COASTAL TEXAS STUDY

Beach & Dune Design

Jason Thies, Paul Hamilton, & Himangshu Das, SWG

10/1/2020

Table of Contents

INTRODUCTION

The upper Texas coastline is retreating, on the order of 2 to 5 feet per year and in excess of 20 feet per year in some regions (HDR, 2014). The Coastal Texas Study was developed in a coordinated effort with local sponsor the Texas General Land Office (GLO) to respond to ongoing shoreline recession and to develop solutions to improve Texas coastal resilience. Severe storm events are capable of severely exacerbating shoreline erosion, weakening coastal resilience and creating billions of dollars in damage.

This study specifically addresses the feasibility of nature-based protection and restoration measures along Galveston Island, Bolivar Peninsula, and Follet's Island. Coastal Storm Risk Management (CSRM) and Ecosystem Restoration (ER) measures, though similar in concept, are two distinct sub-categories within this study that can be characterized by their intended purpose and area of interest. Coastal Storm Risk Management is oriented towards protection of coastal structures and their inhabitants, located in more densely populated coastal regions including parts of Bolivar Peninsula and Galveston Island. Conversely, Ecosystem Restoration seeks to restore and sustain the existing habitat in less populated stretches of coastline such as Follet's Island.

The methodologies employed to evaluate CSRM and ER measures are essentially identical. Contiguous, morphologically similar reaches of shoreline are identified, from which a set of representative cross-shore profiles are developed within each area of interest. The numerical model SBEACH (Storm-Induced BEAch Change) is used to simulate the storm-induced cross-shore response of existing profiles and alternative configurations. A review of modeled post-storm profile changes informs decisions on design feasibility and provides the basis for sediment budget requirements.

1. PROJECT SCOPE

The primary purpose of this study is to develop a tentatively selected plan (TSP) that includes the general configuration and dimensions of a dune-berm-beach profile. Selection is based on profile performance criteria that includes the duration and magnitude of profile inundation, and dune overtopping, relative to volume estimates calculated for initial construction and periodic nourishment. The development of volume estimates is primarily intended for use as an order of magnitude comparison between alternative profile configurations. However, estimates serve an auxiliary function as a low-resolution estimate of the required sediment budget for construction and periodic nourishment of the selected plan.

The development of a detailed sediment budget will require extensive surveying and computational modeling with higher spatial-resolution, longer timescales, and coupling of regional longshore and cross-shore sediment transportation processes that account for local shoreline variations.

There have been substantial efforts to research and document historic shoreline changes, and to model longshore processes along Galveston and Bolivar shorelines. Historic shoreline change is based on review of historic aerials and shoreline surveys and is typically measured in terms of shoreline advance or retreat. An ERDC Technical Report titled *Wave and Beach Processes Modeling for Sabine Pass to Galveston Bay, Texas, Shoreline Erosion Feasibility Study* compares historic trends in the study area to modeled longshore losses using a STWAVE/GENESIS coupled model (King, 2007). Model results show good comparison to historic trends and provide a link between shoreline movement and net volumetric changes. Model results show an average annual transport rate within the Bolivar Peninsula study area ranging between approximately 80K to 160K cubic yards per year of net losses in the southwest direction (King, 2007, pp. 103, Figure 56). In West Galveston, King similarly reports net losses in the southwest direction, but at a reduced rate that peaks at approximately 52K cubic-yards per year and averages closer to 32K cubic-yards per year (King, 2007, pp. 104, Figure 57). Longshore processes contribute heavily to long-term changes in beach morphology, however they are confined to the littoral zone and have no direct impact on dune performance, provided there is a large enough buffer (beach/berm) between the dune and surf-zone. Dune performance is primarily influenced by cross-shore sediment transportation, which is the dominant process during a solitary storm event. Therefore, the longshore effects are not considered in the analysis of storm-induced dune and berm performance and are not directly involved in estimating the sediment budget. Instead a probabilistic approach is used to calculate the advanced nourishment equivalent to 10-years of periodic nourishment, which is included in the overall sediment budget estimate.

2. COASTAL STORM RISK MANAGEMENT (CSRM) AREA OF INTEREST

The Coastal Storm Risk Management (CSRM) study site is located on the upper Texas coastline, enveloped within the borders of Galveston County, including portions of Galveston Island and Bolivar Peninsula. More specifically, the site includes approximately 19 miles of western Galveston Island shoreline, from San Luis Pass to the western end of the seawall and 26 miles of western Bolivar Peninsula, from Fort Travis to High Island. The region is characterized by its sandy barrier island terrain with two bay inlets including San Luis Pass at the western end of the site, and the Galveston Entrance Channel entrance, which separates Bolivar Peninsula from Galveston Island. The landward (cross-shore) project limit is the CSRM alignment, a shore-parallel line approximately equivalent to the leeward toe of the existing dune system. The CSRM line serves as the baseline (zero point) for the development of all cross-shore profiles.

Figure 1: End of Galveston seawall marks beginning of study site's western extent

Most of the study site is characterized by residential development with minimal natural or manmade shoreline protection. Natural dune and berm features exist throughout most of the study site, however dunes are generally less contiguous and vegetated than the dunes on the east end of Galveston Island. The east end of the study site, on Bolivar Peninsula near High Island, dunes are nonexistent and the beach tapers down to a narrow section that provides the only buffer between the riprap lined Highway 87 and the Gulf of Mexico.

Figure 2: Study site near east end of Bolivar, beach narrows between surf zone and Hwy 87

Net shoreline change in the study area is highly segmented, and regions of notable local accretion are distinguished by existing shoreline structures, namely the Galveston Entrance Channel jetties. Net shoreline advance (accretion) exists adjacent to the north and south side of the Galveston Entrance channel jetties, which impound sand trapped in littoral drift currents, as well as north of San Luis pass. For example, the Bureau of Economic Geology reports shoreline advance on Galveston Island's east beach at an average net rate of 12.5 feet per year between the 1930's and 2012, while the region within the study site (west of the seawall) experienced retreat at 3.2 feet per year during the same period (Paine, 2014). The maximum average historic shoreline recession rate on Galveston Island is near the west end of the seawall, where the shoreline recedes at a rate upwards of 8.85 feet per year. To the east, the study site extends to High Island, where it is intended to tie into a similar ongoing dune restoration project along the McFaddin Nature Wildlife Preserve (NWR). Historic average shoreline recession rates on Bolivar are reported as high as 5.9 feet per year (Paine 2014).

The 2013 report by the Bureau of Economic Geology classified the entire Texas coastline with a storm susceptibility index rating based on the general shoreline elevation. The rating ranges from 1 to 8, with 1 being the lowest protection rating and 8 being the highest (Paine, 2013). The protection rating generally decreases from southwest to northeast along the Texas coastline, with the exception of manmade features such as the Galveston seawall.

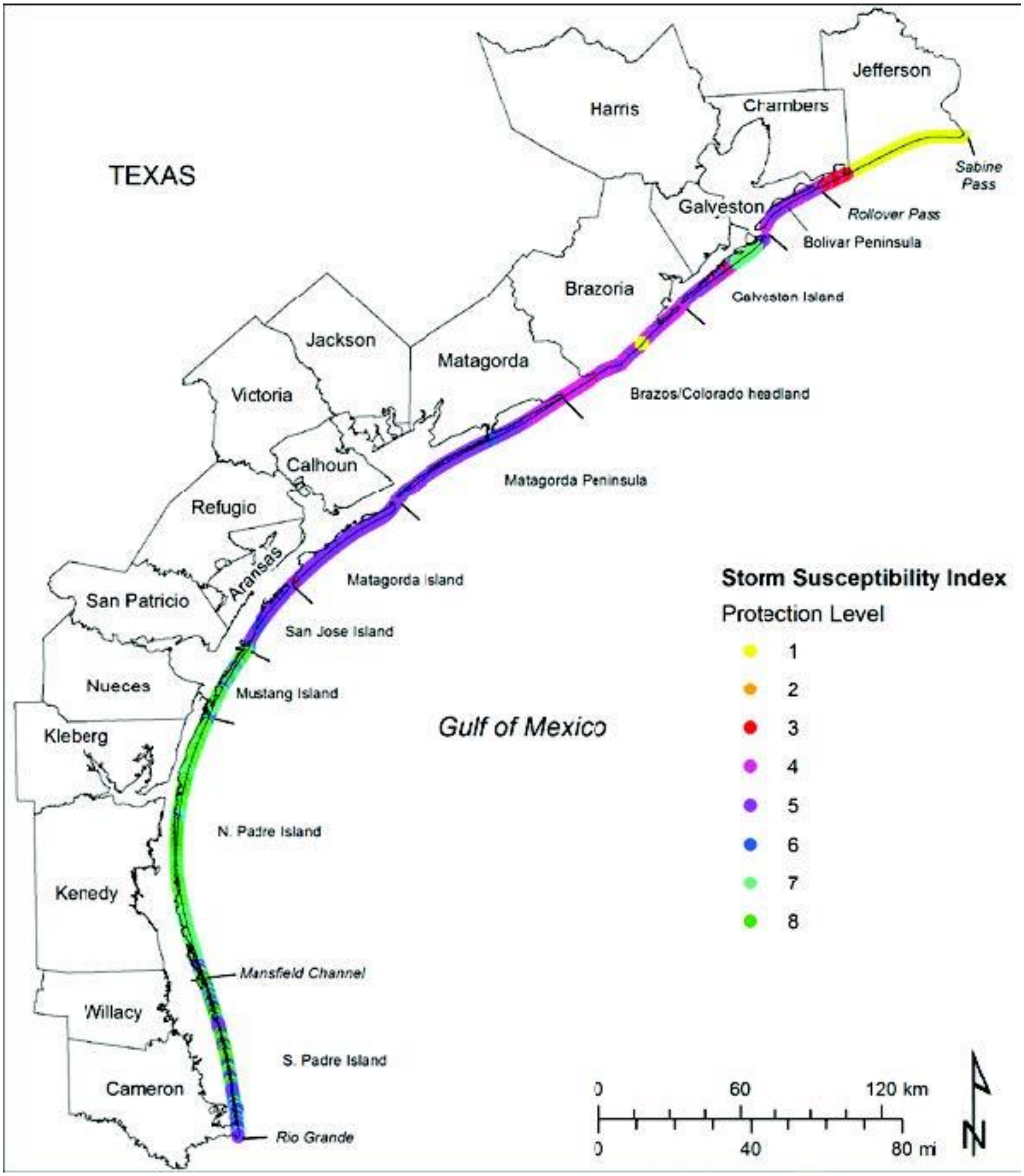


Figure 3: Storm susceptibility rating according to 2013 study from the Bureau of Economic Geology (BEG) at UT Austin (Paine, 2013)

This map is included to provide some context to the condition of study site relative to the rest of the Texas coast. The protection rating within the study area is assigned values ranging between 3 and 5, with the lowest protection rating at the east end of the study site. There is a strong correlation between the rate of erosion and storm susceptibility, both of which are linked to general shoreline elevation. A review of 2018 LiDAR data is processed with ArcMap to determine the percentage of each study area that exceed an arbitrary elevation of 8-feet relative to the North American Vertical Datum of 1988 (NAVD 88). According to results, approximately 3.5% of the Galveston Island study area exceeds the threshold elevation, while Bolivar Peninsula is double that at roughly 7% of the study area.

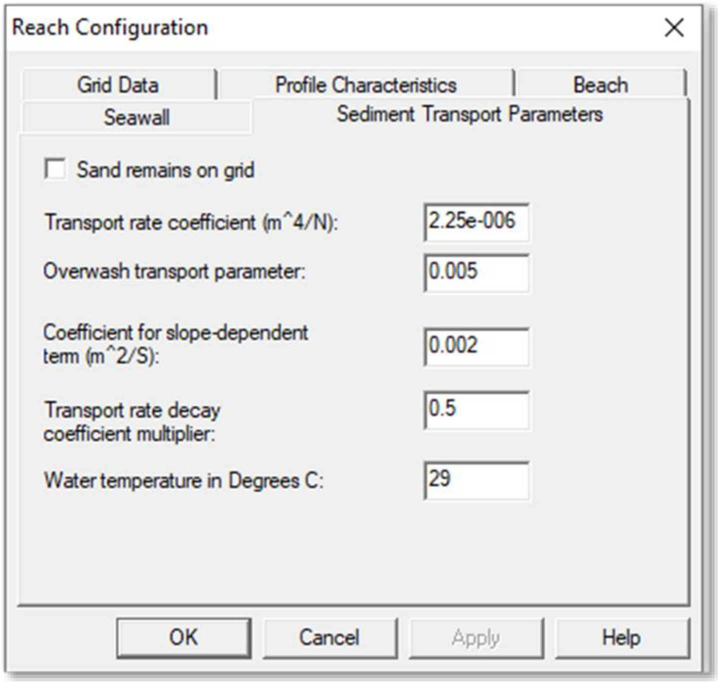
3. ECOSYSTEM RESTORATION (ER) AREA OF INTEREST

The Ecosystem Restoration (ER) area of interest (AOI) is located on Follet's Island, spanning approximately 10 miles from San Luis Pass, west to Surfside Beach city limits. The region is a sparsely populated sandy barrier island, with large expanses of beach, dune and wetland ecosystem throughout. The purpose of the study goal for this region includes restoration of the dune system to the natural elevation, and to place beach nourishment equivalent to compensate for erosion projected over a 10-year period. Restoration efforts are intended to enhance and preserve the natural ecosystem by providing beach nourishment and dune restoration to mitigate susceptibility to storm-induced erosion.

SBEACH MODELING

1. BACKGROUND

SBEACH is an empirically based numerical model that simulates the storm-induced response of beach-dune configurations, isolated to the cross-shore direction. Profiles intended to characterize sections of beach, termed "reaches" are prepared in BMAP (Beach Morphology Analysis Package), a CEDAS program that is dynamically linked with SBEACH. Reaches are directly imported to SBEACH where they are designated as either (1) an initial profile or (2) a hard-bottom profile. Hard-bottom profiles are treated as a monolithic structure that cannot be eroded, while initial profiles are composed of sand and require sediment parameter inputs that govern profile response behavior. Key sediment parameter inputs that control profile response include the effective grain size and maximum slope prior to avalanching. The model also contains several calibration parameters called sediment transport parameters, which can be adjusted against an actual measured profile to calibrate the model.



☐ Sand remains on grid

Transport rate coefficient (m^4/N): 2.25e-006

Overwash transport parameter: 0.005

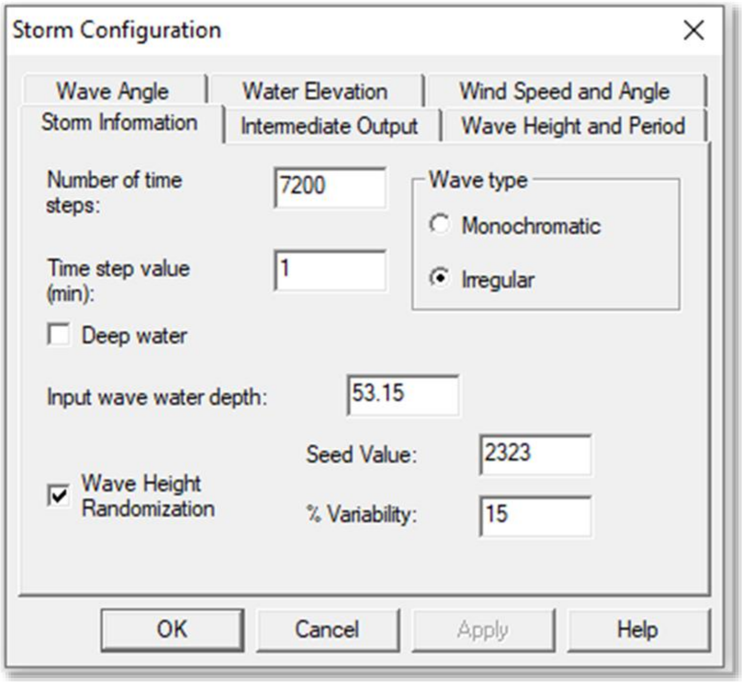
Coefficient for slope-dependent term (m^2/S): 0.002

Transport rate decay coefficient multiplier: 0.5

Water temperature in Degrees C: 29

Figure 4: Reach configuration inputs in SBEACH

SBEACH uses an explicit finite-difference scheme to solve for cross-shore wave height (Larson 1990) along a user-defined two-dimensional grid with constant or variable spacing, set according to user-preference. The main storm parameters required include water elevation, wave height, and wave period. Other storm inputs include wind speed and direction, as well as wave direction, where a wave angle of 0 degrees indicates shore-normal approach; positive angles are from the right-hand quadrant if looking towards the beach, and negative angles are from the left-hand quadrant from the same orientation. All parameters are time-dependent and must be designated as either variable or constant values. Input wave data must be assigned an input water depth or the default "deep water" designation is assumed to solve for wave height as waves propagate from the seaward end of the profile to the beach. The model can simulate monochromatic or irregular waves and an options are provided to randomize wave height in-between input time-series data.



Number of time steps: 7200

Time step value (min): 1

☐ Deep water

Input wave water depth: 53.15

☑ Wave Height Randomization

Seed Value: 2323

% Variability: 15

Wave type

○ Monochromatic

● Irregular

Figure 5: SBEACH Storm Configuration inputs

SBEACH contains several options to track storm-induced erosion including options to set three benchmark contours and three erosion depths that are used to output beach recession and erosion distances, respectively, relative to inputs. Results are output in a standard report after each simulation, which also quantifies the maximum wave runup elevation and total volume difference between initial and final profiles (volume of sand removed from grid). Intermediate results, including wave height and water elevation along the profile, are output at the user-defined time-step, which can be viewed graphically alongside profile change. The model also outputs valuable “miscellaneous” information including the maximum wave height, water depth and water elevation (+ setup) along the profile for each given run.

2. STORM DATA

NDBC’s historical met-ocean data from buoy 42035 (located 22 nautical miles SE of Galveston) was utilized to isolate available time series data from historic, monumental storms. Available WIS time-series met-ocean data was similarly selected at two virtual buoy stations proximal to Galveston (73073) and Bolivar (73077). All met-ocean data required by SBEACH was available at hourly intervals except for water elevation data, which was obtained from NOAA’s closest local geodetic gauge (8771450), located on Pier 21 in the Galveston ship channel. In addition, wave and wind direction was converted to SBEACH orientation, where the shore normal approach is zero degrees (see Section II-1 for details). Originally 9 storms were identified based on the significance of the event and availability of WIS hindcast met-ocean time series data. Next the storm data was cross-referenced with NDBC buoy 42035 and reviewed for overlap with the WIS hindcast data. Time-history data from four storms are selected to represent a range of recent surge events based that overlap with WIS data.

Table 01: Historical Storms Selected for SBEACH Simulations

Storm Name	Year	Start Date – End Date			Reported Storm Surge[1]	Saffir-Simpson Category at Landfall	Annual Return Interval[2] (years)
Ike	2008	09/10	-	09/14	15 to 20 feet	H2	50
Rita	2005	09/21	-	09/25	3 to 5 feet	H3	10
Allison	2001	06/04	-	06/08	2 to 3 feet	TS	5
Frances	1998	09/09	-	09/13	6 to 8 feet	TS	20

Notes:

[1] Storm surge values are based on reports from NOAA's National Hurricane Center archives

[2] ARI estimates are geographically dependent, based on available surge records (Needham, 2010)

Table 1 above highlights the Saffir-Simpson scale categorization for each of the selected storms, as well as the landfall location and the max reported storm surge. The Saffir-Simpson categorization can be misleading as it often does not reflect the magnitude of storm surge for large storm systems such as Ike or Frances.

The duration of each storm simulation is set to 120 hours (5 days) and the peak of the event is approximately centered. It should be noted that peak water level slightly lags the peak storm wave heights, due to the distance between the Pier 21 gauge and the NDBC buoy, however given the uncertainty of the storm track and speed relative to the recorded data it was not deemed necessary to precisely align the peaks. Input water level does not account for relative sea level rise or subsidence of the land, the historic events are modeled according to conditions at the time.

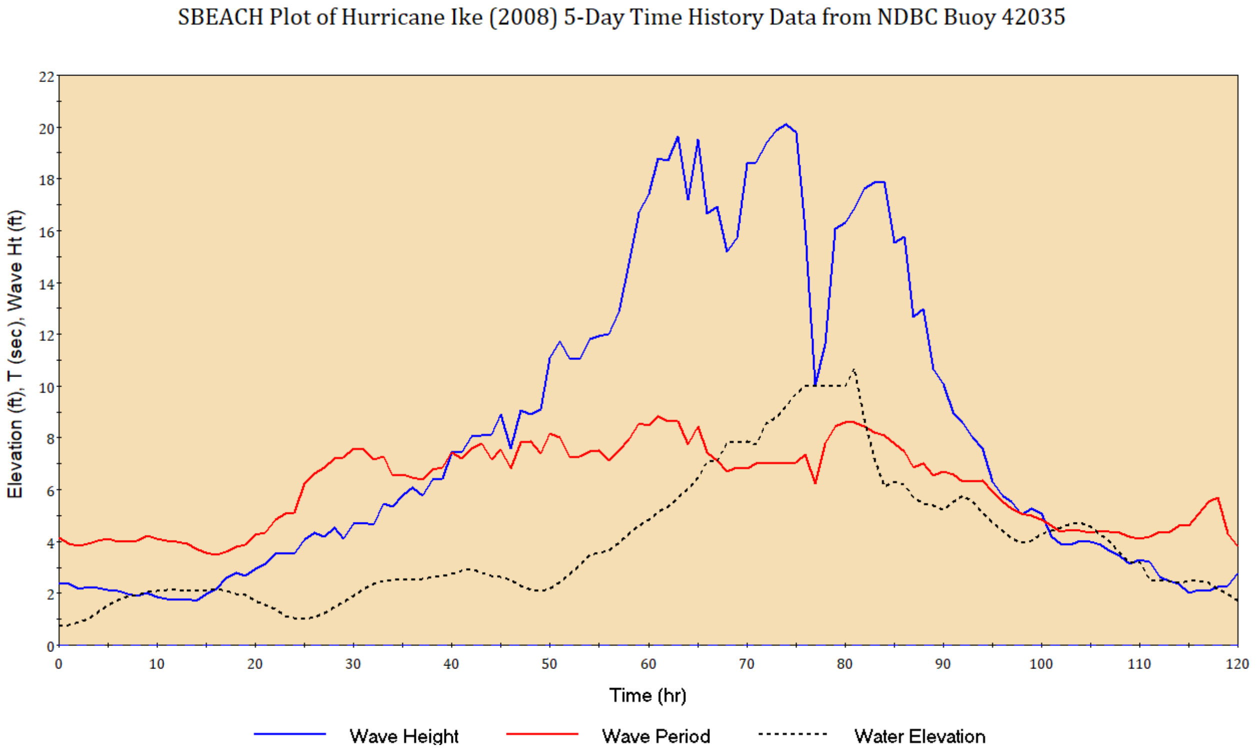


Figure 6: Hurricane Ike time series data from NDBC Buoy 42035 input into SBEACH

The storm surge reported by NOAA's Hurricane Center archives was used for comparison with output water elevation data from model simulations. The model runs with WIS hindcast data consistently underestimate peak water elevation and wave heights for all storm events. The largest discrepancy in model results is seen with the Hurricane Ike simulation, wherein the WIS simulation yields a maximum water elevation (setup + surge) at 7.08 feet versus 12.84 feet for the NDBC based simulation along the same profile. Results from SBEACH runs with NDBC storm data are consistent with water levels reported in the NOAA Hurricane Center archives. The WIS storm data was eventually abandoned in favor of the NDBC data.

3. BATHYMETRIC/TOPOGRAPHIC DATA

All topographic and bathymetric coordinate data collected is converted to the NAD 83 (North American Datum of 1983) Texas South Central (4204) State Plane coordinate system in US survey feet and elevations are shifted to the NAVD 88 (North American Vertical Datum of 1988) vertical datum wherever necessary.

