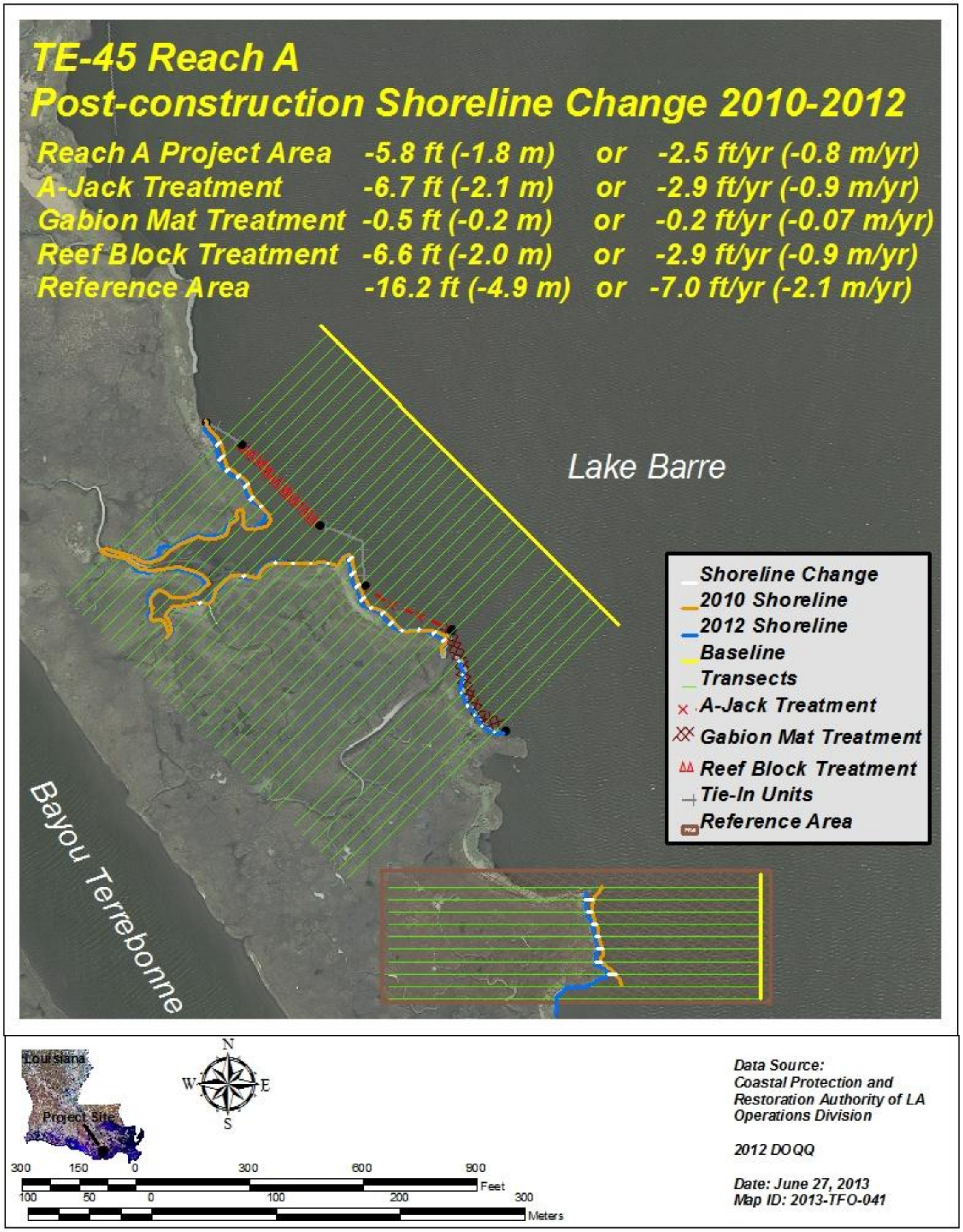


Figure E-10. Post-construction (2010-2012) shoreline change for Reach A at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

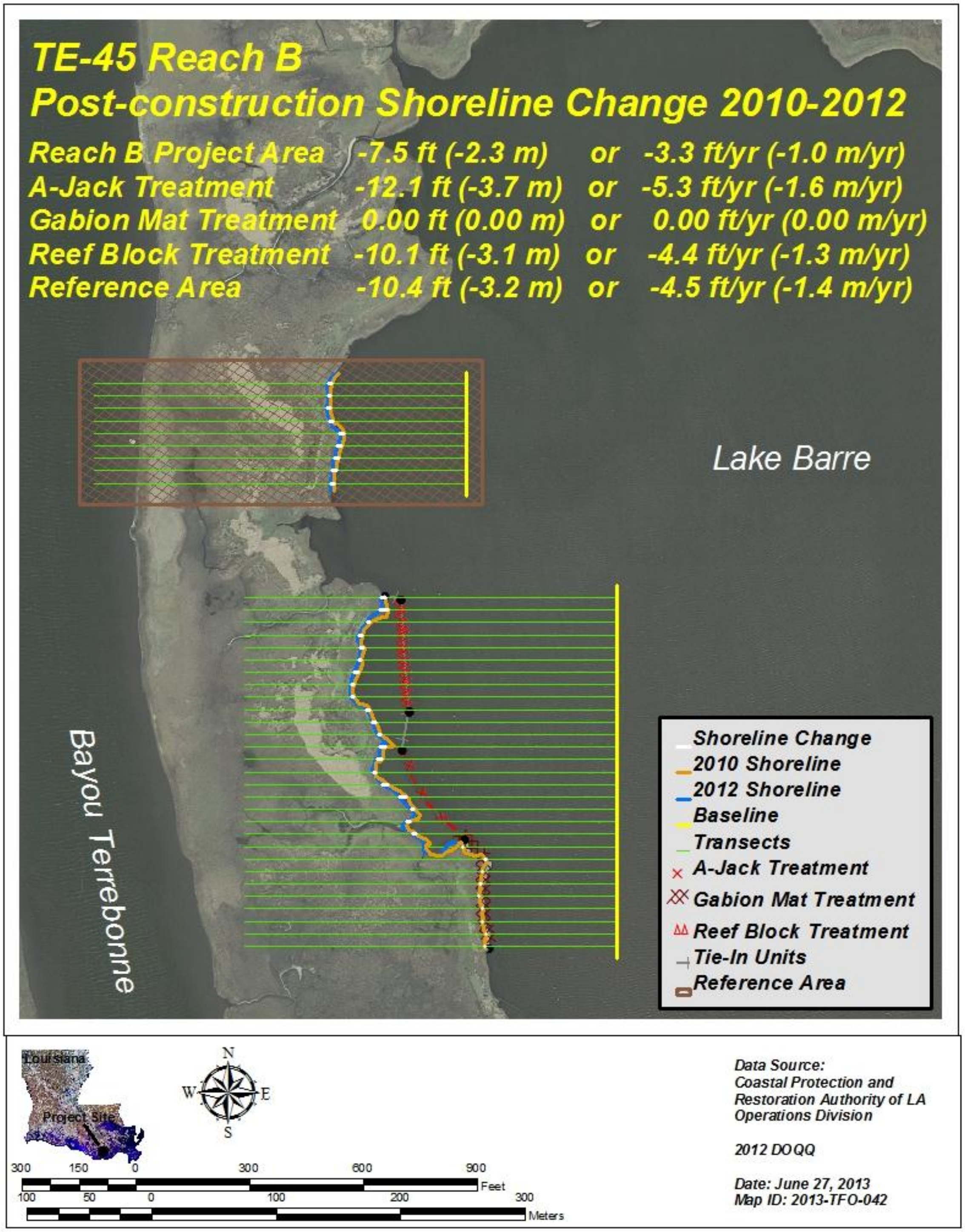


Figure E-11. Post-construction (2010-2012) shoreline change for Reach B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