Excel, Esri ArcMap, and BMAP (Beach Morphology Analysis Package), a program within the CEDAS suite, are used for pre and post-processing survey data used to develop the SBEACH profiles. Available data is reviewed for selection based on its 1) cross-shore extent (to the depth of closure), 2) date of survey, and 3) consistency with compared data. The cross-shore extent of survey data is considered the most important criteria for SBEACH modeling. Bathy/topo data must extend from the CSRM line, or ER footprint, to beyond the depth of closure to capture profile changes and depth dependent wave transformation.

NOAA's (National Oceanic and Atmospheric Administration) data access viewer is used to review and download available LiDAR (Light Detection and Ranging) flyover survey data. The most recent data available within the study site is from a 2018 topographic survey, collected by the TWDB (Texas Water Development Board). However, the survey does not contain bathymetric data within the study site, so it is not used to develop representative profiles.

The second most recent flyover data is a 2016 USACE topographic/bathymetric (topo/bathy) survey. This survey contains good bathymetric data for Follet's Island, the ER AOI, however the extent of bathymetric data is limited to Galveston Island in the CSRM AOI. The 2016 LiDAR data is imported as a raster file into ArcMap to develop a digital elevation model (DEM). Follet's Island ER profiles, and Galveston CSRM profiles are ultimately derived from the 2016 DEM.

The most recent available topo/bathy data within the CSRM AOI that meets all evaluation criteria is a 2006 Texas A&M survey of cross-shore transects. The survey contains 16 transects within the CSRM AOI that extend from the CSRM line to roughly 5,000 feet offshore, or a depth of approximately -20 feet (NAVD 88). The 2006 transect data is selected for development of Bolivar Peninsula CSRM SBEACH profiles in lieu of more recent LiDAR data due to the limited cross-shore extent. Galveston CSRM profiles are developed by extracting elevation data from the 2016 LiDAR DEM at the same coordinates as 2006 transect data.

3.1 ER EXISTING CONDITIONS REPRESENTATIVE PROFILES

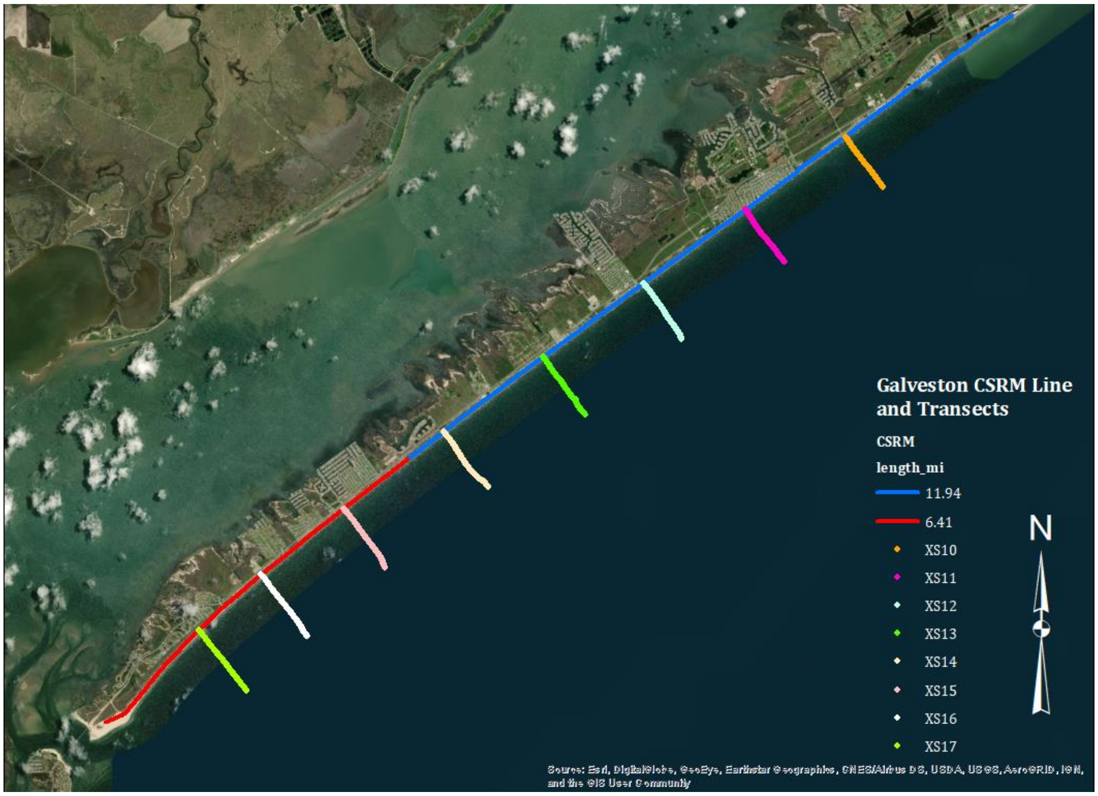
Nine transects are set up in ArcMap at 1-mile intervals alongshore and data points are extracted from the 2016 LiDAR DEM at 1-foot intervals in the cross-shore direction (orthogonal to the beach). The estimated mean higher-high water level (MHHW) elevation contour 0.85’ (NAVD 88) is also extracted from the DEM. The data points are exported for use in RMAP (Regional Morphology Analysis Package), a tool within the CEDAS suite that is used to prepare profiles along a shoreline for use in SBEACH. The profiles are aligned at the MHHW elevation contour and reviewed for morphological similarities. Adjacent cross-sections that exhibit similar characteristics are averaged to create two representative existing conditions profiles that are exported to SBEACH and Microsoft Excel.

3.2 ER DESIGN PROFILES

An Excel spreadsheet is used to develop ER design profiles. Dune features are identified in the existing conditions profiles and the existing side-slopes are used to determine the restored dune top height. The side slopes are extended, leaving room for a 12’ wide dune crest. Representative profile 1 has existing side slopes at 1:5 (1’ vertical to 5’ horizontal), while profile 2 has side slopes at 1:10, but both dunes extend to a top of crest elevation of +9’ NAVD88. The ER profiles are used to determine initial construction volume estimates and review storm-induced profile response in SBEACH. Storm-induced profile response is utilized to develop advanced fill requirements, and to develop a construction template profile.

3.3 CSRM REPRESENTATIVE EXISTING CONDITIONS PROFILES

Transect coordinate and elevation data from the 2006 Texas A&M survey are imported into ArcMap in addition to the 2016 LiDAR DEM and CSRM coordinates spaced at 1-foot intervals alongshore. Elevation data is extracted from the 2016 DEM at transect coordinates located in Galveston. The transect elevation data is used to categorize morphologically similar reaches of shoreline.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 7: Map of Galveston CSRM line and corresponding morphologically similar reaches (8 total)

Data landward of the CSRM line is removed from transects so that the baseline is the CSRM line and transect data is interpolated to 1-foot cross-shore intervals. The profiles are imported into BMAP and superimposed onto other profiles in the same morphologically similar reach.

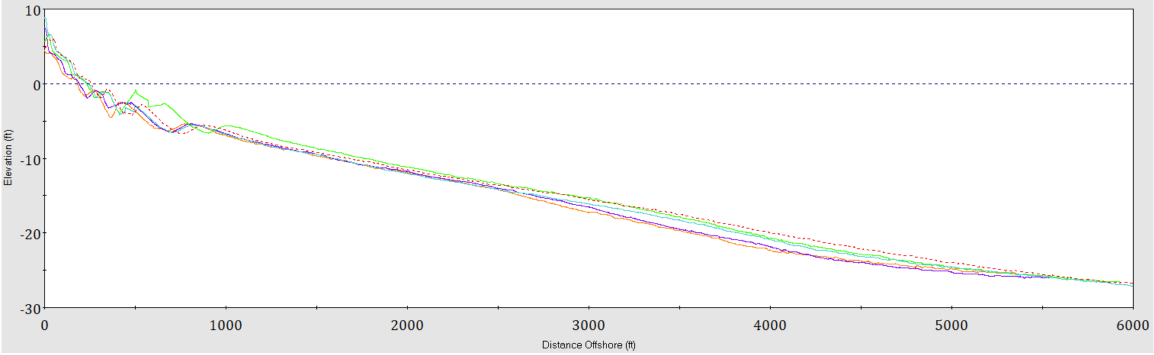


Figure 8: Five morphologically similar 2016 reaches identified on Galveston, profiles are averaged in BMAP to create representative XS1

The profiles are averaged in BMAP to create four CSRM cross-sections intended to represent two distinct reaches on West Galveston and two reaches on Bolivar Peninsula. The profiles, or reaches, are exported to SBEACH and reach configuration options are set up.

3.4 CSRM INITIAL DESIGN PROFILE CONCEPT

A healthy beach system is typically comprised of a system of one or more dunes and berms, both of which are ephemeral features that are elevated and landward of the surf zone. The dune complex is intended to be less ephemeral and self-maintaining in the proper environment and at a position sufficiently landward of the water. A beach profile typically has one or more berms situated between the dune and surf zone. Berms are dynamic features that are constantly being shaped by wave runup and aeolian processes. A healthy berm functions as a buffer zone that dissipates most incident storm waves prior to their arrival at the toe of the dune. This allows vegetation to proliferate on the dune, which gives rise to seaward dune growth through aeolian processes, and further strengthening the dune's resistance to storm surge and wave attack.

A range of initial design profile dimensions and configurations are developed for trial simulations based existing conditions and EM guidance from Part V, Chapter 4 of the Coastal Engineering Manual.

- **Dune Configuration:** Single Dune / Double-Dune configuration
- **Dune Composition:** Sand / Hardened Core
- **Dune Side Slopes:** 1:3 to 1:5
- **Dune Crest Elevation:** 10' to 18' (NAVD 88)
- **Dune Crest Width:** 12' to 16'
- **Berm Slope:** flat / 1:100 / 1:150
- **Berm Top Elevation:** 4' to 6' (NAVD 88)
- **Berm Width:** 0' / 30' / 60' / 100' / 150' / 200'

The existing elevation at the CSRM line serves as the starting elevation for the leeward toe of the design dune profile. The CEM provides a recommended range of dune side slopes between 1:3 and 1:5 (vertical Δ : horizontal Δ) and a berm profile slope between 1:100 and 1:150, depending on existing beach slope conditions.

The minimum dune crest elevation is based on local average elevations observed in regions with more developed dunes. The crest width is based on the ratio between crest height and width seen in CEM examples. The minimum top of the berm elevation is based on the 2% runup limit elevation (with setup) calculated for a 10-year return event according to the WIS (Wave Information Studies) wave hindcast data at stations offshore of Galveston (73073) and Bolivar (73077). Runup with setup is calculated at approximately +4' (NAVD88) with the empirically based Stockdon method and modified Mase method formulas (Melby 2012).

According to the CEM V-4, the shape of the design profile below the beach berm is a function of the local morphology and grain size of the fill. For placement of fill with equal grain size, the remainder of the design profile beyond the added berm width is determined by translating the existing profile between the elevation of the design berm end and the depth of closure.

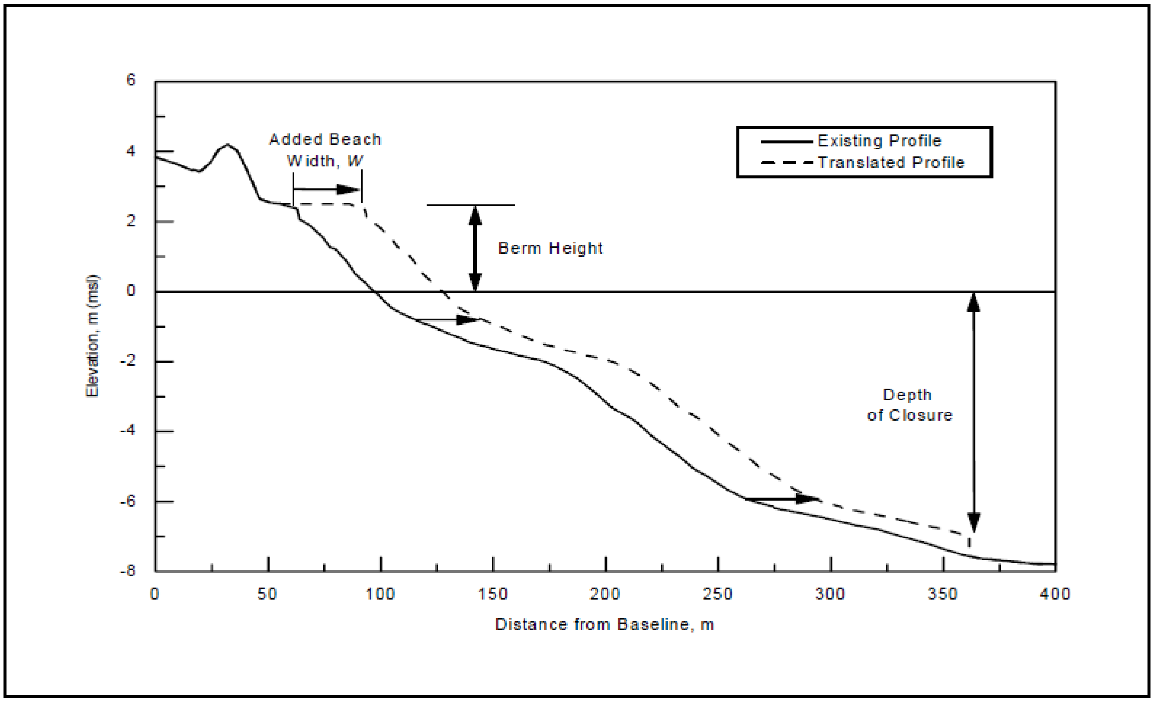


Figure 9: Design profile translation (CEM Figure V-4-14) graphically represented

The depth of closure (DOC) serves as the end point of the translated profile, where it ties back into the existing profile. The DOC is the theoretical depth at which energy from overhead waves is unable to suspend sediment at the seafloor. It is dependent on input wave, water level and sediment parameters, depending on the calculation method. For the purposes of this study, the DOC is calculated with the Hallermier equation in BMAP at approximately 15' deep for normal conditions. . The DOC is typically the offshore extent of beach equilibrium profiles.

3.5 CONSTRUCTION TEMPLATE

It is important to note that the design profile is intended to provide an estimation of the profile shape over time to develop volume calculations, it is not intended as a construction template. Typically construction of the beach fill is completed close to shore rather than over the extent of the design profile, by over-building the berm beyond the intended design width to equal the design volume. The design profile is eventually reached by allowing natural processes to distribute sand along the profile, as seen in CEM Figure V-4-2 (Figure 15 below).

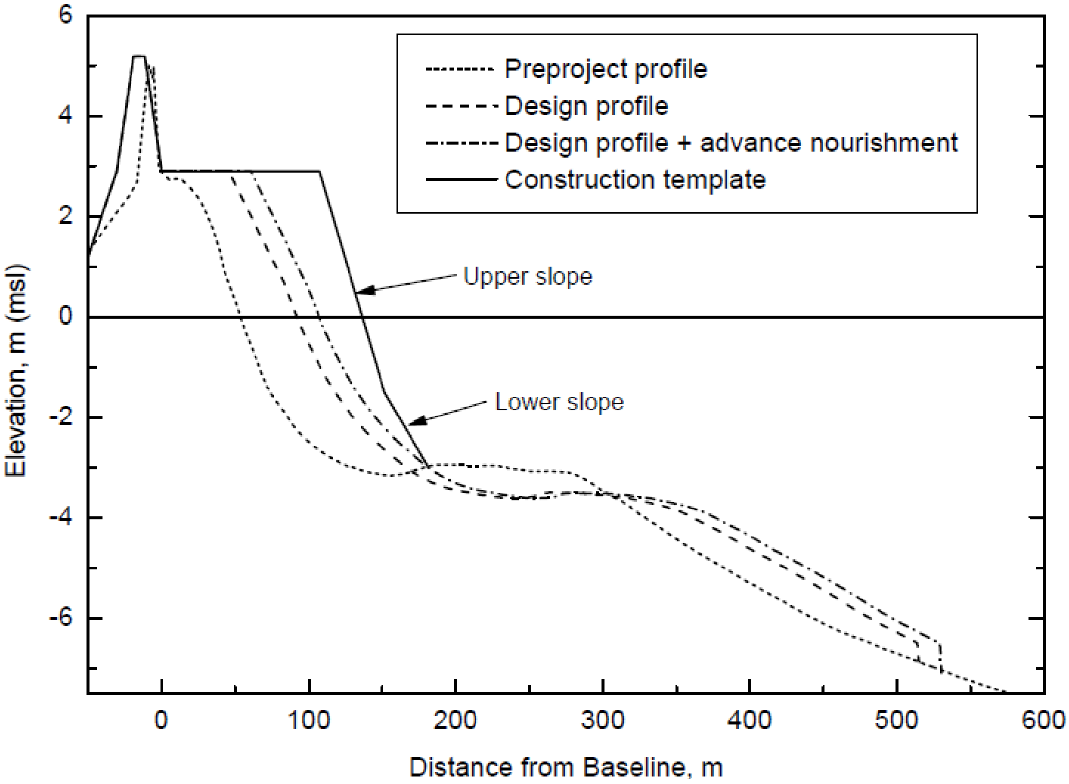


Figure 10: Construction template superimposed over design profile; CEM Figure V-4-33

A construction template generally begins at the seaward toe of the dune, and is built to a volume that includes design fill, advanced fill, and overfill required beyond the seaward toe of the dune. Design estimates were developed under the assumption that borrow fill sediment characteristics are equivalent to that of the native fill.

4. SEDIMENT INPUTS AND BEACH EQUILIBRIUM CONCEPTS

Sediment parameters, including median grain size diameter (d_{50}), and maximum slope prior to avalanching are key inputs for SBEACH reach (profile) configuration. For SBEACH purposes, an effective grain size of 0.16mm, 0.14mm, and 0.13mm is used for Bolivar Peninsula, Follets Island, and Galveston Island, respectively (King, 2007; Dellapenna, 2012).

Sediment parameters are the primary input for empirically derived formulas that predict beach equilibrium shape. In fact, it is widely accepted that a profile shape parameter (A-parameter), based solely on the d_{50} grain size, can be used to determine the shape of a beach profile according to guidance from the Coastal Engineering Manual (EM 1110-2-1100) with Equation IV-3-7:

$$h = Ay^{2/3}$$

where

h = water depth at a distance (y) from the shoreline

A = a scale parameter based on sediment particle size

The beach equilibrium profile concept can be used to fit an equivalent grain size to an existing beach profile, or to modify a translated design profile based on native and borrow fill sediment parameters. A comparison between actual profiles and profiles derived from reported grain size and theoretically derived grain size is performed, based on guidance from EM 1110-2-1100 Part V. The added distance of translation W_{add} (V-4-5) is used to modify the translated profile as a function of depth (*y)* based on the sediment characteristics of the native and borrow fill.

$$W_{add}(y) = y^{3/2}\left[\left(\frac{1}{A_F}\right)^{3/2} - \left(\frac{1}{A_N}\right)^{3/2}\right]$$

The A-parameter, sometimes known as a profile scale parameter, is directly correlated to the d_{50} sediment grain size for native (A_N) fill and borrow (A_F) fill. The resultant W_{add} added distance is positive if fill material is finer than native sand, which produces a gentler design profile slope with additional volume required. If added fill material is coarser than native sediment the result is negative and a steeper slope is produce, which shortens the distance to the depth of closure and reduces the total design volume required.

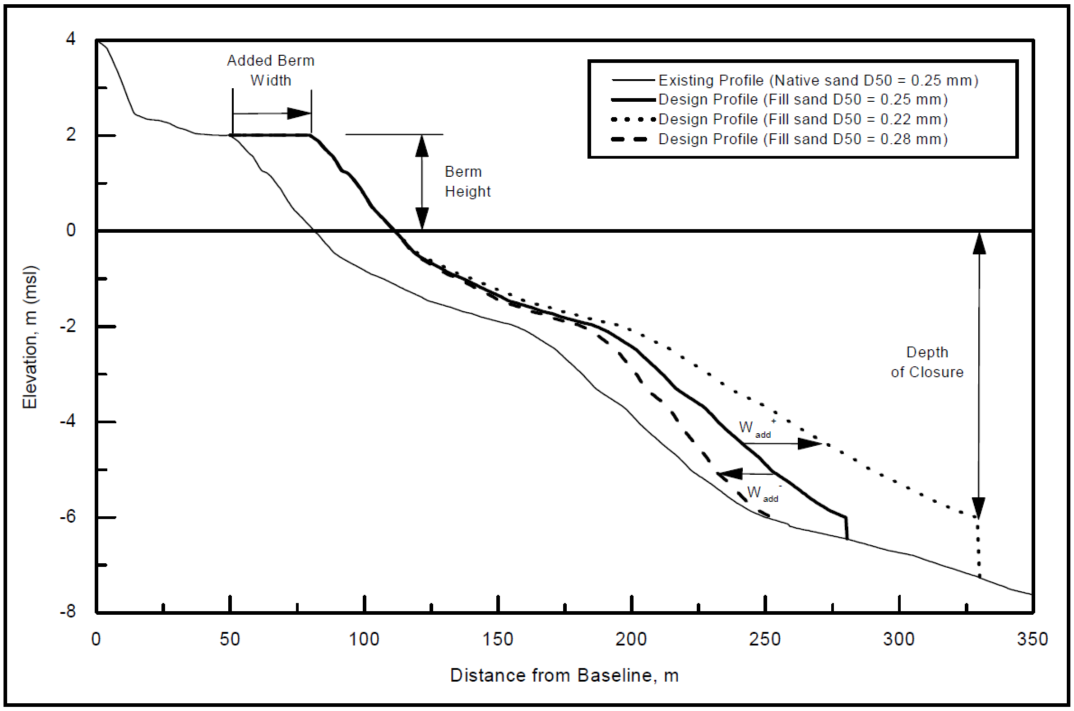


Figure 11: Figure V-4-17 from EM 1110-2-1100 provides an example of added translation distance based on sediment parameters and equilibrium beach profile concepts

BMAP software provides automated tools derived from this equation, which can be used to match a theoretical beach equilibrium profile and equivalent theoretical grain size to actual transects. A summary of reported average sampled sediment grain sizes for each region is compared to equivalent theoretical grain sizes, derived from representative profiles with BMAP.

Table 02: Comparison of reported average grain size to theoretical equivalent grain size per region of study site

Region	Representative Profile	Reported d_{50} Grain Size (mm)	Theoretical d_{50} Grain Size (mm)
CSRM: Bolivar Peninsula	XS1	0.16	0.06
	XS2		0.07
CSRM: West Galveston Island	XS1	0.13	0.08
	XS2		0.07
ER: Follets Island	XS1	0.14	0.07
	XS2		0.09

The theoretical grain sizes are consistently lower than reported values, indicating that reported samples may not be representative of the average sediment size across the entire profile. The reported values are more consistent with the initial slope of the beach and shore face. The theoretical values are used to determine A_N, the A-parameter associated with the native fill, and reported values are assumed to represent A_F for the placed beach fill. Results indicate a steeper profile with a net reduction in volume required to create the design profile assuming borrow fill sediment is consistent with reported beach fill. The beach equilibrium profile concept is applied to Galveston XS1 in Figure 12.