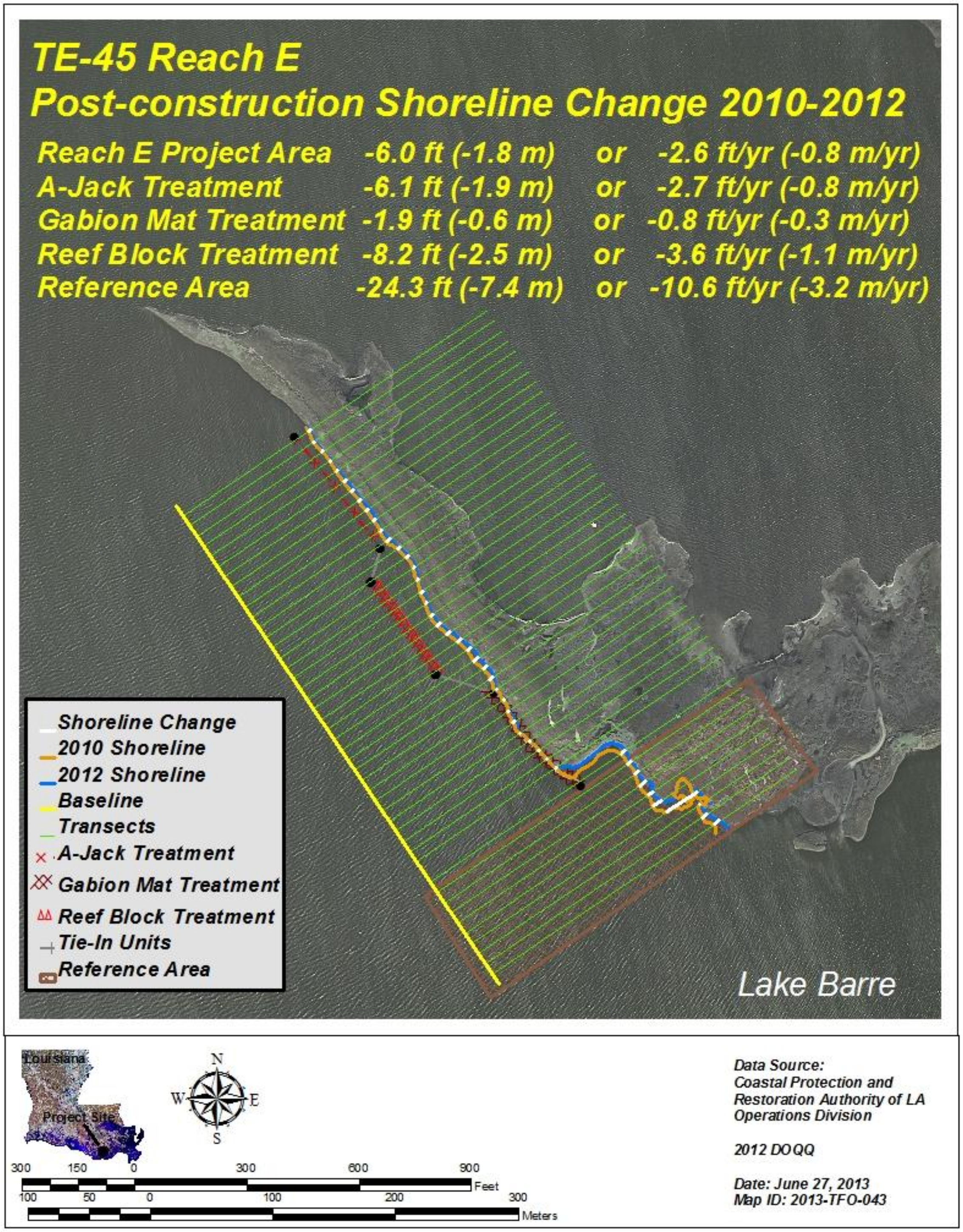


Figure E-12. Post-construction (2010-2012) shoreline change for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

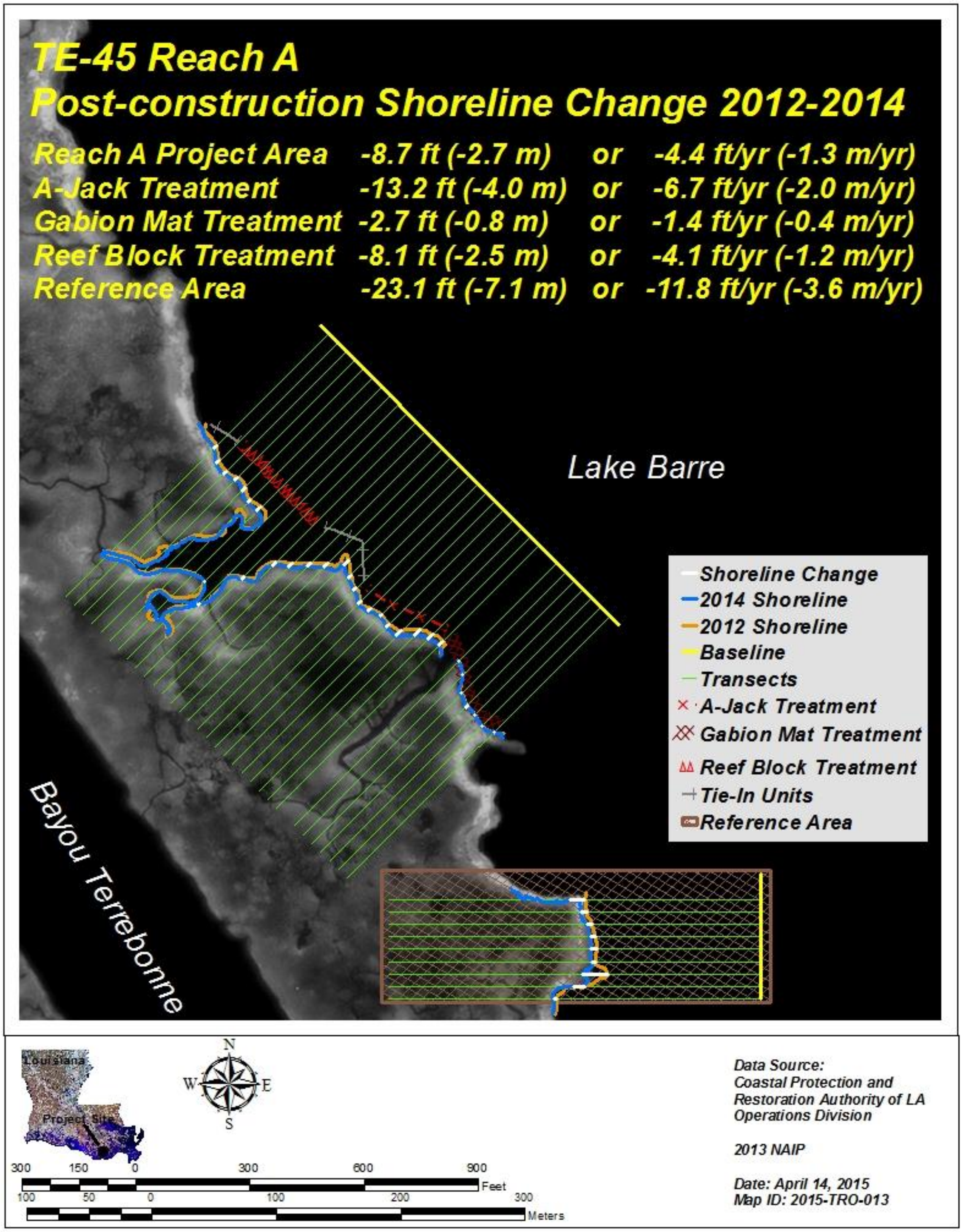


Figure E-13. Post-construction (2012-2014) shoreline change for Reach A at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