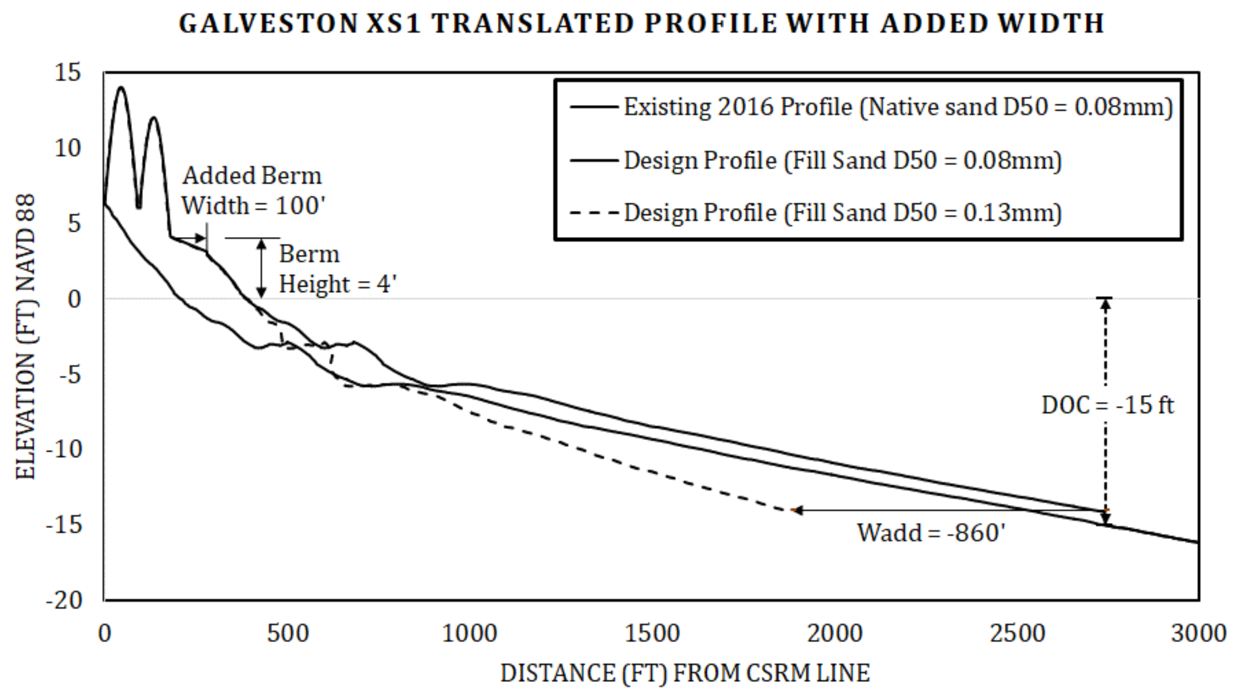


Figure 12: Galveston XS1 beach equilibrium profiles with theoretically derived d50 versus reported average

The theoretical profile associated with the 0.13mm grain size maintains roughly the same slope as the beach, and intersects the existing profile due to a negative added width value associated with the sediment parameters. This results in a net reduction at approximately 40% in overall volume of design fill required for all profiles if the added width concept is applied.

Due to incomplete information regarding both native and borrow fill sediment composition, the added width is not applied to the design profiles in favor of a more conservative estimate that assumes borrow fill is equivalent to native fill. Conservatism in the estimate is intended to offset the sediment deficit in the pre-project beach profile, which is not accounted for with beach equilibrium profile concepts. This is reviewed further in Section 3 of the Results/Discussion, with a historically based volumetric comparison of 2006 and 2016 West Galveston profiles.

5. MODEL CALIBRATION

SBEACH parameters are calibrated based on the August 2007 Shoreline Erosion Feasibility Study, where David B. King provides an extensive review of SBEACH model calibration according to pre and post Hurricane Claudette beach profiles on Galveston Island. The key SBEACH calibration coefficients, from Table 39 of King's report (seen below in Figure 13) were utilized for the purposes of this study.

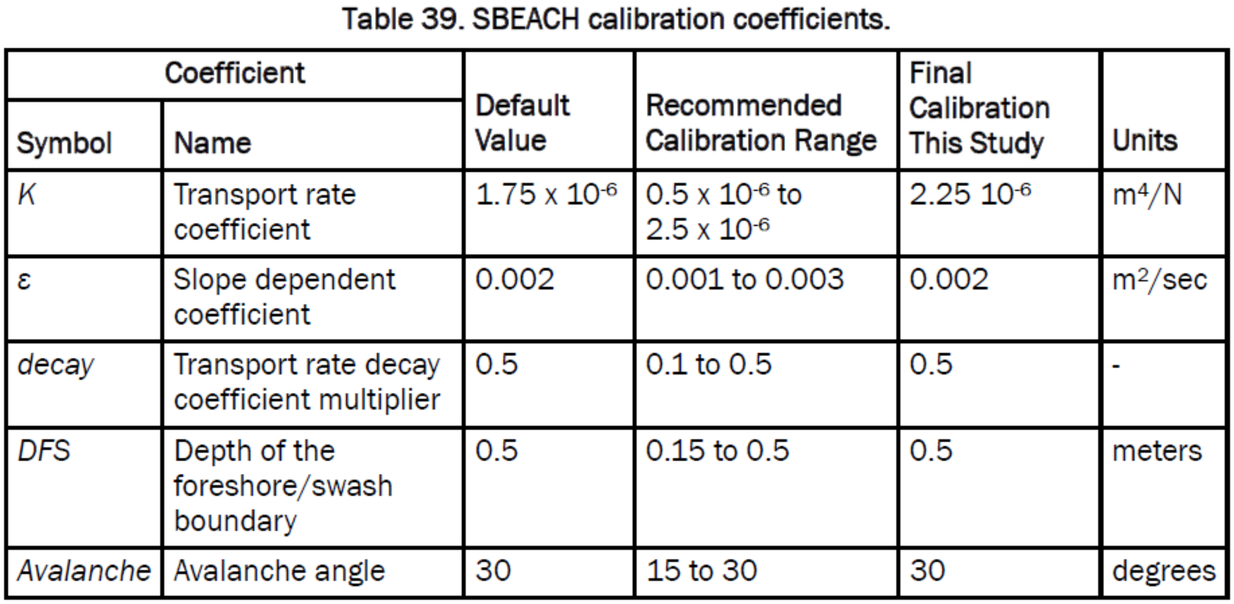


Table 39. SBEACH calibration coefficients.

Coefficient		Default Value	Recommended Calibration Range	Final Calibration This Study	Units
Symbol	**Name**				
K	Transport rate coefficient	1.75×10^{-6}	0.5×10^{-6} to 2.5×10^{-6}	$2.25\ 10^{-6}$	m^4/N
ε	Slope dependent coefficient	0.002	0.001 to 0.003	0.002	m^2/sec
decay	Transport rate decay coefficient multiplier	0.5	0.1 to 0.5	0.5	-
DFS	Depth of the foreshore/swash boundary	0.5	0.15 to 0.5	0.5	meters
Avalanche	Avalanche angle	30	15 to 30	30	degrees

Figure 13: Table 39 from King's report on SBEACH calibration with pre and post Hurricane Claudette reaches (King, 2007)

Model results for erosional losses are further compared against HDR's measured erosional losses between 2005 and 2008, a storm-prevalent period defined by Hurricane Rita and Hurricane Ike regional impacts. HDR reports results for average, minimum, and maximum net volume changes in an area defined as the sub-aerial beach, between the 1.3 meter (4.2 ft) contour and the 0.7 meter (2.3 ft) contour (HDR, 2014). The SBEACH results for Hurricane Rita and Ike simulations along existing conditions profiles are summed and compared with HDR results in Table 03.

It should be noted that results are not directly comparable due to differences in time scale and spatial resolution. SBEACH results do not represent constructive forces between storms and the summation of storm induced erosion an oversimplification that assumes the same initial profile conditions prior to each simulation. Therefore, cumulative model results are expected to over-represent erosional losses, however the comparison does provide some context for an acceptable range of model results.

Table 03: Comparison of Sub-aerial Beach Volume Change Results with HDR Measurements

Region		**Net Volume Changer per Alongshore Length (cy/ft)**	
		HDR Results (2005-2008)	SBEACH Results (Rita + Ike)
Bolivar Peninsula	**AVG.**	**0.3**	**-6.59**
	MIN	-26.9	-6.94
	MAX	16.6	-6.25
West Galveston Island	**AVG.**	**-2.7**	**-5.86**
	MIN	-14.1	-6.03
	MAX	24.3	-1.55
Follets Island	**AVG.**	**1.6**	**-6.27**
	MIN	-7.9	-6.81
	MAX	7.5	-5.74
Note: Results are not directly comparable due to differences in time scale and methodologies, intended for qualitative, order-of-magnitude comparison only			

Multiple model-sensitivity tests were also conducted to evaluate the influence of the region leeward of the dune by extending the landward boundary beyond the CSRM line, including extensions of 50’, 100’, 200’ & 500’ with and without hard-bottom. Unless a profile configuration option is selected that forces sand to remain on the grid, the landward extensions had no bearing on model results.

RESULTS/DISCUSSION

1. CSRM DESIGN

Optimization trial simulations are used to review and compare profile configurations with combinations of the physical parameters outlined previously. A semi-qualitative approach is used to assess profile performance relative to volume requirements in initial trials. Initial trials intuitively indicate that (1) during severe storm surge events the max profile elevation is key to reduction of overtopping and ensuing dune failure, and (2) during more frequent storm events the berm width is key to reducing runup and dune toe scour.

1.1 BERM

According to model results the dune feature has the most notable impact on performance during Hurricane Ike simulations. The physical dune characteristics (primarily volume and elevation) are directly linked to the magnitude and duration of landward inundation during Ike model runs, which is the primary metric for profile performance during Ike simulations. This metric is measured according to model output for max wave height, as well as the magnitude and duration of water depth that occurs at the CSRM benchmark in any given model run. The berm’s influence on landward inundation is negligible according to model results. For example, model results for Ike simulations show no decrease to landward inundation or wave height due to the addition of a 100’ wide berm feature in otherwise identical profiles. Theoretically, the berm should have some impact in limiting the incident wave height (and energy) experienced by dunes, however the degree of impact is relative to the elevation of both the berm and the water level.

The berm has a more obvious impact on overall profile performance during other model runs, which include storms with a reduced storm surge component (Frances, Allison, and Rita). Since model results show no landward inundation to any of the design profiles during these model runs, profile performance is based on mitigation of dune and beach erosion. Dune erosion is of primary concern since additional time, money, and effort must be invested in the construction and maintenance of dunes and establishment of vegetation. The berm effectively reduces dune erosion during these simulations. For example, the addition of a 100’ berm that extends from the seaward dune toe at a 1:100 slope, reduces dune erosion by approximately 4 cubic-yards per linear foot for otherwise identical Galveston dune profiles, according to model results for Frances simulations. The berm effectively extends the longevity of the dunes and reduces maintenance requirements. Similarly, it reduces the frequency of vegetation exposure to waves, prolonging the time allotted to the natural proliferation of vegetation between storm events. This may be a significant benefit to long-term dune stability that is not captured in model results.

A number of variations in berm dimensions are tested for performance, relative to fill estimates. Ultimately a 100’ berm width with a 1:100 slope is incorporated into the design profile. This provides an average dry beach width of 200-feet, which is commonly considered to be characteristic of a healthy beach. The sloping berm reduces volume requirements relative to the flat berm by approximately 25% (for the 100’ wide berm) and offers the ancillary benefit of reduced beach scarping during simulations. The 1:100 slope tends to match existing conditions better than the 1:150 slope.

1.2 DUNE FOUNDATION

The hardened core option was reviewed to assess the benefit of a clay or stone core that forms the foundation of the dune. The idea is similar to Geotube (geotextile bags filled with sediment, grout, or concrete) dune cores, which have been employed in various spots throughout the study site with varying degrees of short-term success. The most appealing benefit offered by the hardened core alternative is increased durability relative to overlying sand. In concept, the core is essentially a last line of defense against a severe storm event capable of eroding the overlying sand layer, in which case the exposed core is intended to serve as an erosion resistant wave break that reduces energy transmission of waves passing overhead. The core alternative may also provide an auxiliary benefit in potential cost savings on fill material, however this likely offset by increased construction and maintenance costs associated with the alternative material. Simulations were run with multiple configurations of the core using the "hard-bottom" profile option in SBEACH, which operates under the assumption that material underlying the designated hard-bottom profile will not erode. This is an unrealistic assumption for a clay composition, however it is not possible to model cohesive sediment in SBEACH. Further, the model does not allow for failure from undermining (or otherwise) that may occur as a result of excessive toe scour in front of the exposed core.

Model results show identical erosion trends to non-core options until the core is exposed, at which point the hardened portion of the profile remains intact, increasing scour adjacent to the seaward toe, while reducing transmission of wave energy leeward of the core. The model results are not useful for quantitative analyses and are unreliable for comparison with "all sand" profiles. The alternative may warrant further exploration during the PED phase; however the concept has given rise to some concerns that should also be addressed if pursued. When exposed to waves, the core will cause toe scour (increased erosion at the seaward toe), which may lead to failure. Failure at a single location may spread alongshore or weaken adjacent defense depending on the material used, length of units (in the case of precast concrete or geotubes), and on connections between units. Failed or exposed units pose aesthetic, environmental and maintenance concerns that do not exist in a sand-only system. Further, the interface between the core and overlying sand has the potential to reduce internal stability and to promote seepage, due to differences in material properties.

1.3 DUNE OPTIMIZATION

The goal of design optimization is to balance cost with storm-induced profile performance. The performance of the profile is primarily based on the magnitude and duration of profile inundation during extreme surge events, i.e. – flooding and wave transmission landward of the dune feature. Inundation is inextricably linked to the majority of damage and associated cost caused by tropical storms and hurricanes. Prevention or mitigation of inundation with proposed design profiles is not solely predicated on dune failure itself, but on when and how the dune fails. Dunes are soft coastal features that can continue to provide protection past failure due to the residual elevation. Ultimately the profile performance during extreme events, such as Hurricane Ike, is controlled by the size and shape of the dune system.

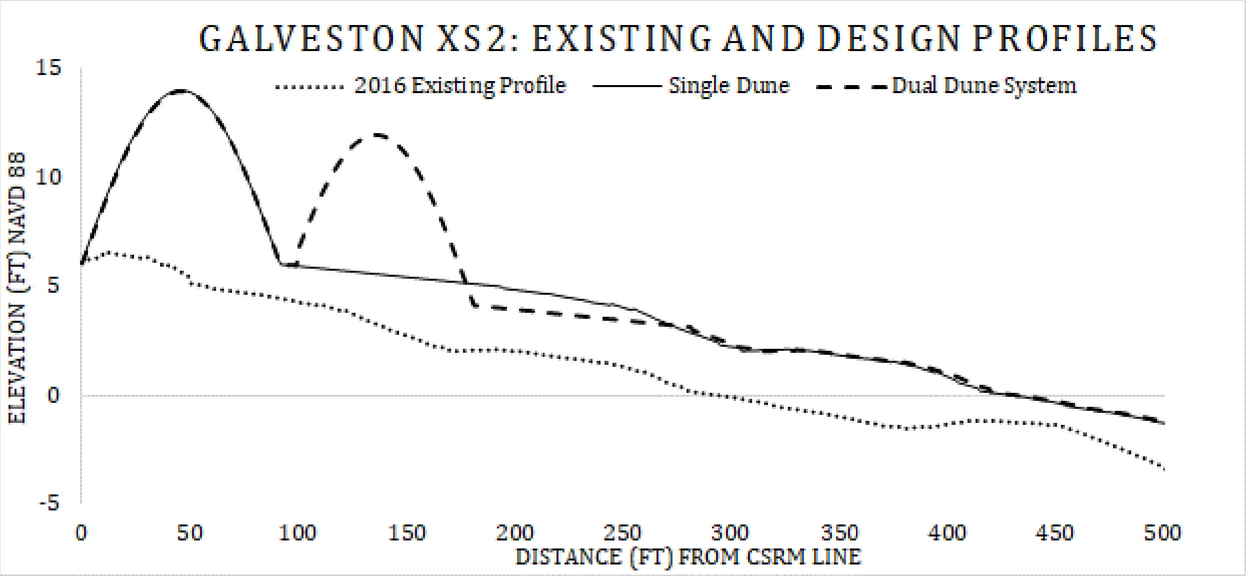


Figure 14: Galveston XS2 existing and design beach profile configurations

Figure 14 shows Galveston XS2 representative beach profile for single and double dune profile configurations selected with a primary dune elevation at +14’ NAVD88. The dune side slopes of the dune are set to 1:5 to accommodate environmental concerns regarding the ability of native species to traverse a steeper slope. The shallower slope increases the volume required for project construction by approximately 25% relative to the 1:3 slope at the low end of the recommended range, however the slope is similar to local dunes, and the added volume benefits dune performance as well.

Figure 15: Natural double dune complex on the east end of Galveston Island (August 2019)

The difference between the double dune system and the single dune is the addition of a foredune, with a crest elevation at +12' NAVD88 and the same 1:5 side slopes as the primary dune. Natural examples of this concept are prevalent on the east end of Galveston Island and in other healthy systems, as seen in Figure 15.

The volume required to construct the double dune configuration is approximately 16% greater than the single dune configuration with the same primary dune dimensions. However, benefits of the double-dune feature include more than the simple provision of additional "sacrificial" material volume. The formation effectively increases the duration of protection, relative to fill required, during a severe surge event such as Ike. This effect would likely be more pronounced if the model accounted for the stabilizing effects of vegetation, since the double-dune formation provides increased surface area, subsequently increasing the capacity for vegetation. Though not yet quantified, the shape of the formation and the potential for increased vegetation provide additional benefits in the promotion constructive aeolian processes by "capturing" sediment transported by wind.

Table 4 summarizes quantitative benefits of the double-dune system according to SBEACH results for maximum wave height, maximum water depth and duration of inundation landward of the CSRM line for the existing conditions profile, single dune profile, and double dune profile seen in Figure 14.

Table 4: SBEACH Output for Hurricane Ike - Inundation, Water Depth and Wave Height at the CSRM line

Profile Configuration		**Duration of Inundation (hours)**	**Max Water Depth at CSRM (feet)**	**Max Wave Height at CSRM (feet)**
Existing Profile	**Average**	**51.75**	**9.66**	**4.73**
	Minimum	47.25	8.72	4.07
	Maximum	61.5	11.61	5.81
Single Dune Profile	**Average**	**9.56**	**2.49**	**1.14**
	Minimum	8.25	1.69	0.97
	Maximum	10.5	3.34	1.43
Double Dune Profile	**Average**	**2.44**	**1.13**	**0.63**
	Minimum	1.5	0.64	0.45
	Maximum	3.75	1.95	0.99

Results show a reduction in wave height at 76% for the single dune and 87% for the double dune relative to the existing profile. Similarly, the single dune reduces water depth by 74% and the double dune by 88%. The most significant reduction is in the duration of inundation, which is reduced by 82% with the single dune profile and 95% with the double dune configuration. The average duration and depth of inundation for the double dune configuration is just under 3 hours at 1.13 feet. It will require additional analysis to quantify the relative risk reduction, however the model results show a significant reduction to the hazard associated with surge events.

A single dune crest elevation of +17' NAVD88 is found to be the threshold elevation to equal the decreased inundation seen by the +14' double dune, however the associated volume increase is approximately 10% relative to the +14' double dune profile. Further, this assumes that the integrity of the single dune will not be degraded by less severe storms prior to an Ike-magnitude storm surge.

2. ADVANCED NOURISHMENT FILL ESTIMATION

Advanced fill placement is an erosion mitigation technique used to compensate for anticipated erosion over a specified period of time. The concept is simple, a sacrificial surplus of sand is placed on the beach/berm at a volume equivalent to the erosional losses anticipated over a period of time until the first scheduled nourishment. Advanced nourishment typically coincides with initial construction, and is monitored to evaluate the design nourishment period.

This concept is particularly beneficial to dune restoration/improvement efforts because the buffer provides time for dunes to stabilize and establish vegetation, which is essential to their efficacy against severe storms. In addition, advanced nourishment provides cost-savings in comparison to periodic nourishment since it is included in the original construction template. Contractor remobilization fees are avoided, and material savings are generally seen when purchased in larger quantities.

Advanced fill, equivalent to 10-years of anticipated erosion, is estimated and included in the construction template of CSRM and ER profiles. The basis for estimates is rooted in the storm-induced profile response of each profile, seen in Appendix B. Estimates are based on the measured difference between design and post-storm profiles, from the CSRM line (or zero point for ER profiles) to the pre-storm MHHW elevation contour for each respective region. Alongshore (cubic-yard per linear foot) estimates can be found in Appendix B of this report, in addition to normalized (cubic-foot per square foot) estimates for direct comparison between profiles.

The NOAA Tides & Currents webpage is used to determine MHHW levels for each region. The datum at Rollover Pass (station 8770971) is used for Bolivar Peninsula, Pleasure Pier (station 8771450) is used for Galveston Island, and San Luis Pass (station 8771972) is used for Follet's Island. The MHHW level for Bolivar Island, Galveston Island and Follet's Island is 0.61 feet, 1.41 feet, and 0.85 feet, respectively. Advanced beach nourishment estimates are highly dependent on temporal and spatial parameters. It is difficult to predict future needs for a particular time interval, however long-term trends provide the best means to develop these estimates. For the purposes of this study, the probabilistic approach is used to determine advanced fill requirements.

2.1 PROBABILISTIC ANALYSIS RESULTS

Advanced fill requirements are developed with a simple probabilistic approach, assuming a 10-year design life for advanced fill. First available storm surge records for the region are compiled from NOAA's Hurricane Center archives and Needham (2010). Storms are ranked according to reported surge levels over a 122-year period to develop an approximate annual return interval (ARI) for each storm modeled. The estimated ARI of each storm, is used to calculate the probability of exceedance (P_E) over a 10-year period,

$$P_E = 1 - (1 - T^{-1})^n$$

where T is the annual return interval of each storm, and n is the period of interest in years.

Erosion volume estimates (from model results) for each storm are weighted by the exceedance probability and summed to develop a cumulative frequency estimate that represents anticipated erosion losses over a 10-year period for each respective profile. Advanced fill estimates are summarized in Table 05.

Table 05: Advanced Fill Estimates for a 10-year Period per Probabilistic Analysis

Region	Profile	MHHW (NAVD88 - ft)	Advanced Fill Estimate (cyd/ft)	Regional Total (cyd)
Bolivar Peninsula	XS 1	0.61	16.13	1,897,000
	XS 2	0.61	12.34	
West Galveston Island	XS 1	1.41	7.23	850,800
	XS 2	1.41	11.67	
Follets Island (ER AOI)	XS 1	0.85	10.81	587,000
	XS 2	0.85	11.31	

Advanced fill is intended to compensate for anticipated erosion over a 10-year period range, meaning annual estimates range between 0.75 cyd/ft and 1.6 cyd/ft annually. Estimates are measured from the CSRM line to the respective MHHW level for each region.

The construction template profile is modeled in SBEACH to measure the storm-induced profile response and preservation of ER features. The results show good performance against all storms except for Ike, where the profile is completely inundated as expected. Frances simulations show complete erosion of the advanced fill berm, however ER dune measures are intact.

3. COMPARISON OF WEST GALVESTON PRE AND POST-IKE PROFILES

The Bureau of Economic Geology (BEG) at UT Austin reports a historic mean change rate (1930's to 2012) of -0.27 meters (0.89 feet) for Galveston Island, however the trend reverses between 2000 and 2012 to nearly 1 meter per year (~3.28 feet/year) of shoreline advance (Paine, 2014). Further, the rate between 2010 and 2011 is reportedly 12.2 meters (40 feet) of advance (Paine, 2013). The uptick is attributed to post-Ike constructive forces.

A volume comparison between 2006 transects and 2016 LiDAR data, extracted at the same coordinates, is completed for all regions with available 2016 LiDAR data. The results from 7 West Galveston transects and 6 transects on Follet's Island, for the same swath of sub-aerial beach, are compared with HDR results in Table 06.

Table 06: Sub-aerial beach (between 4.2' & 2.3' elevation contours) volume change results comparison with HDR measurements per region (HDR, 2014)

Region		Net Volume Change Per Unit Length Alongshore (cyd/ft)	
		HDR Results (2005-2012)	Study Results (2006-2016)
Bolivar Peninsula	**AVG.**	**-2.5**	-
	MIN	-24.0	-
	MAX	9.0	-
West Galveston Island	**AVG.**	**-0.1**	**3.59**
	MIN	-9.6	-5.55
	MAX	16.2	15.53
Follets Island	**AVG.**	**-0.5**	**2.75**
	MIN	-15.1	-0.45
	MAX	3.8	7.27

NOTE:
Results are not directly comparable due to differences in time scales, spatial domain and methodologies, and are intended for order of magnitude contextual comparison

Results from these studies are intended to provide context rather than for direct comparison due to differences in the study domain, time scale, and the methodology used to evaluate shoreline erosion. HDR reports mild shoreline erosion between 2005 and 2012 for the sub-aerial beach on West Galveston, averaging -0.1 cubic yards per linear foot of shoreline (HDR, 2014). The study results generally fall within the range of volumetric losses reported by HDR and follow trends of net shoreline advance reported by BEG. HDR results do show net erosion over the study duration, however the magnitude is lower than expected given the overlap with Hurricane Rita and Hurricane Ike during the time period.