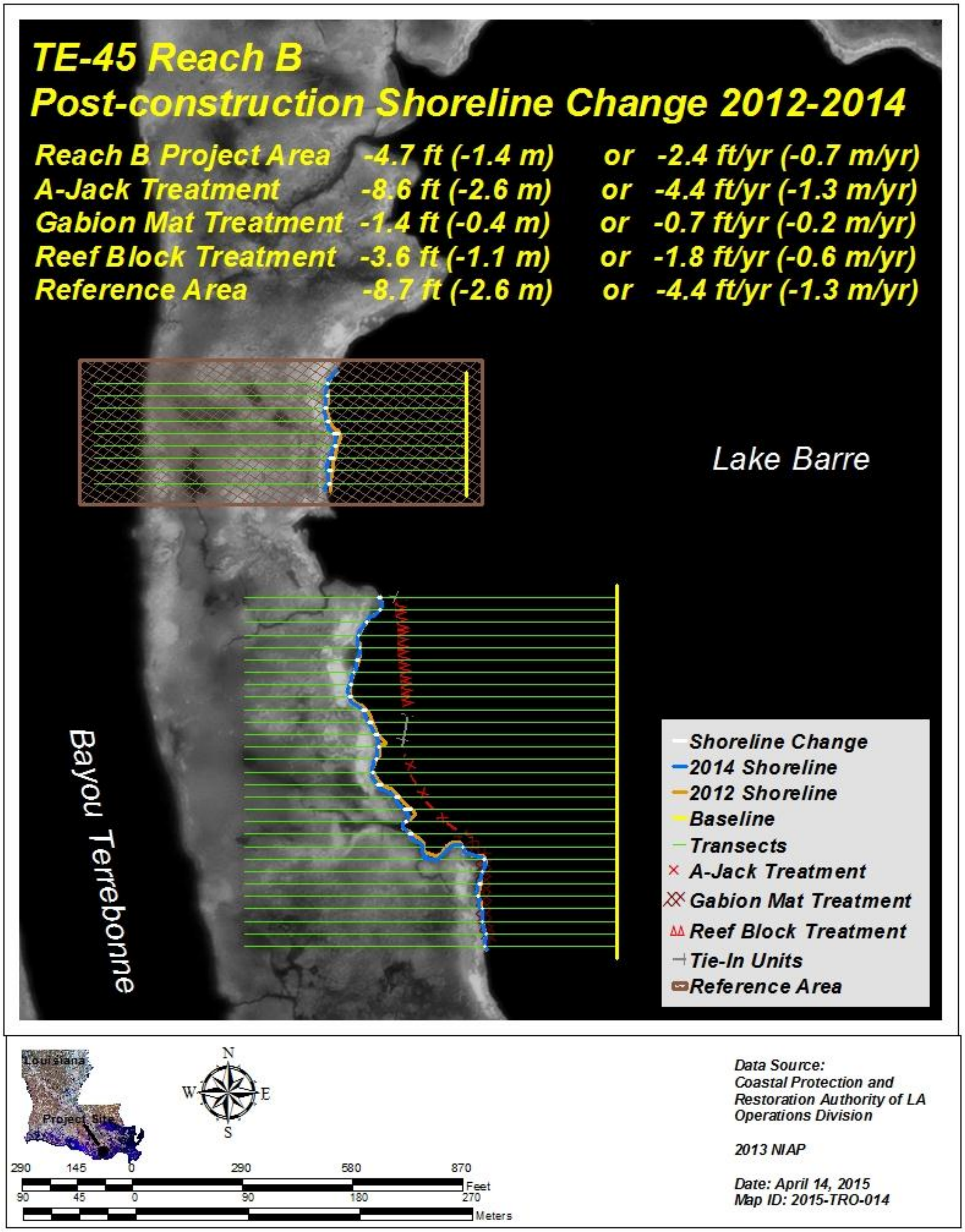


Figure E-14. Post-construction (2012-2014) shoreline change for Reach B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

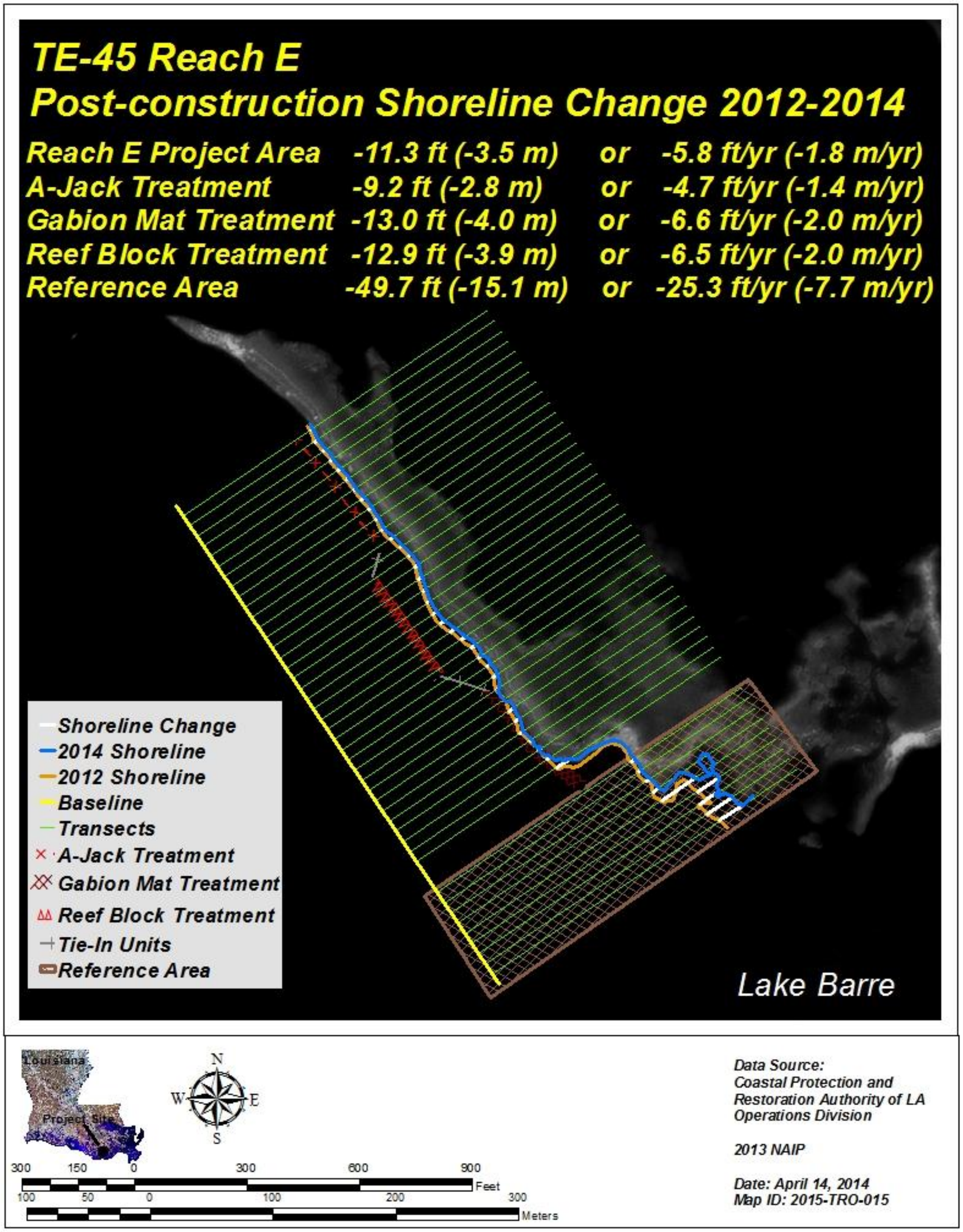


Figure E-15. Post-construction (2012-2014) shoreline change for Reach E at the Terrebonne Bay EShore Protection Demonstration (TE-45) project.