Dr. Tim Dellapenna reports net losses of 103-million cubic-yards of fill on the beach/shore face of Galveston Island according to pre and post Hurricane Ike mapping completed in 2006 and 2011 (Dellapenna, 2012). It is further suggested that this is likely an underestimate of the total deficit since the comparison does not include the western 3.7 miles of Galveston Island. The magnitude of reported losses is difficult to reconcile with results from other studies that suggest either net shoreline advance or mild retreat during overlapping time periods in the same region. The results are not directly comparable, but the question remains as to how the magnitude of reported post-Ike losses could exist simultaneously with reports of shoreline advance in the region. The answer is found when the profile comparison is extended further offshore.

Plots of the 2006 and 2016 West Galveston profiles are provided in Appendix A, and a plan view of cross-sections is seen in Figure 07. Profile plots show an interesting trend from east to west. The furthest eastern profiles are located near the seawall, where local historic erosion rates are highest on Galveston Island. These profiles (XS 10-14), plotted in Figure 16, exhibit the most erosion on the beach and shore face, consistent with historical trends, however the post-Ike (2016) profiles show convergence with the 2006 profile near the depth of closure, which is not seen with western profiles (XS 15-17). The pre-Ike western profiles are much shallower than eastern profiles, with a larger active profile (distance to depth of closure). The shallower profiles are indicative of finer sediment composition, which may have accumulated due to net positive alongshore contributions and proximity to the bay inlet where fine sediment is exchanged between tidal cycles.

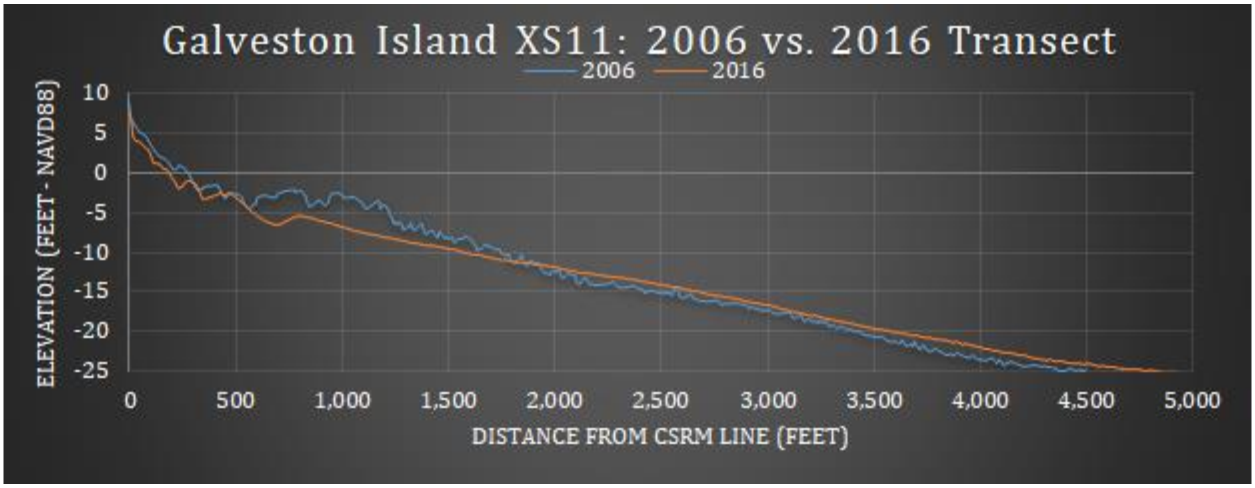


Figure 16: A temporal comparison of eastern transect XS 11 show post-Ike near shore impacts, and profile convergence near the depth of closure followed by observations of profile accretion

The western profiles are located in a portion of West Galveston that is associated with net shoreline advance according to historical shoreline trends dating back to 1930 (Paine, 2014). The temporal comparison of an example western profile (XS16), seen in Figure 17, shows accretion on the beach and shore face of the profile, consistent with local historic trends. However, the 2016 profile diverges precipitously from the 2006 profile in the offshore direction, nearly the inverse of eastern profile trends. The comparison provides spatial context to reports of shoreline advance during the same time frame as Hurricane Ike impacts and provides evidence that both can occur simultaneously.

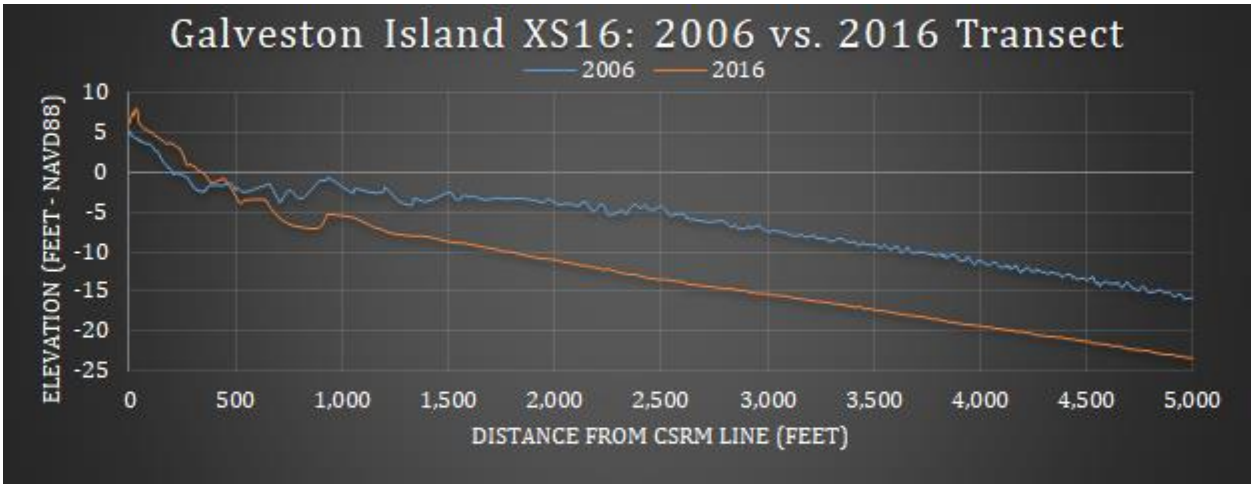


Figure 17: A comparison of pre and post-Ike impacts at westernmost profile (XS16) reveal shoreline advance above the water line and significant deepening of the offshore profile

Figures 18 & 19 show all Galveston Island CSRM transects in 2006 and 2016, respectively. The 2006 survey reveals significant disparity in elevation between the western (XS15 - 17) and eastern (XS10 -14) profiles, while 2016 profiles maintain a remarkably uniform shape along the length of the shoreline.

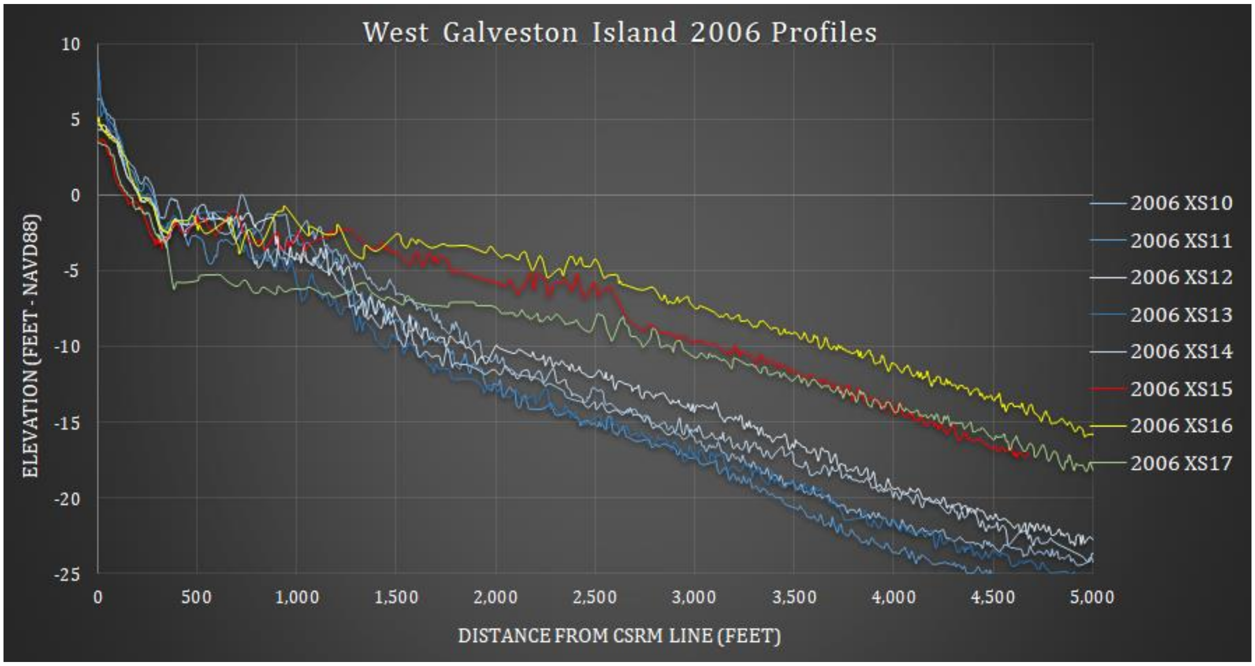


Figure 18: West Galveston Island 2006 transects prior to Ike, ordered chronologically from east to west

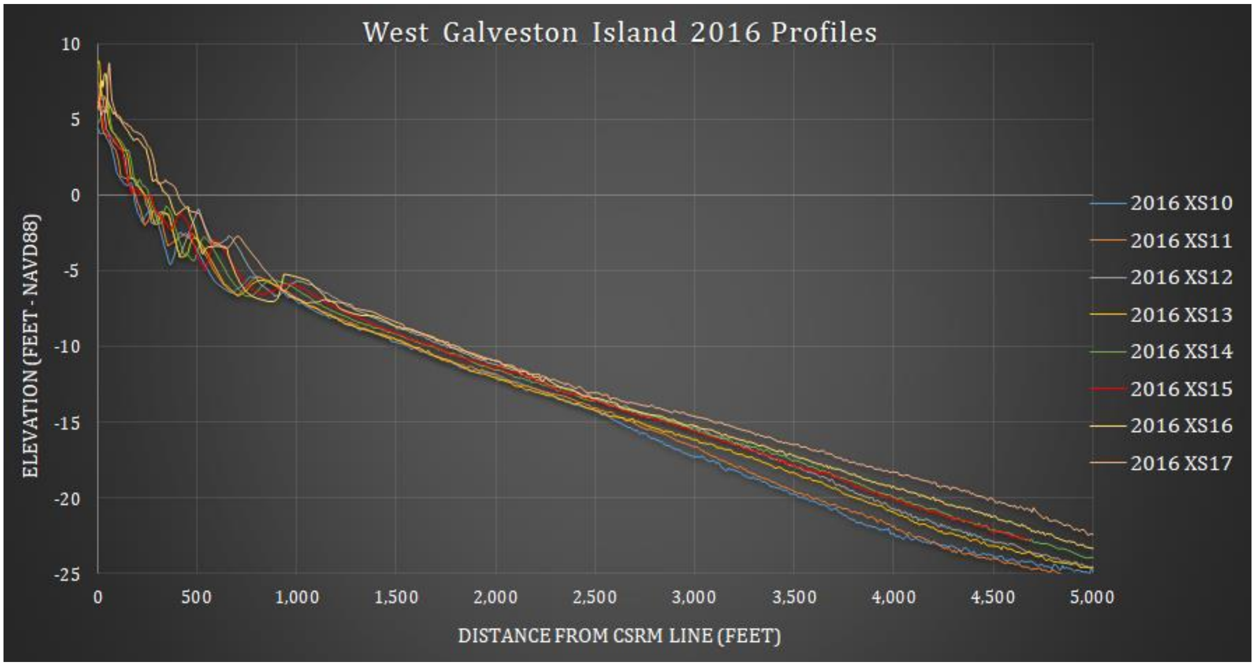


Figure 19: West Galveston Island 2016 transects (post-Ike); XS15, XS16 & 17 conform to the general shape of other Galveston profiles suggesting uniform sediment composition

The volumetric comparison between historical West Galveston profiles is extended to the normal depth of closure. The estimated sediment deficit is over 18.8-million cubic-yards of fill between 2006 and 2016 for an alongshore region between the western end of the seawall to San Luis Pass (a distance of 18.4 miles). The estimate is based on an average of individual profile comparisons, weighted by their representative alongshore distance. The losses from western profiles account for a vast majority of the total erosional losses at approximately 350 cubic-yards per linear foot on average versus 115 cubic-yards per linear foot for eastern profiles. The accuracy of design volume estimates depends on an understanding of the magnitude and composition of the sediment deficit. The volume required for translated design profiles uses a translated existing profile to indicate the anticipated post-nourishment shape of the design profile. The method is versatile, however it may not be a good indicator of post-construction design profile evolution in sediment-starved environments. For example, if the translation method is used to develop west end design profiles for pre- and post-Ike conditions, the volume estimates for the deepened post-Ike profile are lower than the pre-Ike profile. The post-Ike profile has a shortened active profile and an elevated beach relative to the pre-Ike condition, so the required design volume is less despite the sediment deficit calculated between profiles. These estimates, however, do not factor in differences in the effective sediment grain size.

BMAP is used to match an equivalent grain size to profile slopes in 2006 versus 2016 with beach equilibrium concepts. The 2006 pre-Ike profiles show an equivalent d_{50} grain size at 0.04 millimeters for XS15 and XS16, which technically classifies the sediment as silt. The remaining 2006 profile slopes have an equivalent grain size at 0.08 millimeters, classifying the sediment as fine sand, seen in Figure 20. The 2016 profiles have uniform slopes with an effective theoretical grain size equivalent to 0.07 millimeters, nearly equal to eastern pre-Ike profiles. The application of equilibrium beach profile concepts to historical profiles show that a bulk of the sediment lost during Ike may have been unusable fine-grained silt. Further, results indicate that an equilibrium profile with an equivalent grain size equal to average beach samples (d_{50}=0.13mm) would maintain the slope of the existing beach, intersecting the remainder of the profile

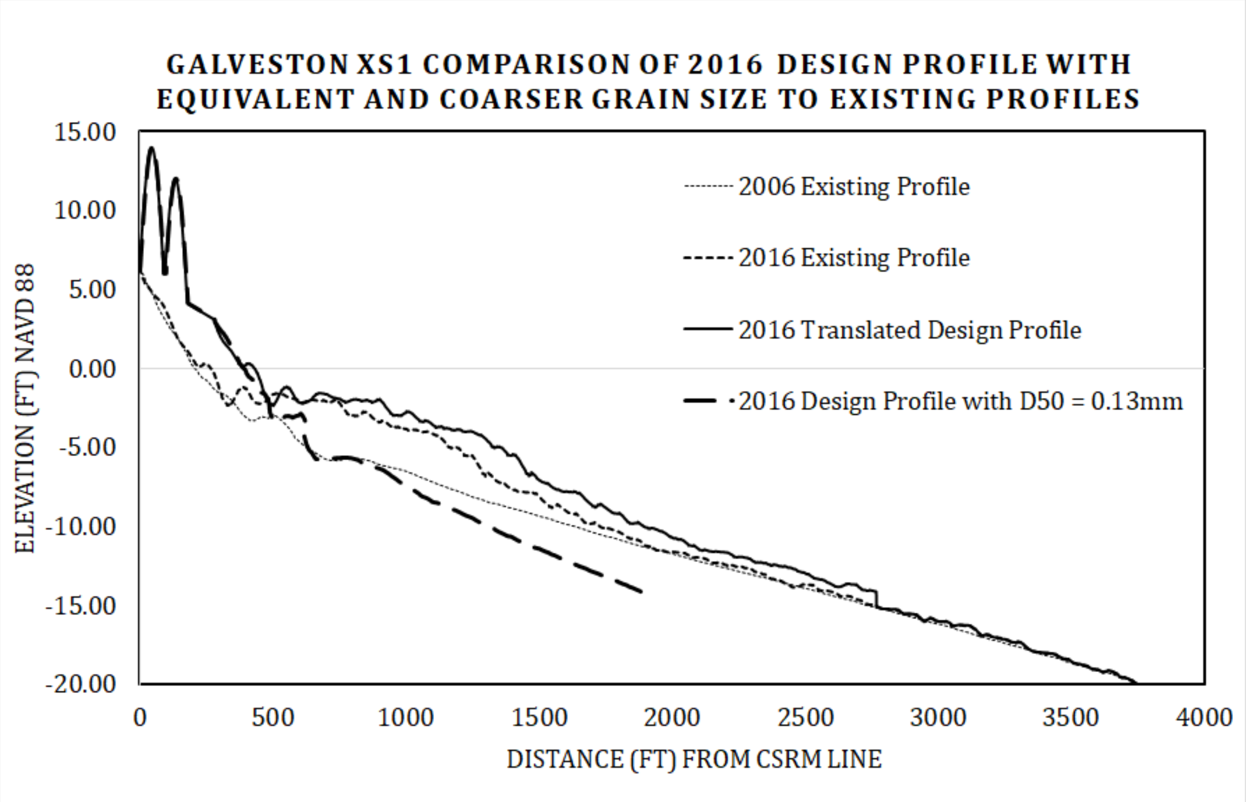


Figure 20: Beach equilibrium profile concepts applied to existing and design profiles

SBEACH model results show the normalized average beach erosion rate for the Galveston CSRM region is approximately -0.91 cubic feet per square foot with a 0.13 millimeter equivalent grain size according to Hurricane Ike model results. The 2006 to 2016 historical comparison show normalized volumetric losses at -1.14 cubic-feet per square-foot for eastern profiles (XS10-14) that have an equilibrium profile shape consistent with a 0.08 millimeter grain size, while western profiles (XS15-17) show normalized volumetric loss at -4.25 cubic-feet per square-foot. The model results show significant reduction in losses for profiles with coarser grain size, comparing well to results from the equilibrium profile concepts.

Results from the volumetric comparison of historical profiles show a significant sediment deficit between pre and post-Ike profiles, with trends substantiated by similar studies. However, equilibrium profile concepts and SBEACH model results suggest that the magnitude of losses can be attributed to the offshore sediment composition. Theoretically if the offshore composition of sediment were uniform with the native beach fill, the sediment deficit would be significantly lower due to a substantially shorter active profile. Further, Galveston results indicate that the construction volume estimates will conservatively offset the sediment deficit related to Ike if placed fill is equal to the native beach fill (d50=0.13mm) according to added width calculations applied to historical profiles. It is assumed that the outcome will similarly apply to Bolivar Peninsula and Follet's Island, however construction volume estimates will need to be revisited upon collection of further data.

RECOMMENDATIONS AND NEXT STEPS

1. CSRM TENTATIVELY SELECTED PLAN (TSP)

The tentatively selected plan (TSP) for the CSRM study site is a double-dune system and sloping berm system. A 3D rendering included in Figure 21, depicts existing conditions and typical CSRM design features. The graphic is not to scale, and dimensions vary relative to local shoreline conditions.

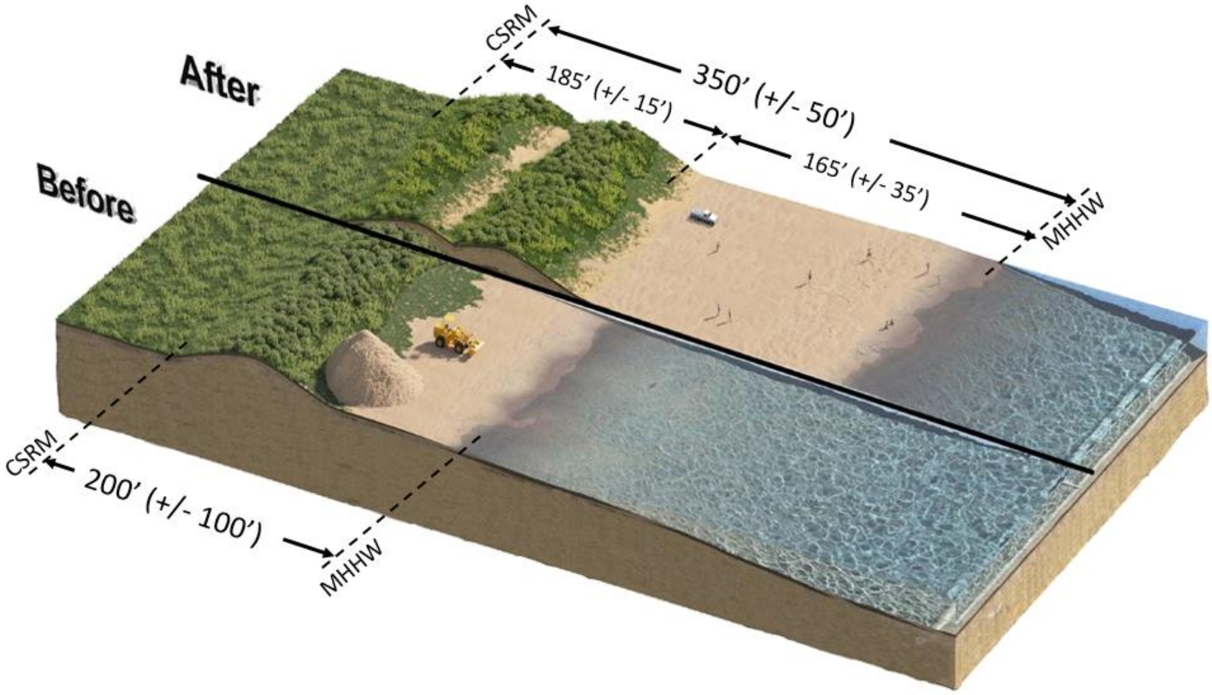


Figure 21: 3D Representation of existing profile and tentatively selected plan with general beach dimensions

Table 07: CSRM Construction Volume Estimate

CSRM Volume Estimates	**West Galveston Island**		**Bolivar Peninsula**		**UNITS**
	XS1	**XS2**	**XS1**	**XS2**	
Design Profile:	162.97	132.30	139.50	135.58	cyd/ft
+ Advanced Fill:	170.45	144.19	155.63	147.92	cyd/ft
Alongshore Distance:	11.94	6.41	13.10	11.99	miles
Subtotal:	10.75	4.880	10.77	9.36	M*cyd
+10%	11.82	5.368	11.85	10.3	M*cyd
Total:	17.19		22.14		M*cyd
Grand Total:	**39.33**				**M*cyd**

The total construction volume feasibility estimate is provided in Table 7. The estimate is intended as an order of magnitude-based methodologies outlined in this report. Final estimates should be developed based on PED phase recommendations included in the conclusion of this report.

Figure 22 depicts a vertically exaggerated Bolivar Peninsula dune-beach design profile with typical dimensions and elevations of CSRM features for the TSP. Dimensions such as the overall dune width are dependent on the leeward toe elevation and vary according to existing conditions.