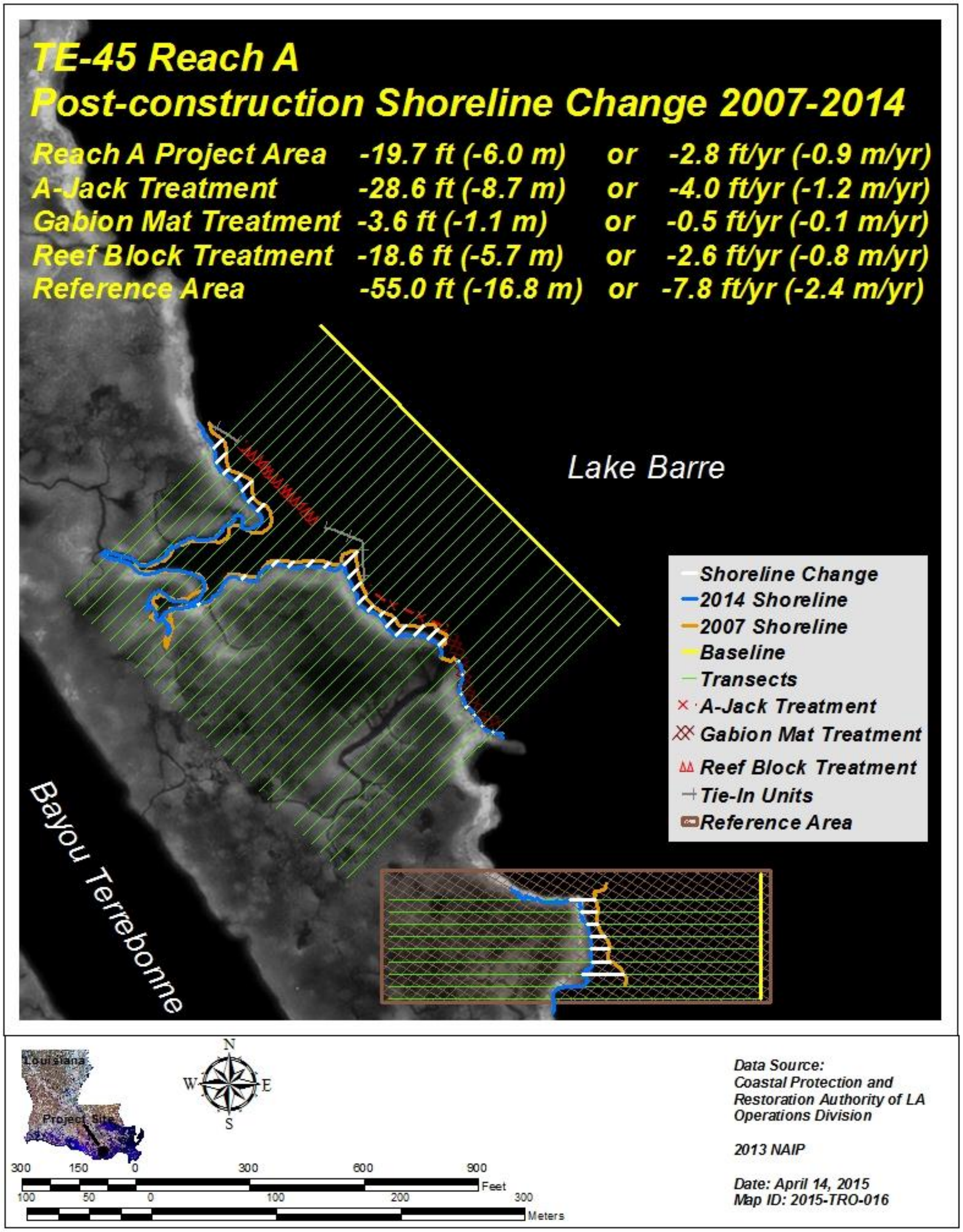


Figure E-16. Post-construction (2007-2014) shoreline change for Reach A at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

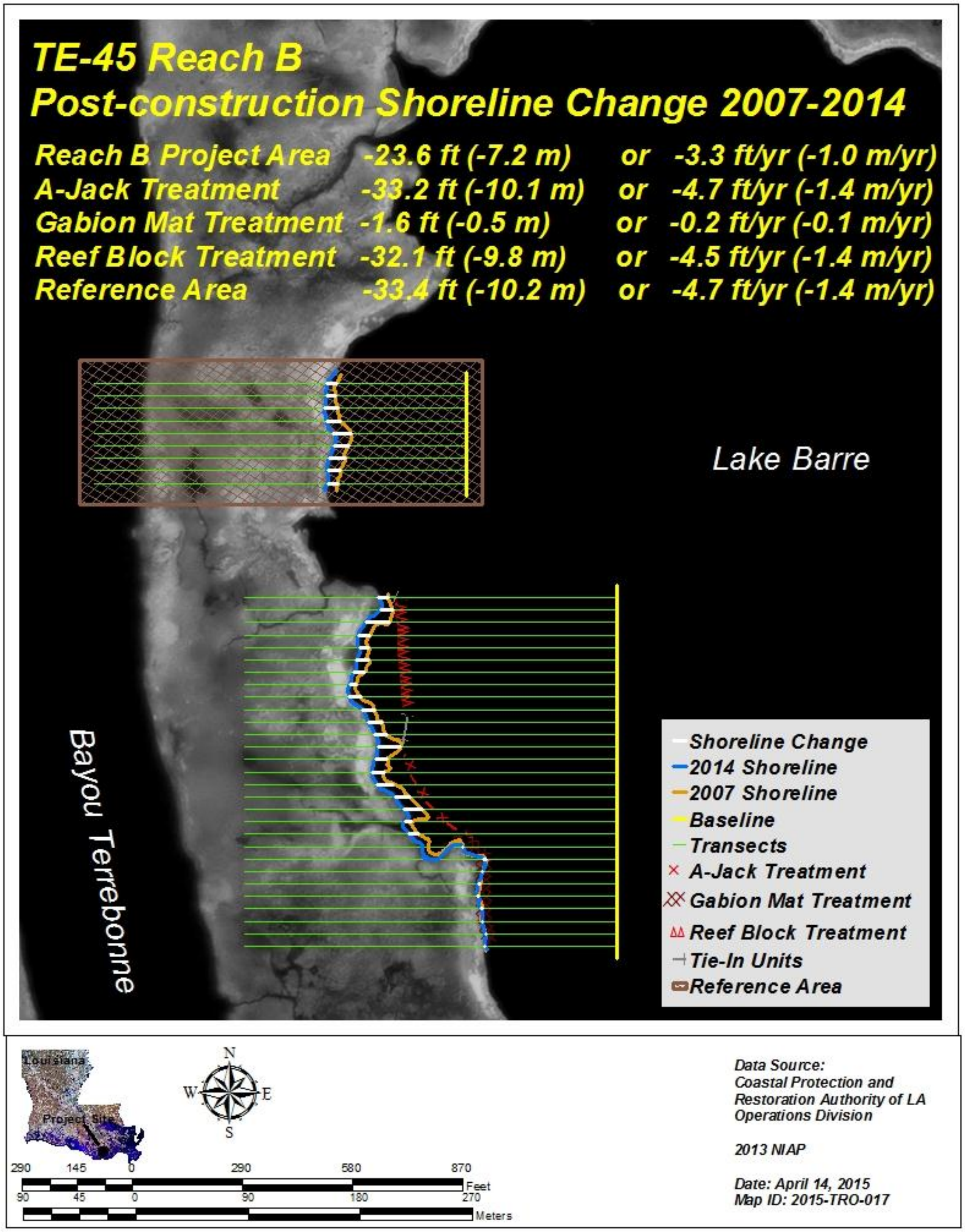


Figure E-17. Post-construction (2007-2014) shoreline change for Reach B at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.