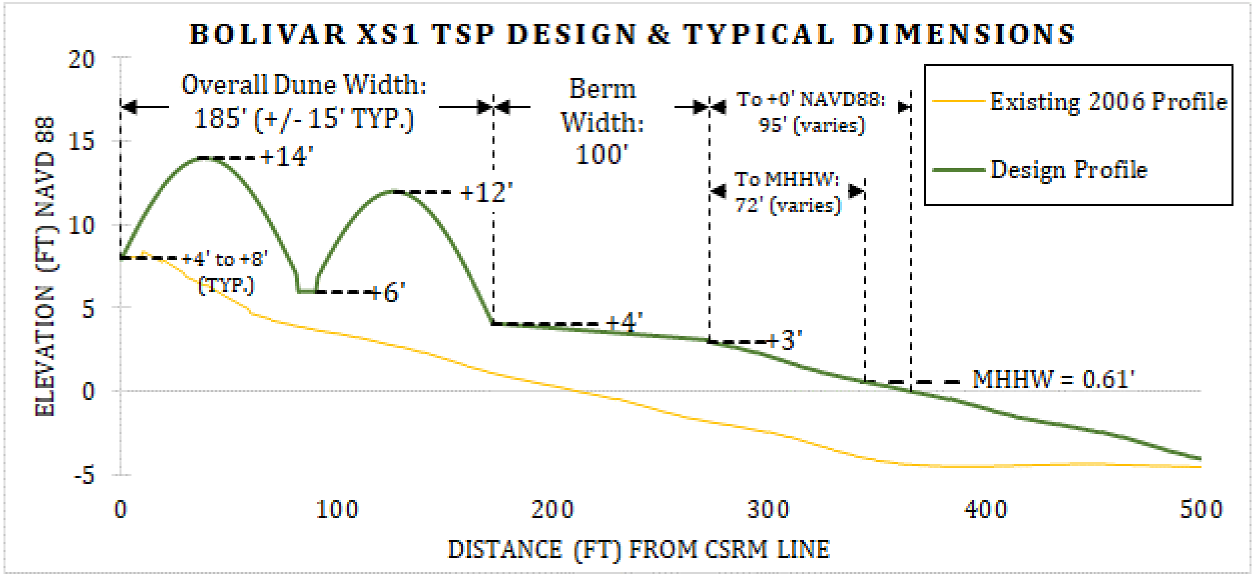


Figure 22: Typical dimensions and elevations for CSRM tentatively selected design profile represented on Bolivar XS1 representative profile; dune side slopes are 1:5

Construction templates extending to the depth of closure are included in Figures 23 through 26. Construction template profiles vary according to existing profile shape and estimated fill requirements. Construction template slope, top elevation and volume of advanced fill are included in captions.

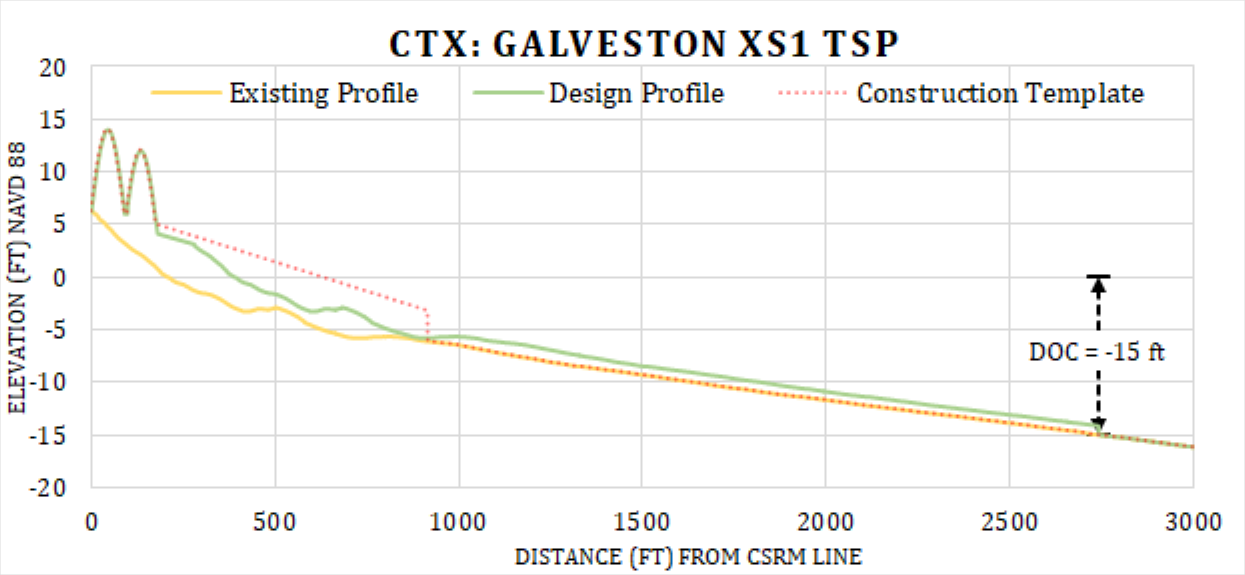


Figure 23: Galveston XS1 TSP; Construction template volume = 7.5 cyd/ft, top elev. at +5', slope at 1:90

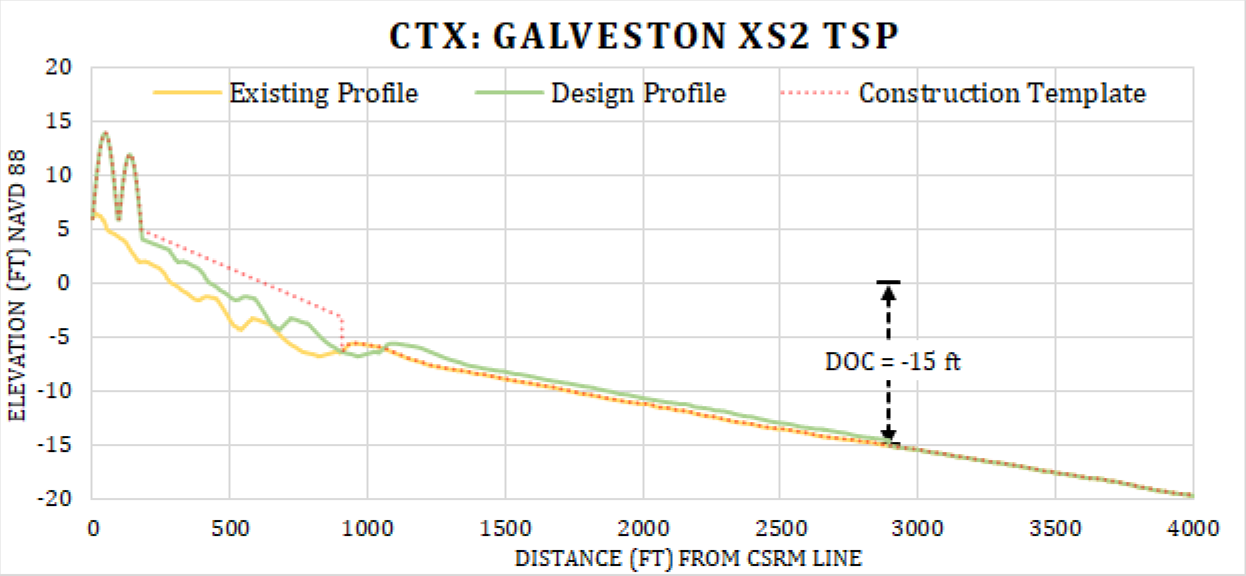


Figure 24: Galveston XS2 TSP; Construction template volume = 11.9 cyd/ft, top elev. at +5', slope at 1:90

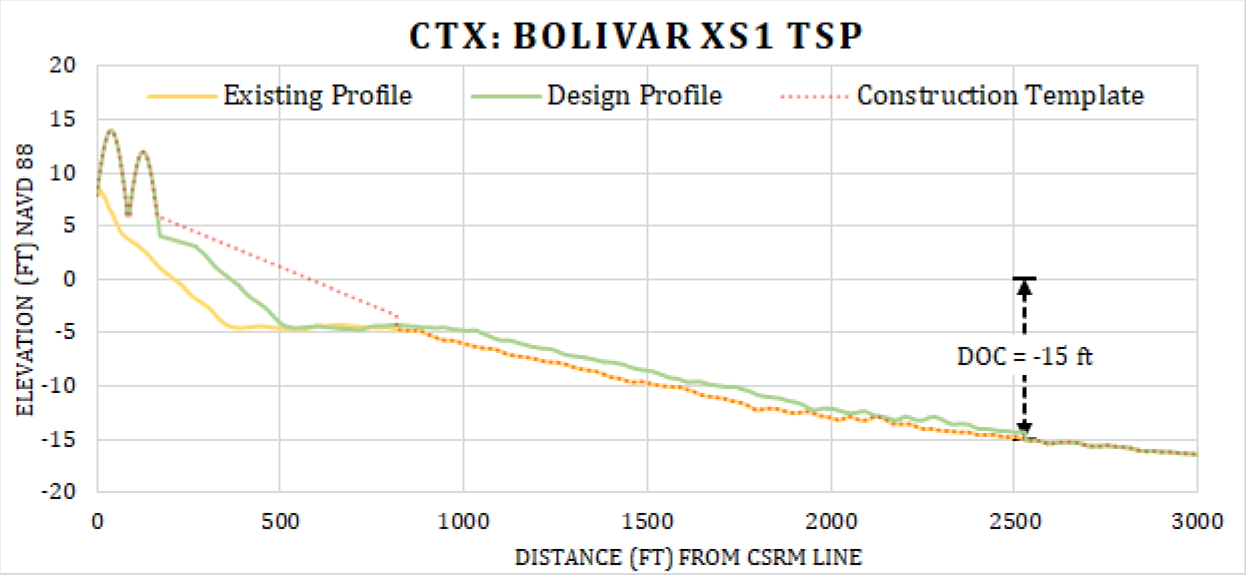


Figure 25: Bolivar XS1 TSP; Construction template volume = 16.1 cyd/ft, top elev. at +6', slope at 1:70

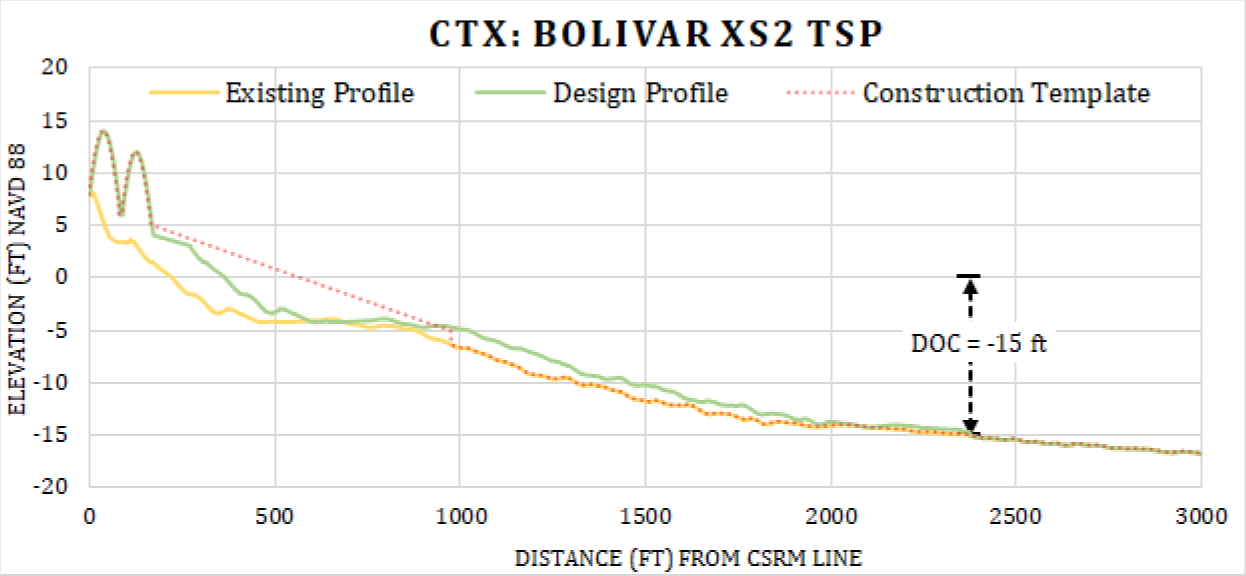


Figure 26: Bolivar XS2 TSP; Construction template volume = 12.4 cyd/ft, top elev. at +5', slope at 1:80

2. ER TENTATIVELY SELECTED PLAN (TSP)

Table 08: ER Volume Estimates

ER Volume Estimates	Follets Island XS1	Follets Island XS2	Units
ER Features:	3.61	1.3	cyd/ft
+ Advanced Fill:	14.46	12.62	cyd/ft
Representative Distance:	6	4	Miles
Subtotal:	456,442	272,138	cyd
+10%:	502,000	299,000	cyd
Grand Total:	**801,000**		**cyd**

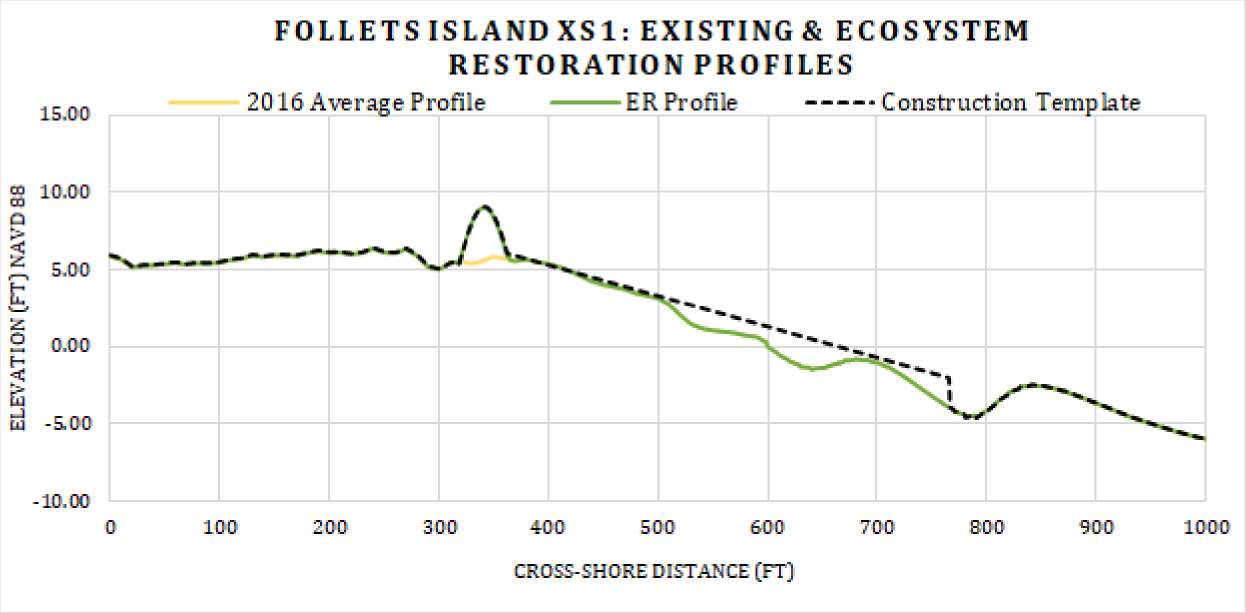


Figure 27: Follets Island XS1 restored profile with construction template; dune crest restored to +9' NAVD88 with side slopes at 1:5, top of berm at +6' NAVD88 and berm slope at 1:50

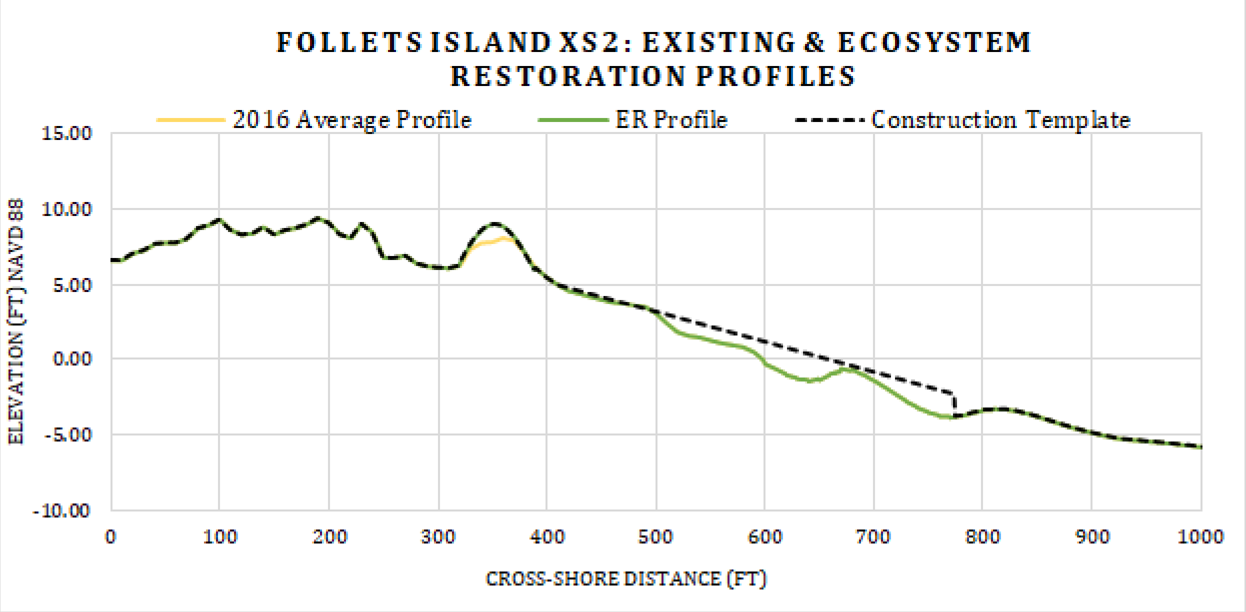


Figure 28: Follets Island XS1 restored profile with construction template; dune crest restored to +9' NAVD88 with natural side slopes at 1:10, top of berm at +5' NAVD88 and berm slope at 1:50

3. PRELIMINARY ENGINEERING DESIGN (PED) PHASE RECOMMENDATIONS

- A high resolution multi-beam bathymetric survey of the study site is highly recommended. This will provide considerable improvements for modeling purposes and developing precise volume estimates.
- Updated higher spatial resolution model with new bathymetry.
- Life-cycle analyses (longer time scale) probabilistic modeling that accounts for background erosion and relative sea-level change, in addition to severe storm-surge events is

recommended. This may require updates to the dune design to accommodate relative sea-level change and other new findings.

- Updated construction volume estimates with three-dimensional CADD software and new bathymetry is recommended.
- Determination of borrow fill location, sediment parameters, and dredge/transportation cost.
- Higher resolution sediment sampling at a distance further offshore and cross-shore model capable of composite sediment modeling, i.e. – accounts for variation in sediment parameters in the offshore direction.
- A generally uniform shoreline planform, with gradual alignment changes is recommended to prevent erosion hot-spots from developing. This will require non-uniform distribution of fill to accommodate local variations in the shoreline. Construction templates should be updated to consider alongshore morphological variations and borrow fill sediment parameters relative to native samples.
- A risk-cost-benefit analysis, considering results from the above recommendations is recommended.
- Dunes are ephemeral features that often require additional planning and maintenance relative to hardened structures. Techniques to promote dune stabilization and growth include sand fence placement, dune grass planting, and irrigation. These require design specifications, an operations and maintenance plan, and a cost-benefit analysis. According to EM 1110-2-1100, dune vegetation typically takes 3-5 years to fully establish under the right conditions. It is recommended that dune grass planting specifications including, spacing, species/root structure, method of installation, maintenance/irrigation requirements, cost, and timing for installation. The GLO's Dune Manual provides a good starting point for the development of dune planting specifications. The City of Galveston has already adopted the following guidance on dune stabilization measures from the GLO dune manual (Ord. No. 15-075, § 2, 9-24-15):
    - *Seaward face of the dune.* Bitter Panicum (grass), Sea Oats (grass), Marsh Hay Cordgrass (grass), beach morning glory (vine, and sea grapes (vine).
    - *Landward side of the dune.* Low-growing plants and shrubs found on the back side of the dunes include seacoast bluestem, cucumber leaf sunflower, rose ring gaillardia, partridge pea, prickly pear, and lantana. Many of these are flowering plants, an attractive alternative to dune grasses though less effective as dune stabilizers.
    - *Native hay.* The use of a three (3) to six (6) inch thick layer native hay, with seeds of the above listed vegetation, on bare sand areas to provide immediate protection from blowing sand and encourage the natural process of re-seeding. The hay must be harvested in fall when mature seeds are present.
    - *Sand fencing.* Encourage limited use of sand fencing to build up dunes where revegetation alone is unlikely to encourage sufficient dune width and height. Sand fencing can be used as a first step prior to revegetation.

Additional Considerations:

- Consider deployment of ocean instruments (such as an Acoustic Doppler Velocimeter (ADV)) to collect field data on measures such as mean bed-stream velocity that may be useful in model calibration.
- A plan should be developed to address education, prevention, regulation and enforcement measures required to mitigate manmade damage to dunes.

REFERENCES

i. BERG, ROBBIE. JANUARY 23, 2009. *HURRICANE IKE, 1-14 SEPTEMBER 2008.* TROPICAL CYCLONE REPORT. NOAA NATIONAL HURRICANE CENTER. UPDATED AUG-11-2011

ii. DELLAPENNA, T.M., K. JOHNSON, 2012. MAPPING AND CORING OF THE INNER SHELF OF GALVESTON ISLAND – POST HURRICANE IKE, FINAL REPORT TO THE TEXAS COASTAL COORDINATION COUNCIL, CMP CYCLE 14. CONTRACT NO. 10-048-000-3744, TEXAS A&M UNIVERSITY AT GALVESTON.

iii. GIBEAUT, J. C., WHITE, W. A., HEPNER, TIFFANY, GUTIÉRREZ, ROBERTO, TREMBLAY, T. A., SMYTH, R. C., AND ANDREWS, J. R., 2000, TEXAS SHORELINE CHANGE PROJECT: GULF OF MEXICO SHORELINE CHANGE FROM THE BRAZOS RIVER TO PASS CAVALLO: THE UNIVERSITY OF TEXAS AT AUSTIN, BUREAU OF ECONOMIC GEOLOGY, REPORT PREPARED FOR THE TEXAS COASTAL COORDINATION COUNCIL PURSUANT TO NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION AWARD NO. NA870Z0251, 32 P

iv. HDR (2014): BEACH AND SHORELINE CHANGES ALONG THE UPPER TEXAS COAST: RECOVERY FROM HURRICANE IKE, HDR ENGINEERING INC., PROJECT NUMBER 166742 PP. 2-61

v. KING, DAVID B., 2007. *WAVE AND BEACH PROCESSES MODELING FOR SABINE PASS TO GALVESTON BAY, TEXAS, SHORELINE EROSION FEASIBILITY STUDY*. TECHNICAL REPORT CHL-07-6. VICKSBURG, MS: U.S. ARMY ENGINEER RESEARCH AND DEVELOPMENT CENTER, COASTAL AND HYDRAULICS LABORATORY.

vi. KNABB, R.D., D.P. BROWN, J.R. RHOME, MARCH 17, 2006. *HURRICANE RITA, 18-26 SEPTEMBER 2005.* TROPICAL CYCLONE REPORT. NOAA NATIONAL HURRICANE CENTER. UPDATED SEP-14-2011

vii. LARSON, M., N. C. KRAUS, AND M. R. BYRNES. 1990. *SBEACH: NUMERICAL MODEL FOR SIMULATING STORM-INDUCED BEACH CHANGE; REPORT 2: NUMERICAL FORMULATION AND MODEL TEST*. TECHNICAL REPORT CERC-89-9. VICKSBURG, MS: U.S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, COASTAL ENGINEERING RESEARCH CENTER.

viii. LAWRENCE, MILES B. NOVEMBER 18, 1998. *TROPICAL STORM FRANCES.* PRELIMINARY REPORT. NOAA NATIONAL HURRICANE CENTER.

ix. MELBY, JEFFREY A., N.C. NADAL-CARABALLO AND N. KOBAYASHI. 2012. *WAVE RUNUP PREDICTION FOR FLOOD MAPPING.* COASTAL ENGINEERING

x. NEEDHAM, HAL. 2010. *IDENTIFYING HISTORIC STORM SURGES AND CALCULATING STORM SURGE RETURN PERIODS FOR THE GULF OF MEXICO COAST.* LSU MASTER'S THESES. 3341.

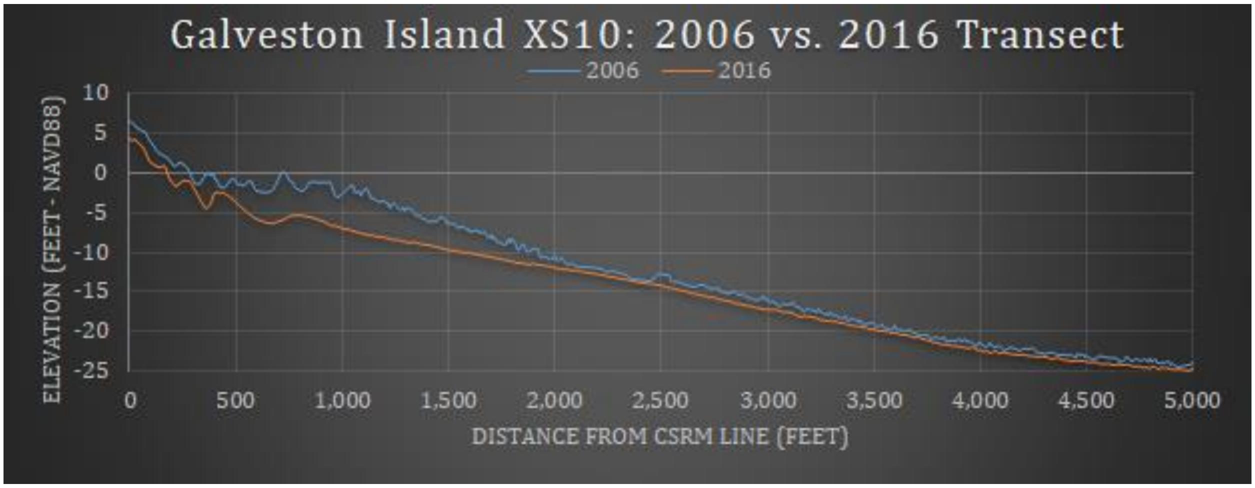
xi. PAINE, JEFFREY G., T. CAUDLE AND J. ANDREWS. 2013. *SHORELINE, BEACH, AND DUNE MORPHODYNAMICS, TEXAS GULF COAST*. BUREAU OF ECONOMIC GEOLOGY. JACKSON SCHOOL OF GEOSCIENCES, THE UNIVERSITY OF TEXAS AT AUSTIN, AUSTIN, TEXAS.

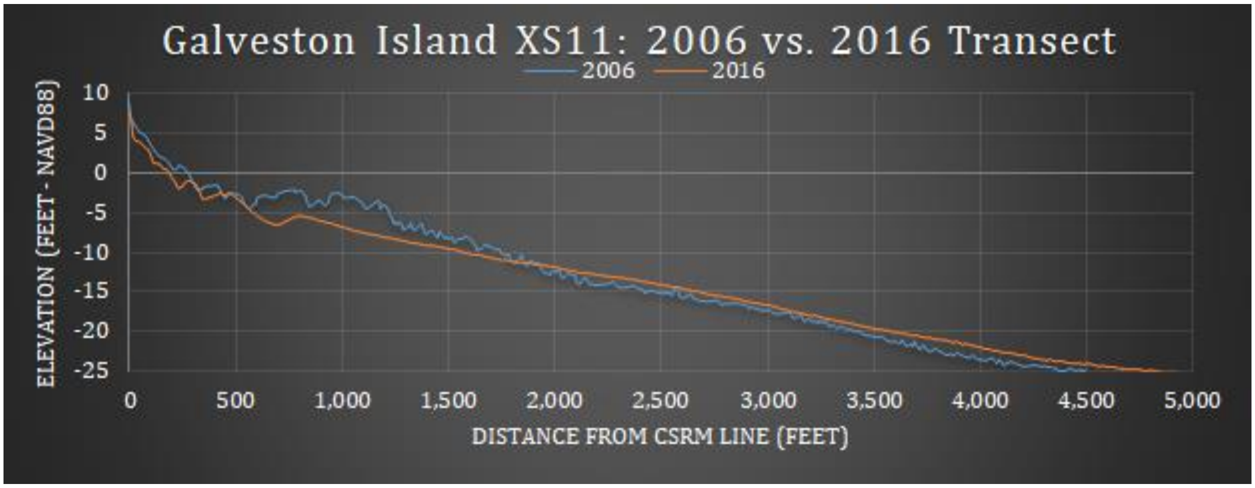
xii. PAINE, JEFFREY G., T.L. CAUDLE AND J.R. ANDREWS. 2014. *SHORELINE MOVEMENT ALONG THE TEXAS GULF COAST, 1930'S TO 2012*. BUREAU OF ECONOMIC GEOLOGY. JACKSON SCHOOL OF GEOSCIENCES, THE UNIVERSITY OF TEXAS AT AUSTIN, AUSTIN, TEXAS.

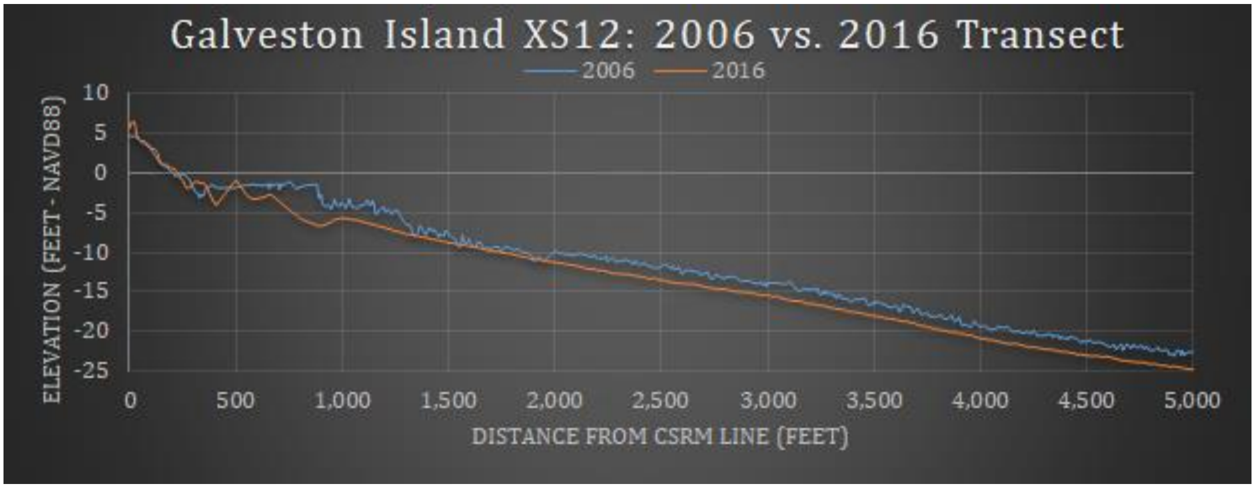
xiii. STEWART, STACY R. NOVEMBER 28, 2001. *TROPICAL STORM ALLISON.* TROPICAL CYCLONE REPORT. NOAA NATIONAL HURRICANE CENTER. UPDATED AUG-11-2011

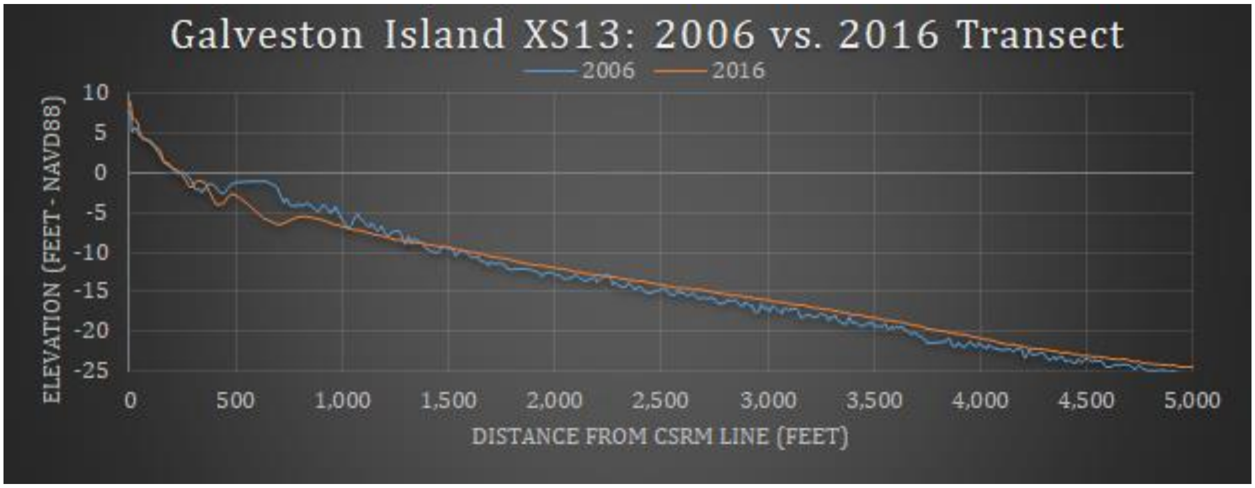
xiv. USACE. (2008). COASTAL ENGINEERING MANUAL. EM 1110-2-1100.

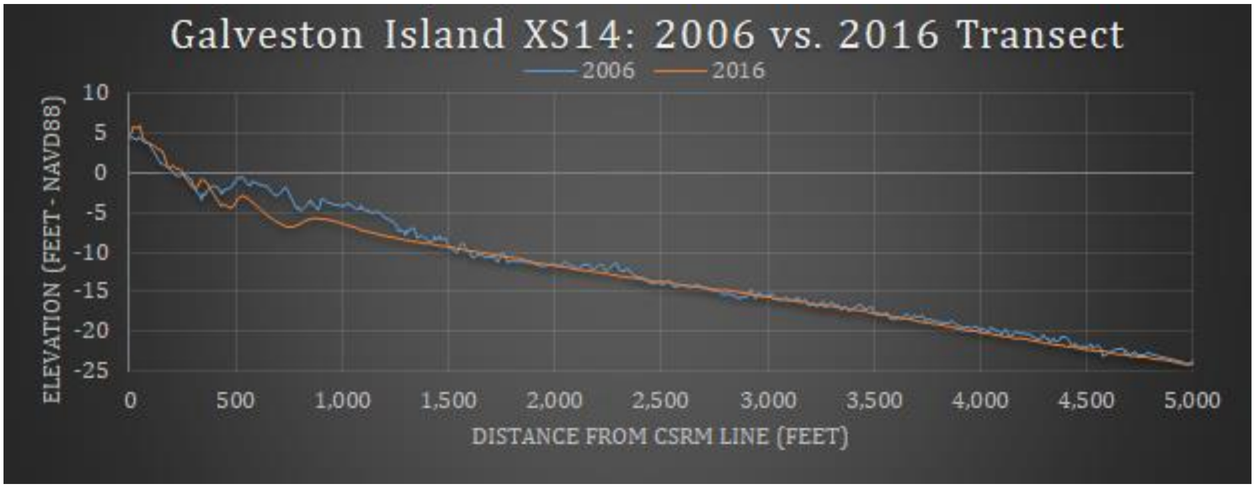
APPENDIX A: HISTORICAL COMPARISON OF WEST GALVESTON PROFILES

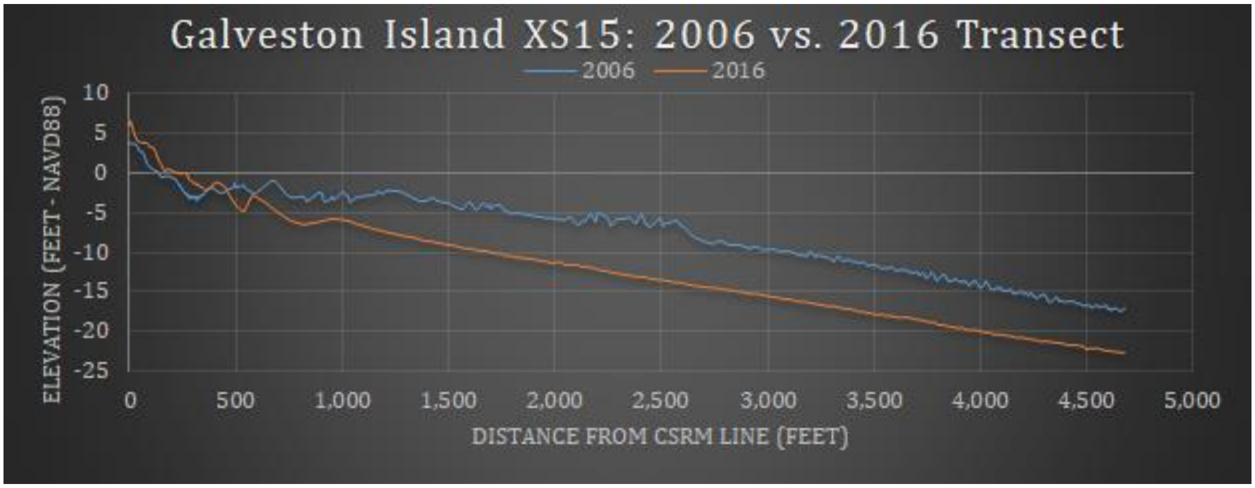


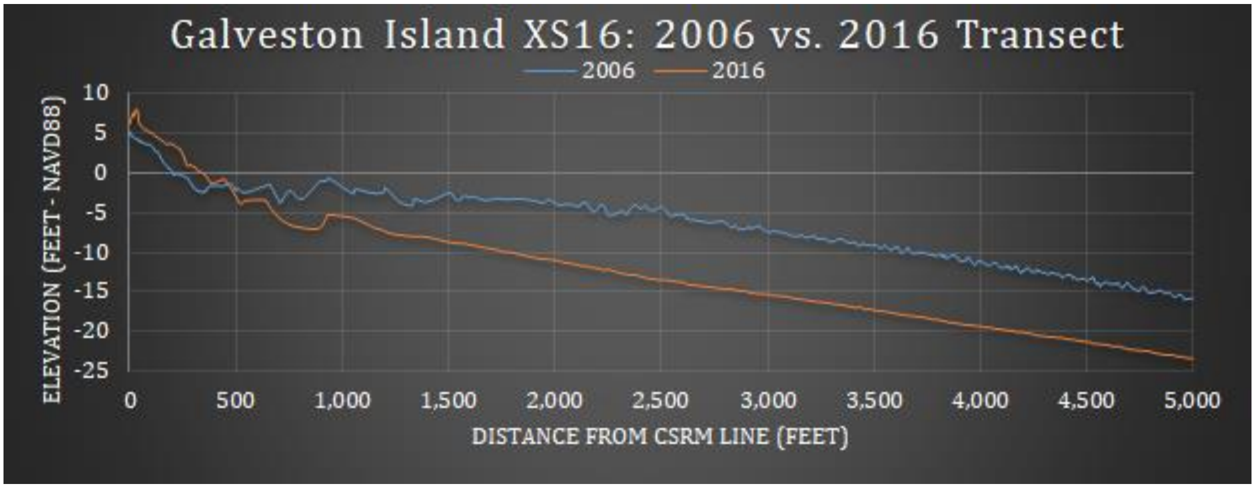




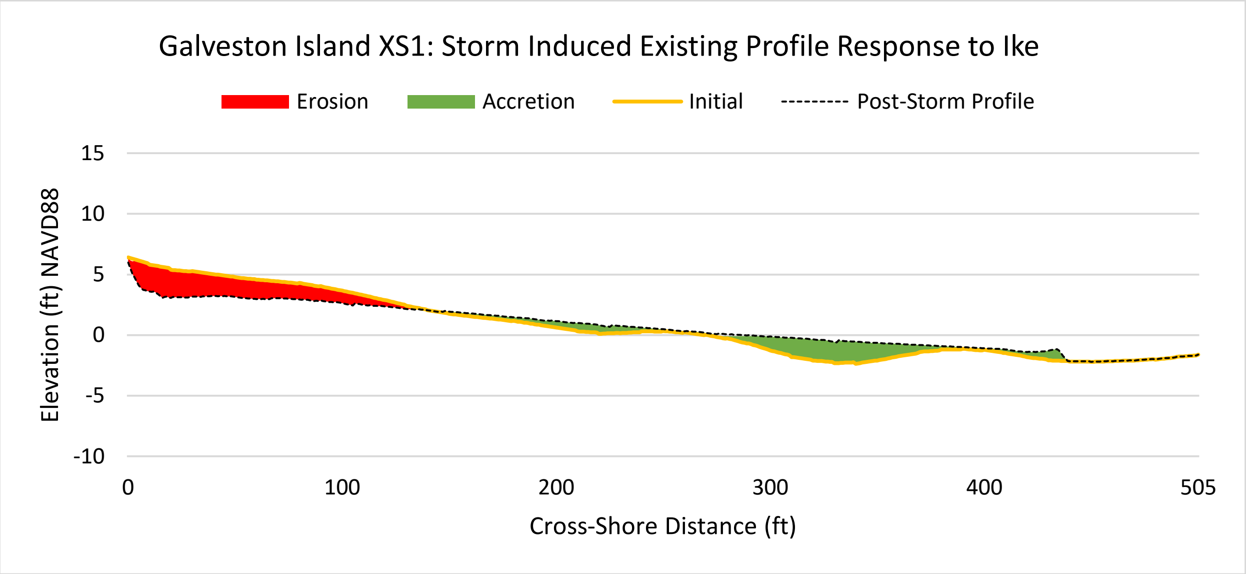

Galveston Island XS13: 2006 vs. 2016 Transect
2006
2016
ELEVATION (FEET - NAVD88)
10
5
0
-5
-10
-15
-20
-25
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
DISTANCE FROM CSRM LINE (FEET)


Galveston Island XS14: 2006 vs. 2016 Transect
2006
2016
ELEVATION (FEET - NAVD88)
10
5
0
-5
-10
-15
-20
-25
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
DISTANCE FROM CSRM LINE (FEET)


Galveston Island XS15: 2006 vs. 2016 Transect
2006
2016
ELEVATION (FEET - NAVD88)
10
5
0
-5
-10
-15
-20
-25
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
DISTANCE FROM CSRM LINE (FEET)

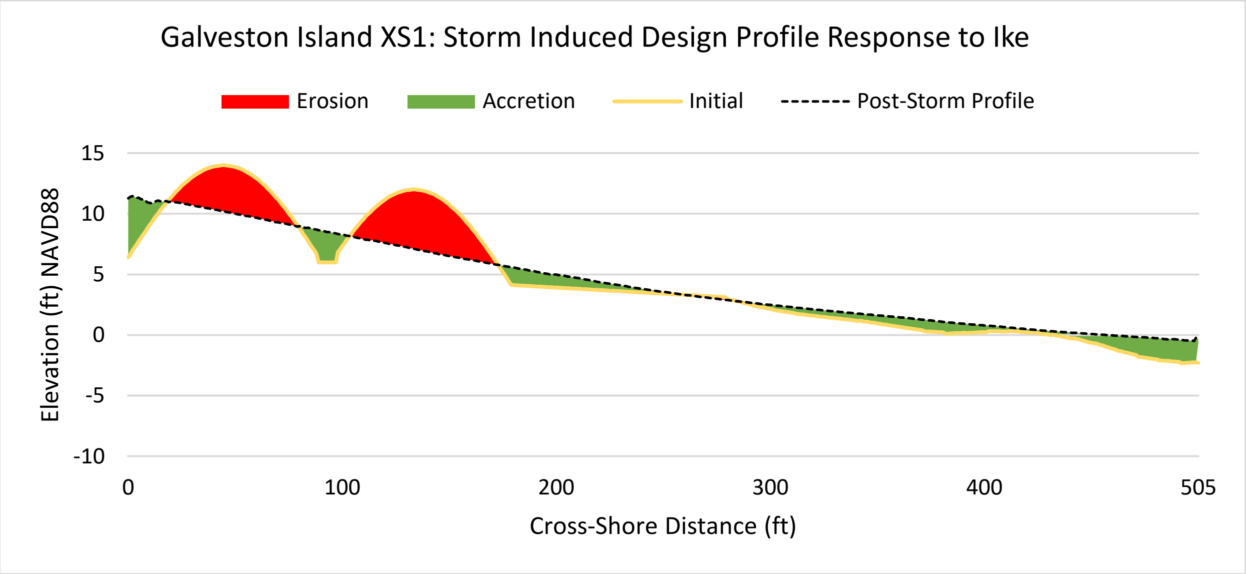

Galveston Island XS16: 2006 vs. 2016 Transect
2006
2016
ELEVATION (FEET - NAVD88)
10
5
0
-5
-10
-15
-20
-25
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
DISTANCE FROM CSRM LINE (FEET)

APPENDIX B: CSRM STORM INDUCED RESPONSE EXISTING AND DESIGN PROFILES



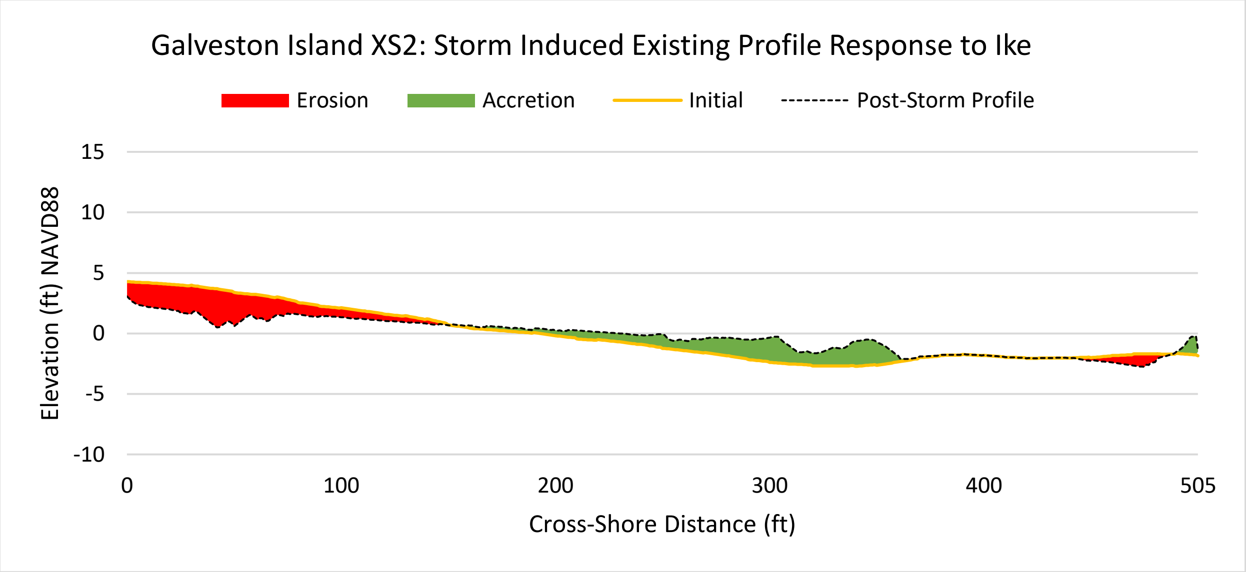
Beach Erosion (CSRM to MHHW= 1.41 ft): -6.89 cubic-yards per linear foot (cyd/lft)

Normalized Erosion (CSRM to MHHW): -1.11 cubic-feet per square foot (cft/sqft)