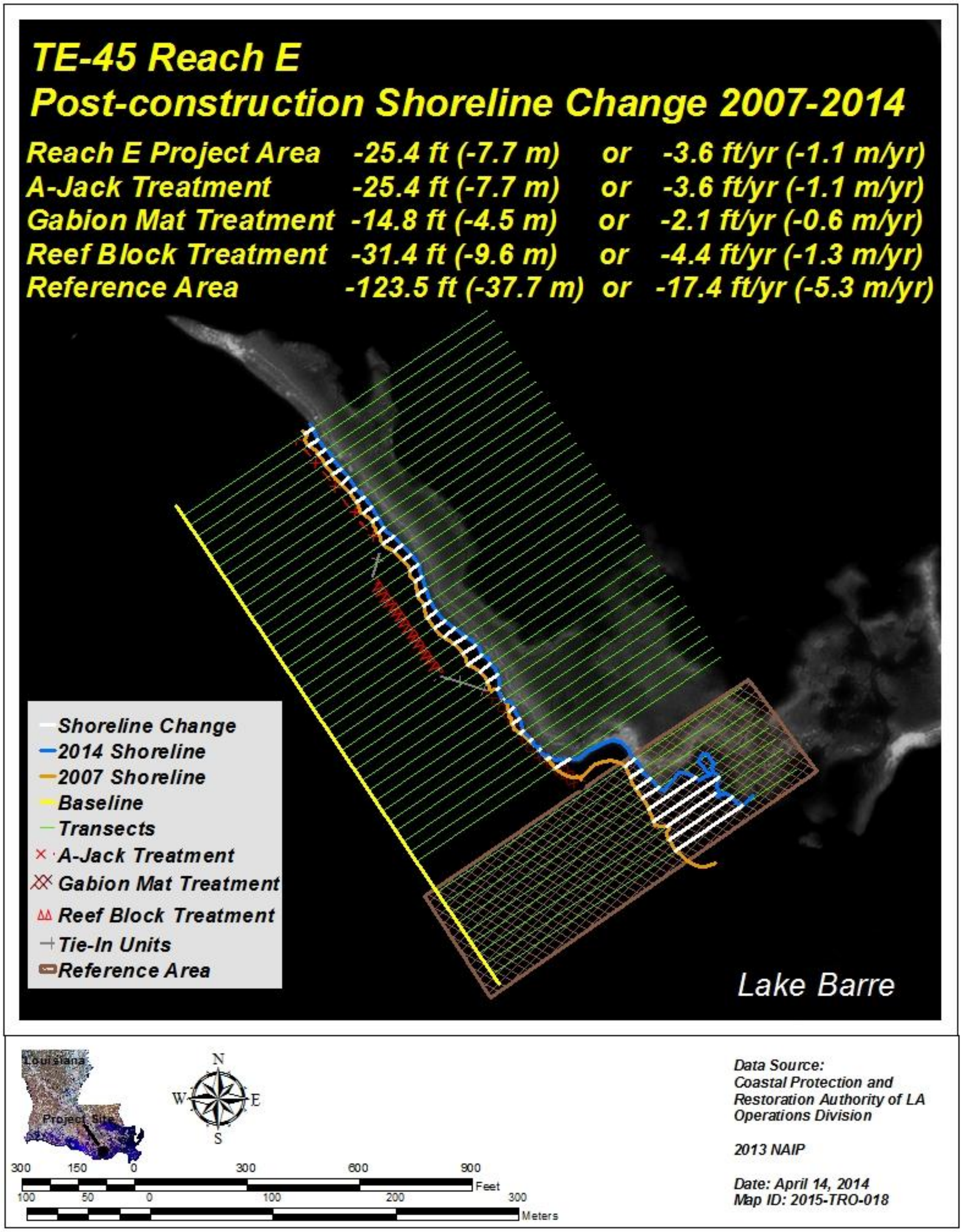


Figure E-18. Post-construction (2007-2014) shoreline change for Reach E at the Terrebonne Bay Shore Protection Demonstration (TE-45) project.