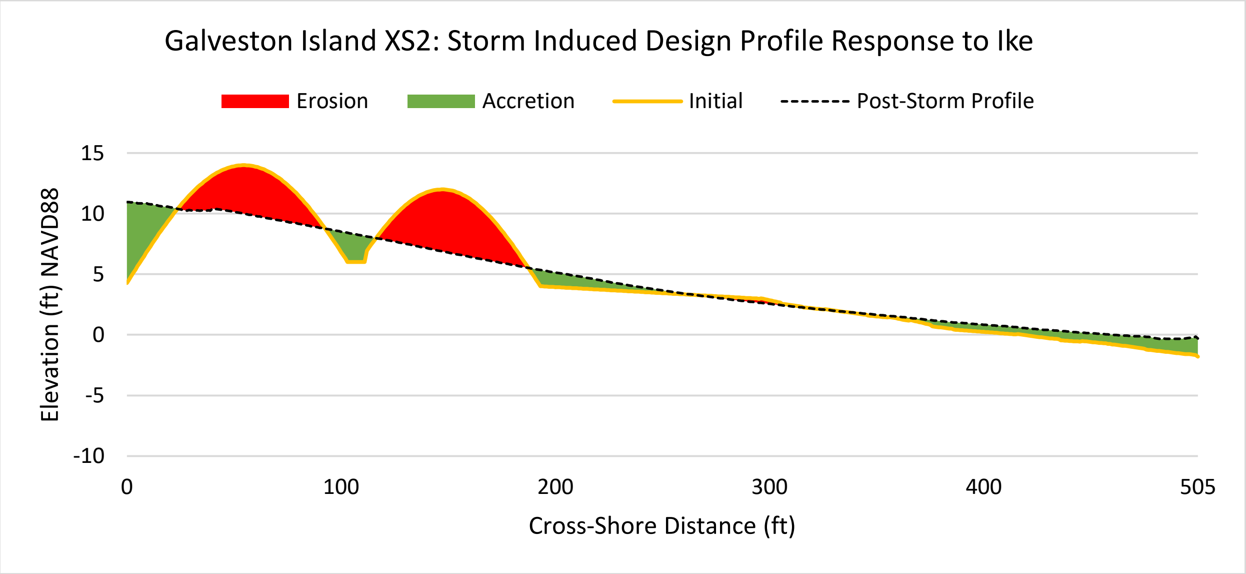
Beach Erosion (CSRM to MHHW= 1.41 ft): -8.1 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.66 cubic-feet per square foot (cft/sqft)



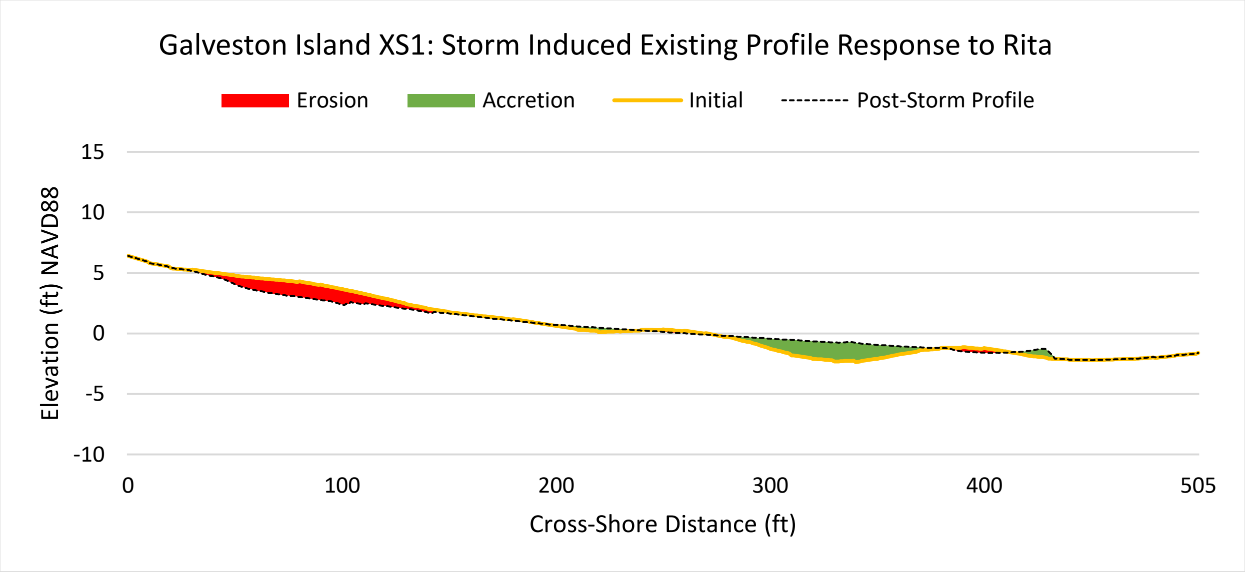
Beach Erosion (CSRM to MHHW = 1.41 ft): -7.55 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -1.54 cubic-feet per square foot (cft/sqft)



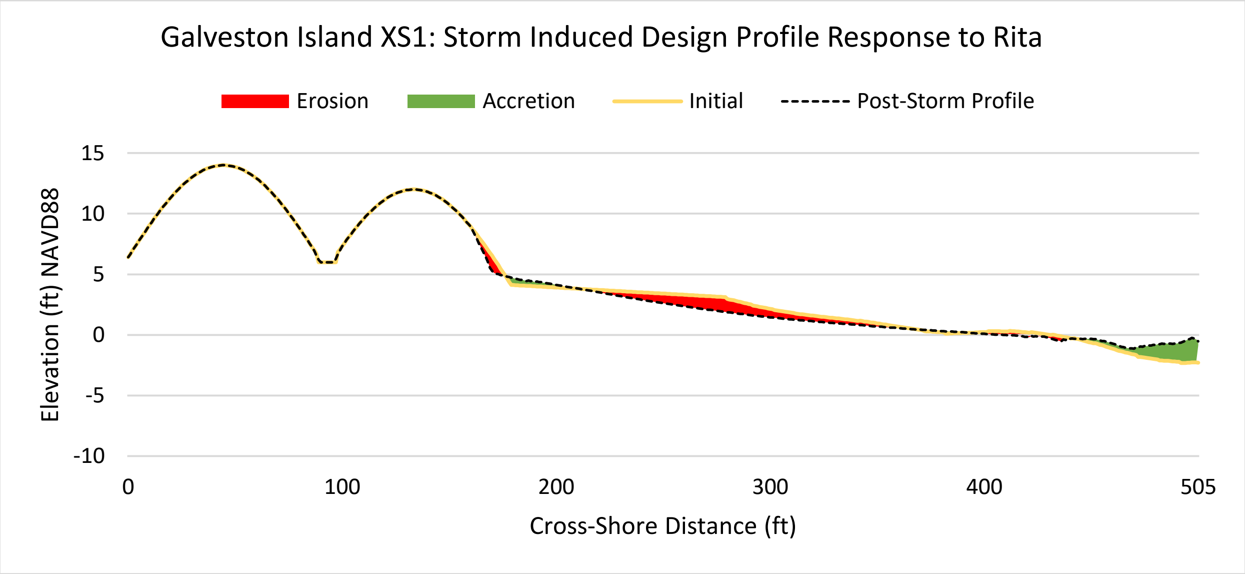
Beach Erosion (CSRM to MHHW= 1.41 ft): -9.83 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.74 cubic-feet per square foot (cft/sqft)



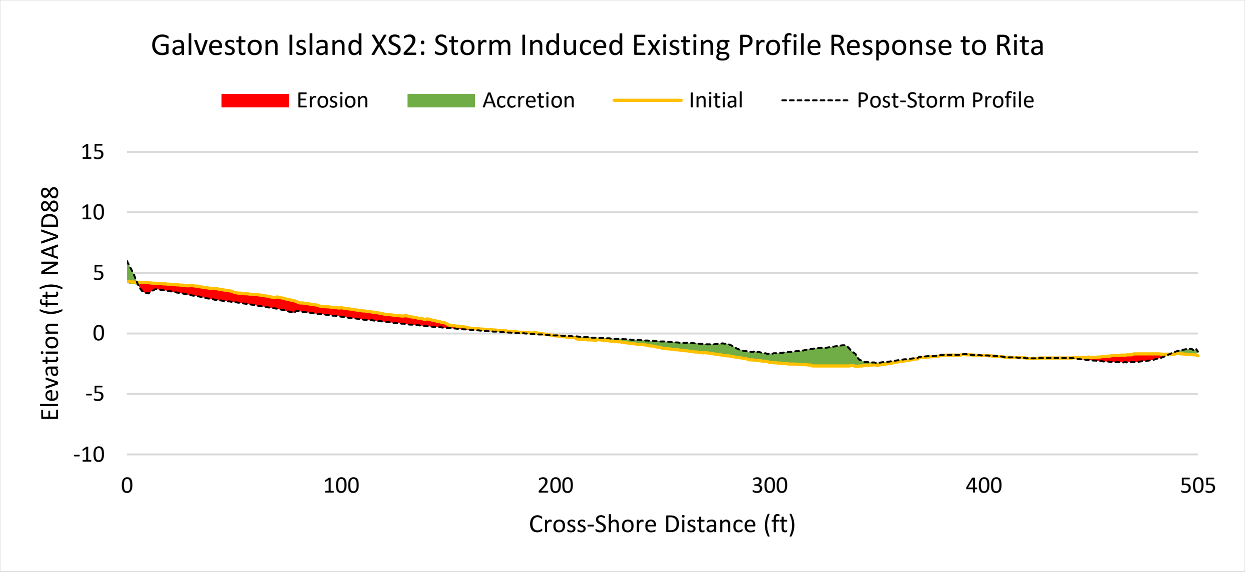
Beach Erosion (CSRM to MHHW= 1.41 ft): -3.47 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.56 cubic-feet per square foot (cft/sqft)



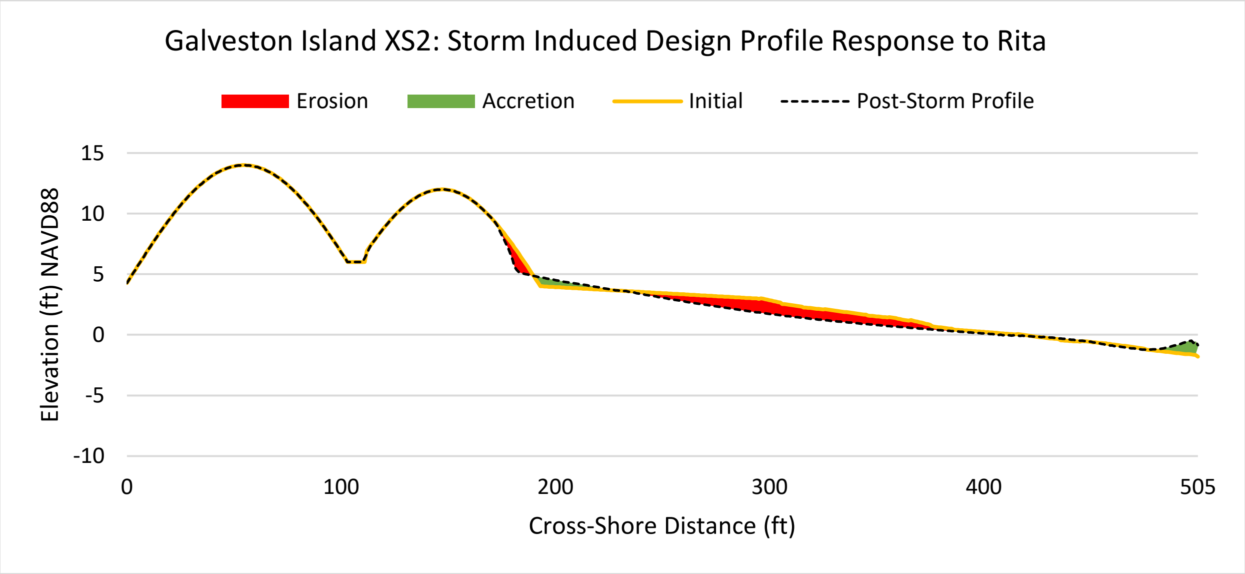
Beach Erosion (CSRM to MHHW= 1.41 ft): -2.94 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.24 cubic-feet per square foot (cft/sqft)



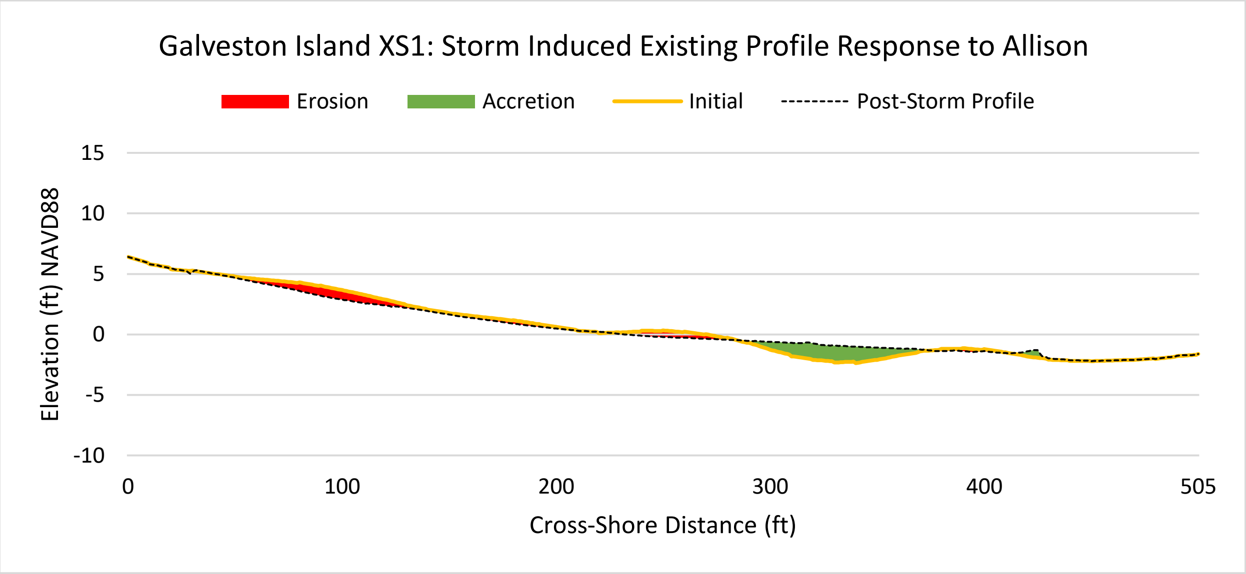
Beach Erosion (CSRM to MHHW= 1.41 ft): -3.31 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.68 cubic-feet per square foot (cft/sqft)



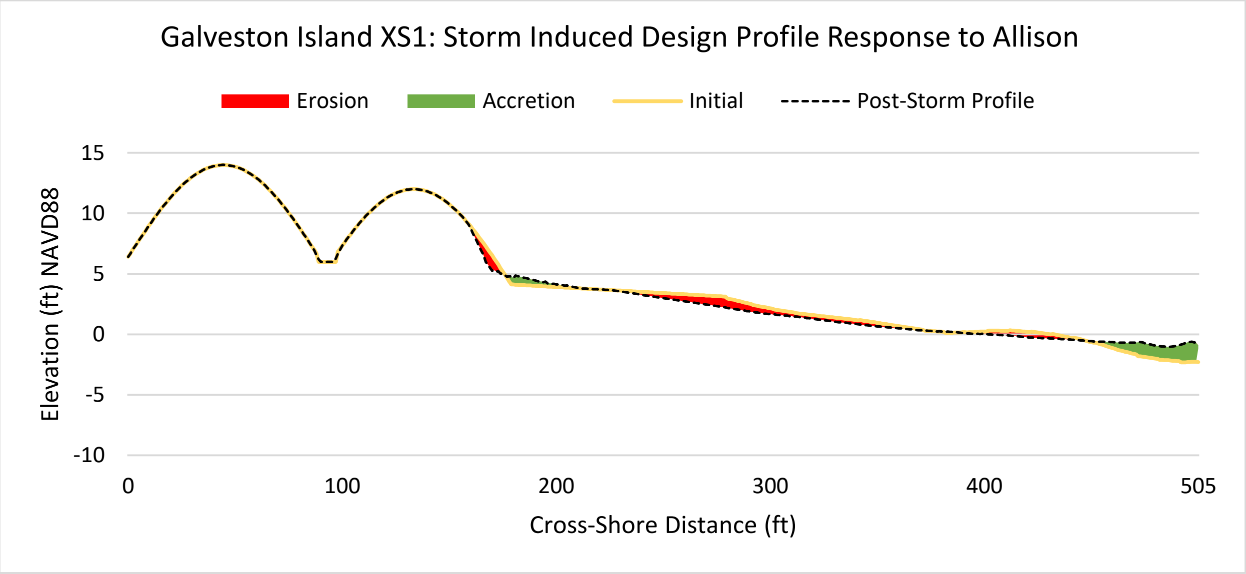
Beach Erosion (CSRM to MHHW= 1.41 ft): -3.47 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.26 cubic-feet per square foot (cft/sqft)



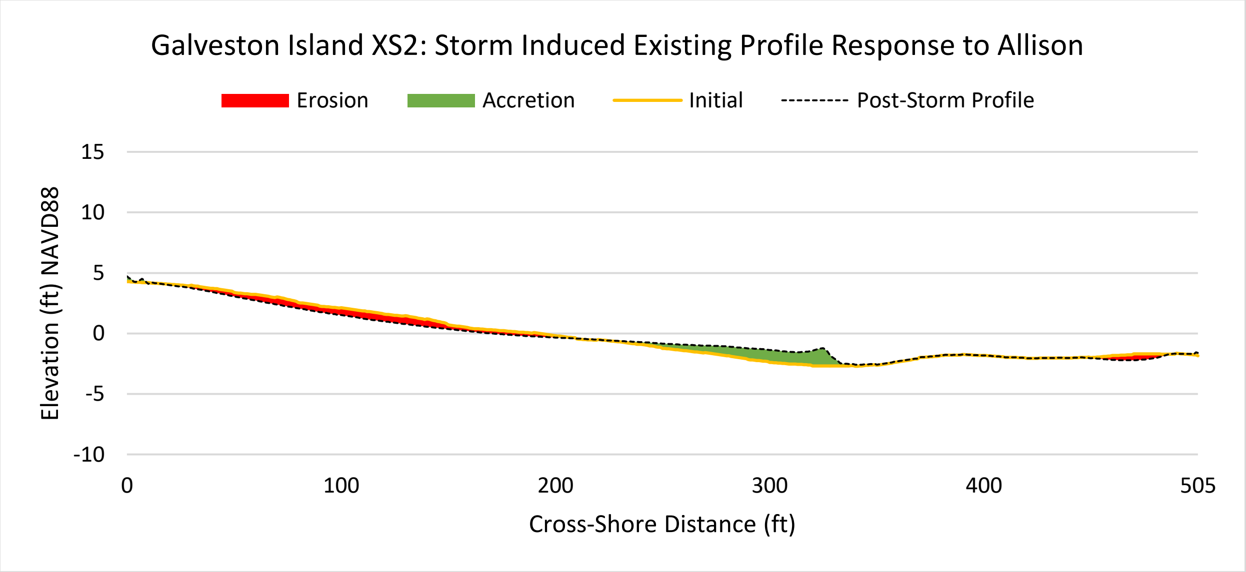
Beach Erosion (CSRM to MHHW= 1.41 ft): -1.84 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.3 cubic-feet per square foot (cft/sqft)



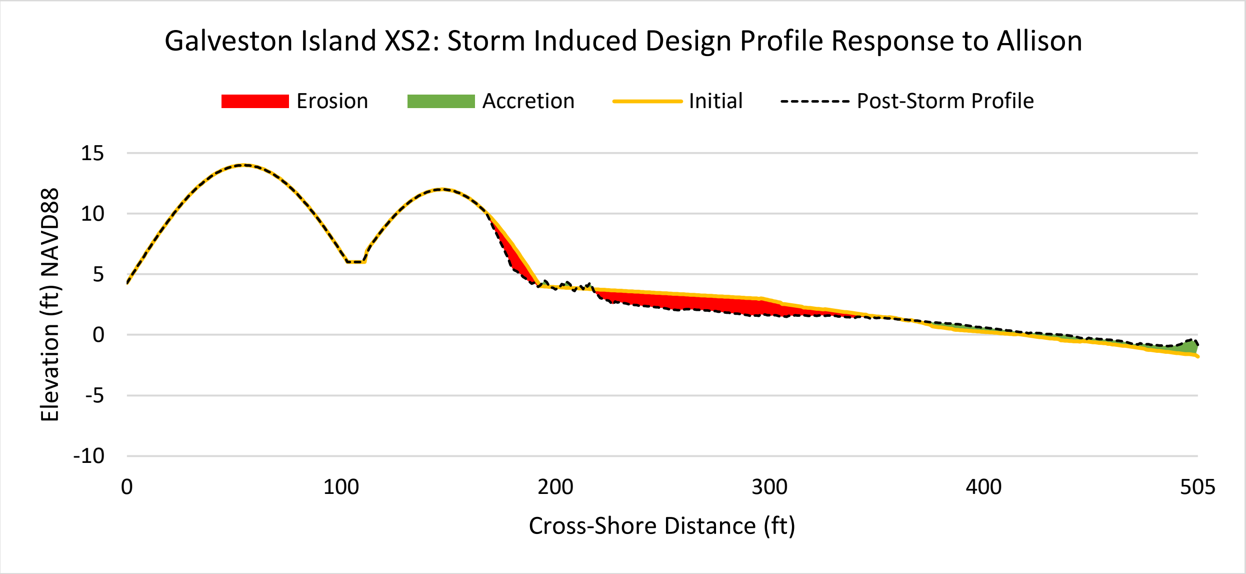
Beach Erosion (CSRM to MHHW= 1.41 ft): -1.74 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.14 cubic-feet per square foot (cft/sqft)



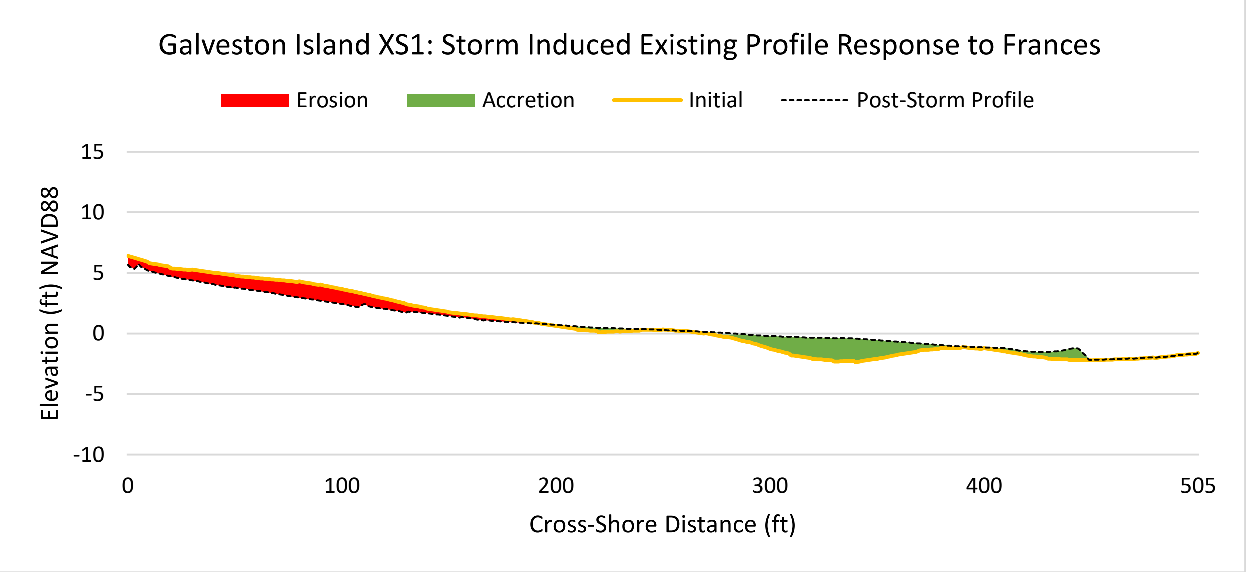
Beach Erosion (CSRM to MHHW= 1.41 ft): -1.88 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.38 cubic-feet per square foot (cft/sqft)



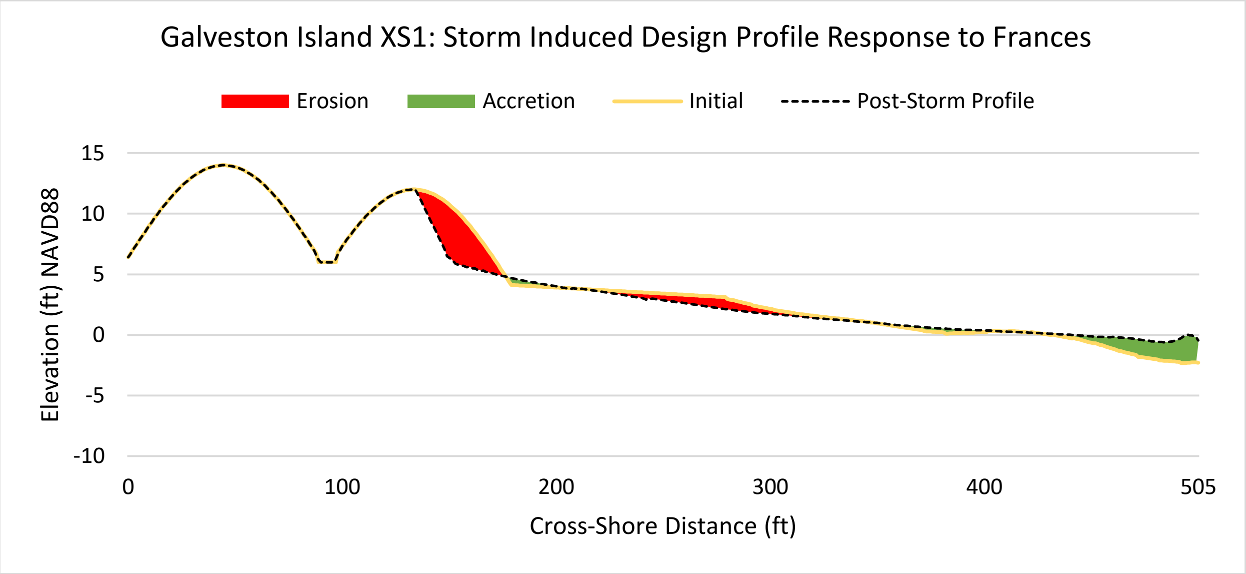
Beach Erosion (CSRM to MHHW= 1.41 ft): -5.55 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.41 cubic-feet per square foot (cft/sqft)



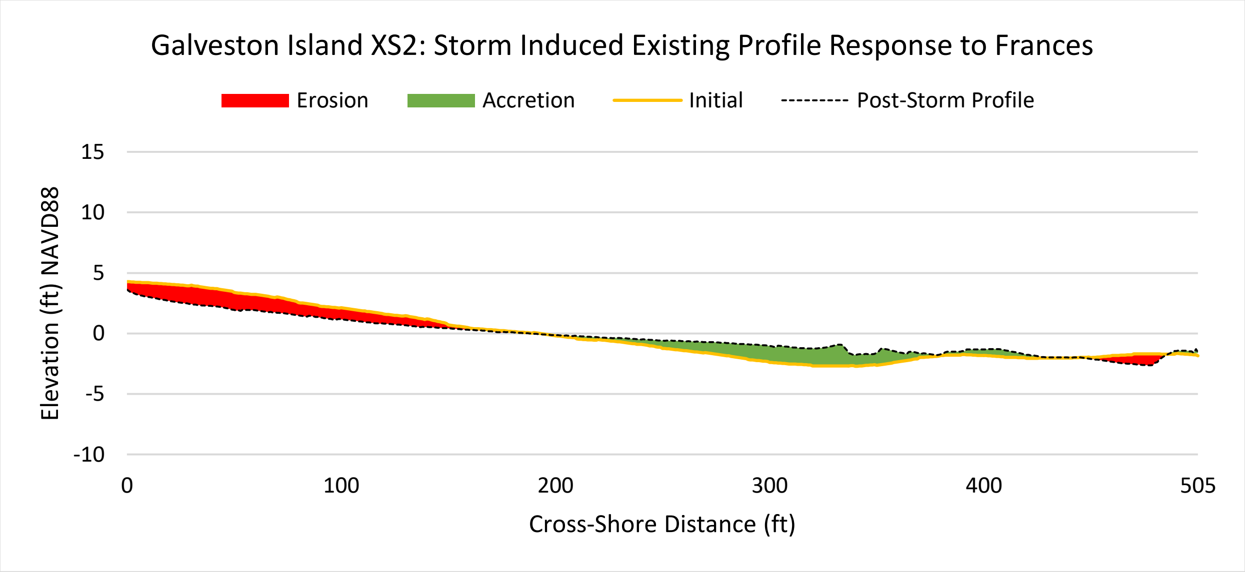
Beach Erosion (CSRM to MHHW= 1.41 ft): -5.31 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.86 cubic-feet per square foot (cft/sqft)



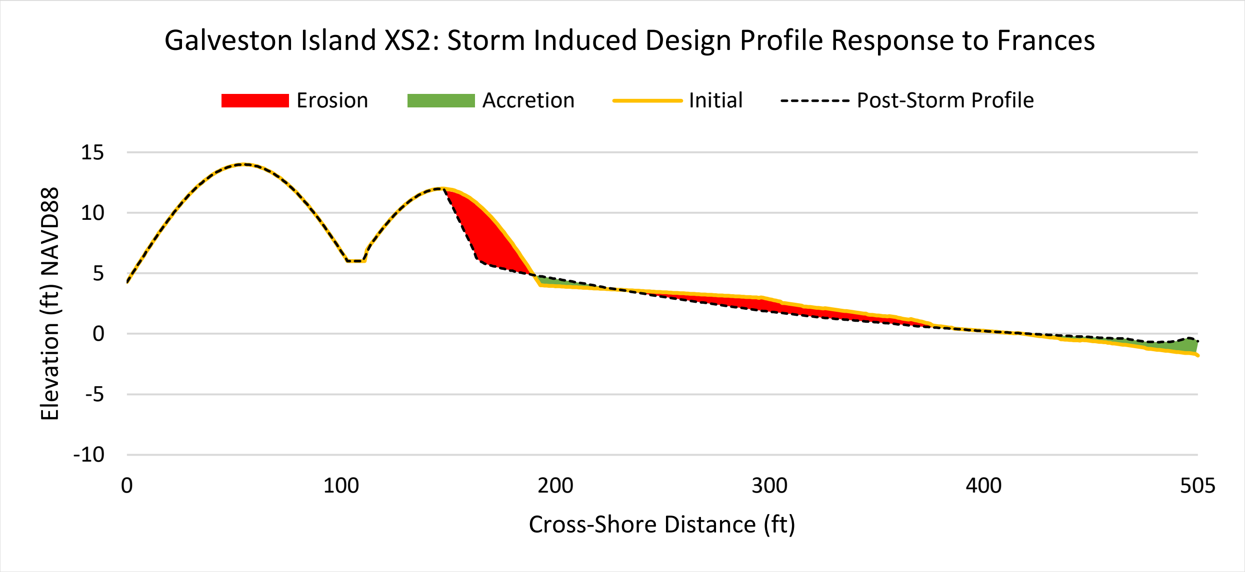
Beach Erosion (CSRM to MHHW= 1.41 ft): -5.7 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.47 cubic-feet per square foot (cft/sqft)



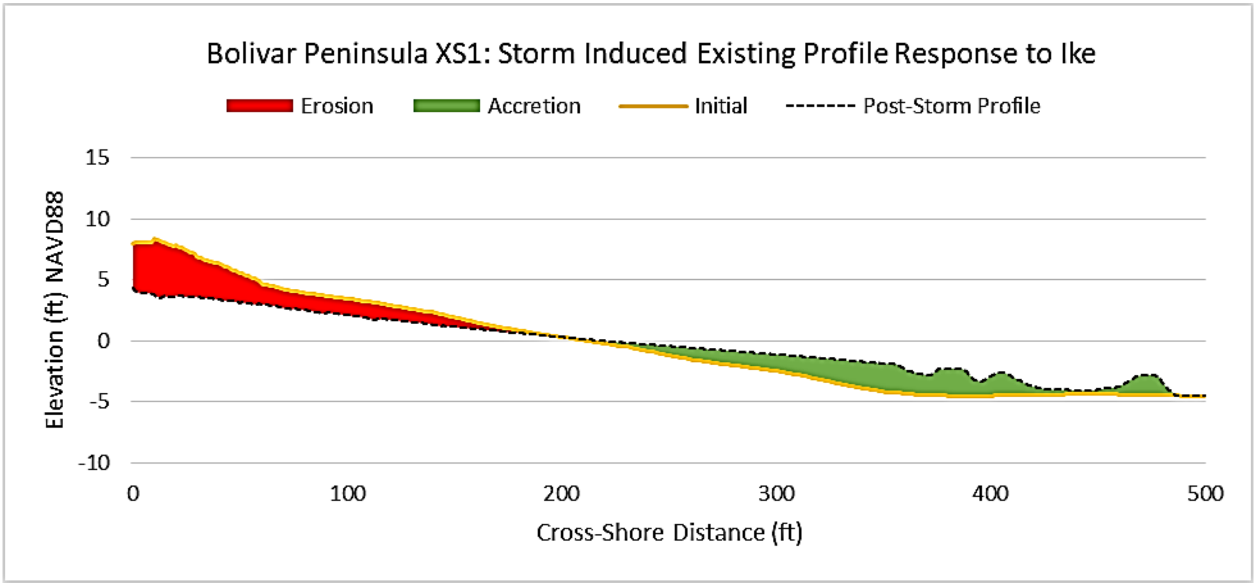
Beach Erosion (CSRM to MHHW= 1.41 ft): -5.66 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -1.16 cubic-feet per square foot (cft/sqft)



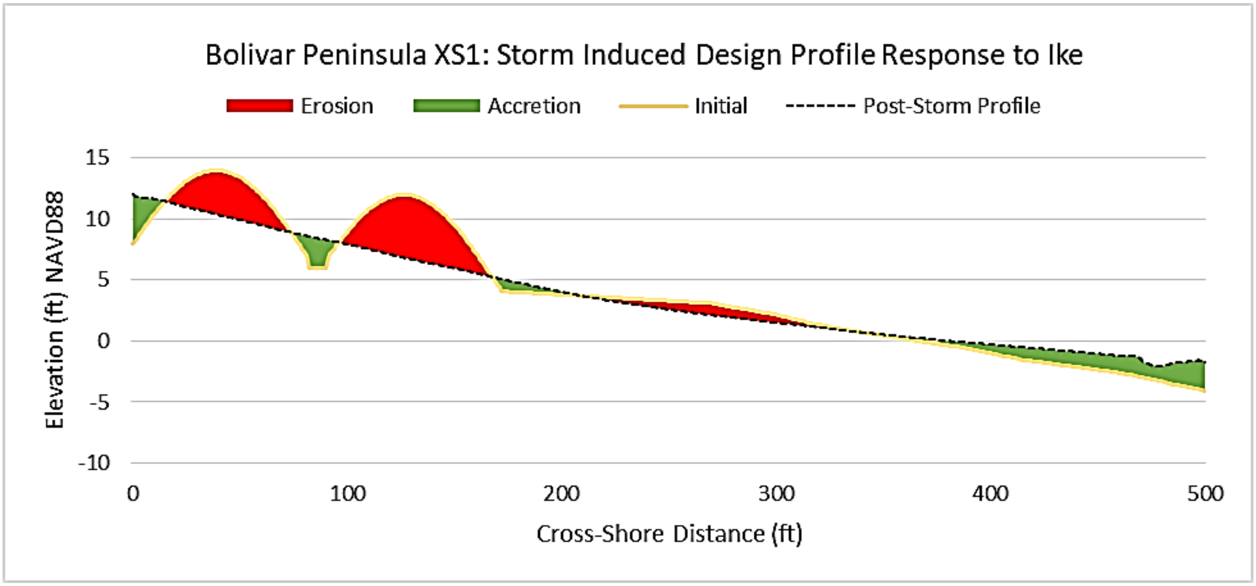
Beach Erosion (CSRM to MHHW= 1.41 ft): -6.6 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.5 cubic-feet per square foot (cft/sqft)



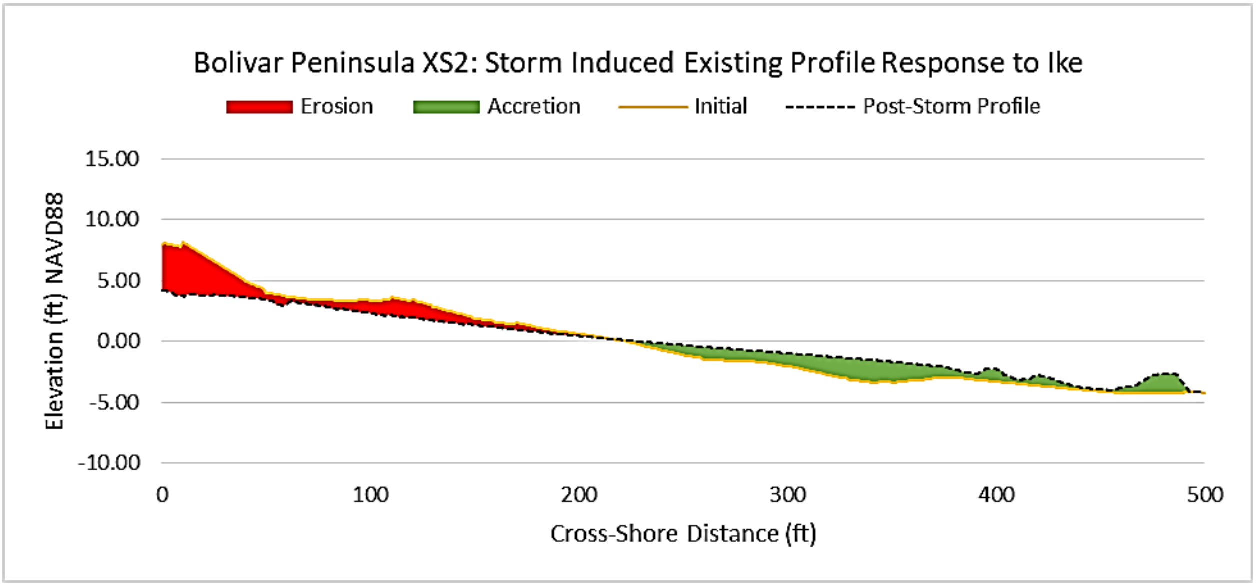
Beach Erosion (CSRM to MHHW= 0.61 ft): -12.51 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -1.78 cubic-feet per square foot (cft/sqft)



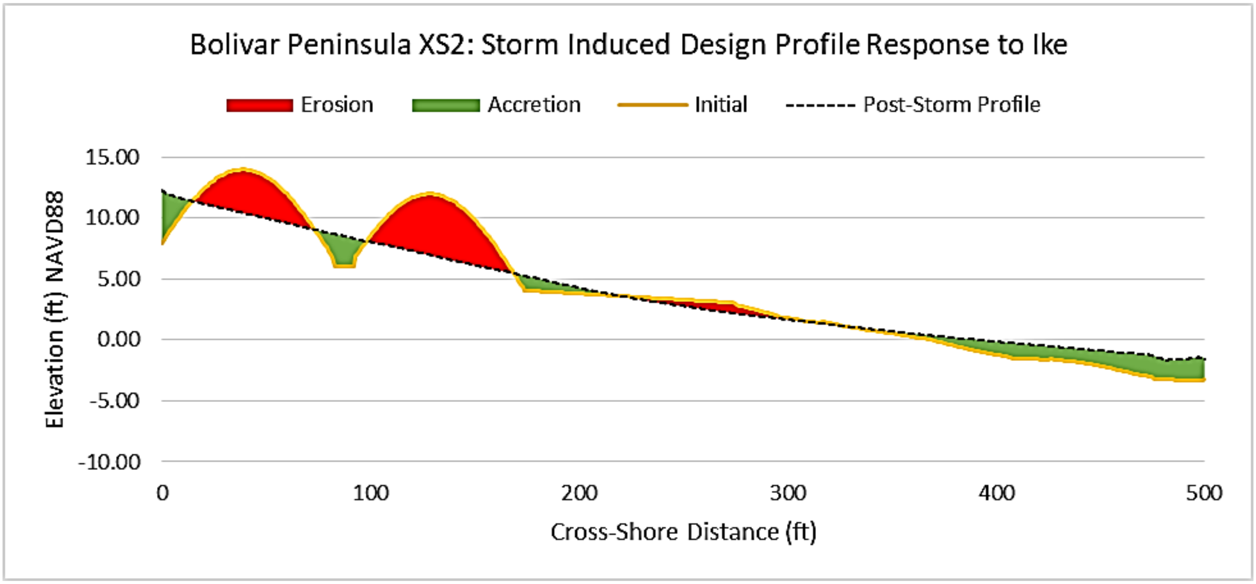
Beach Erosion (CSRM to MHHW= 0.61 ft): -13.57 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -1.06 cubic-feet per square foot (cft/sqft)



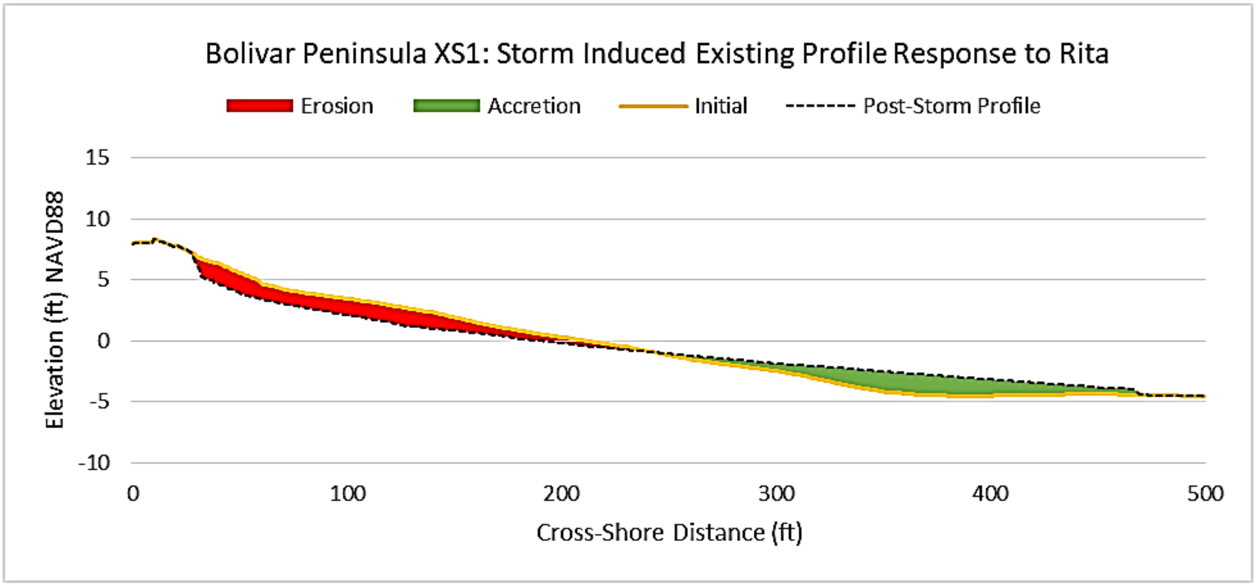
Beach Erosion (CSRM to MHHW= 0.61 ft): -9.26 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -1.24 cubic-feet per square foot (cft/sqft)



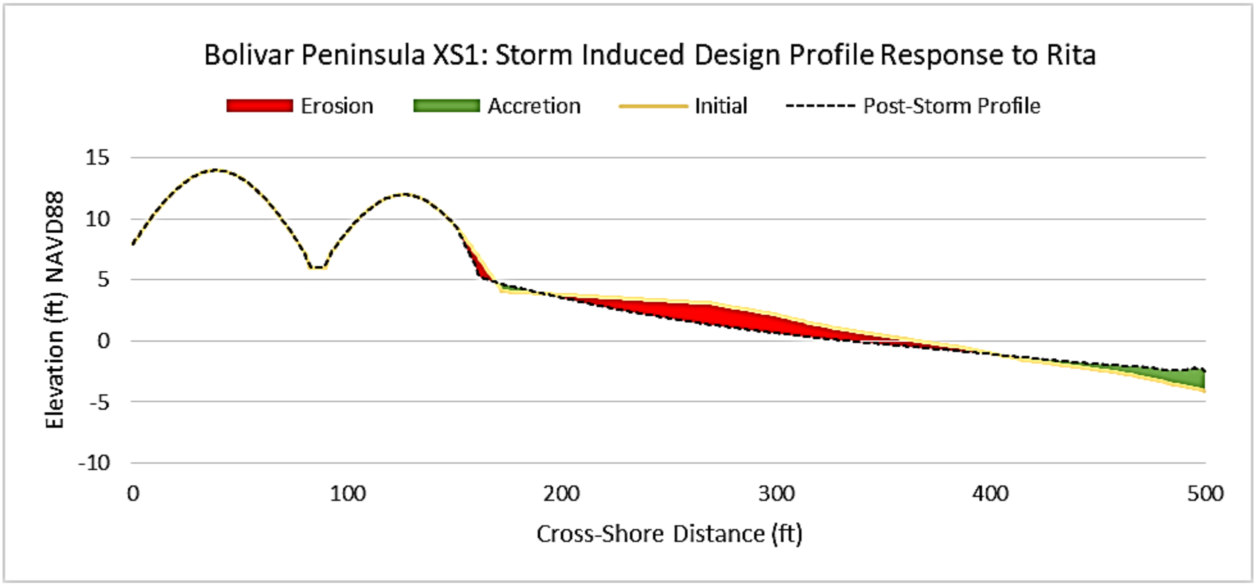
Beach Erosion (CSRM to MHHW= 0.61 ft): -11.45 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.9 cubic-feet per square foot (cft/sqft)



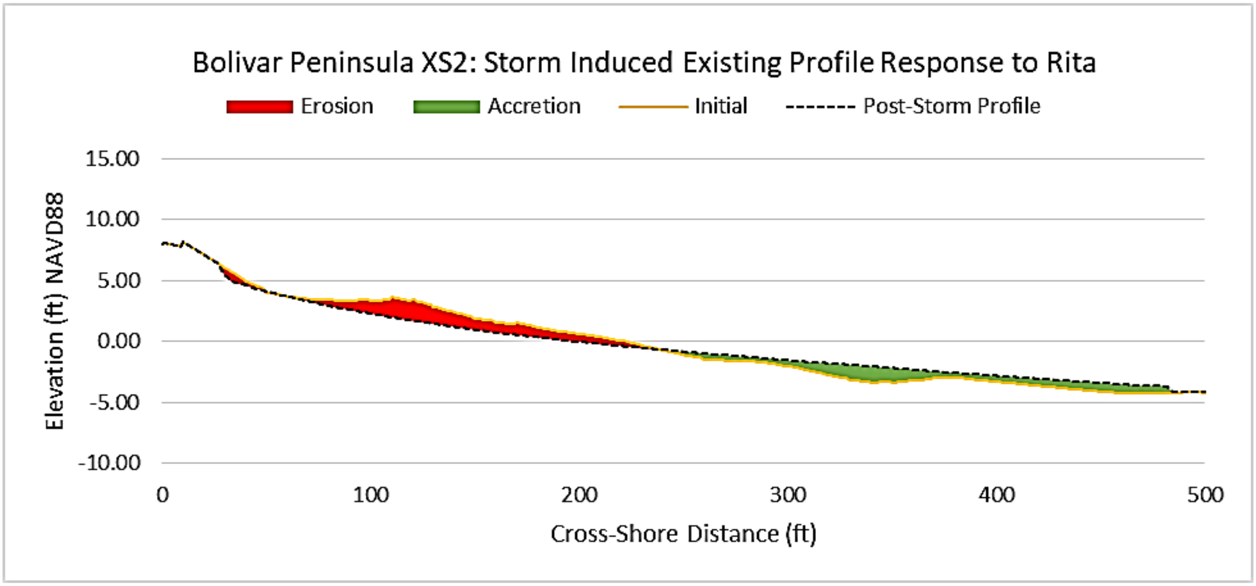
Beach Erosion (CSRM to MHHW= 0.61 ft): -7.31 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -1.04 cubic-feet per square foot (cft/sqft)



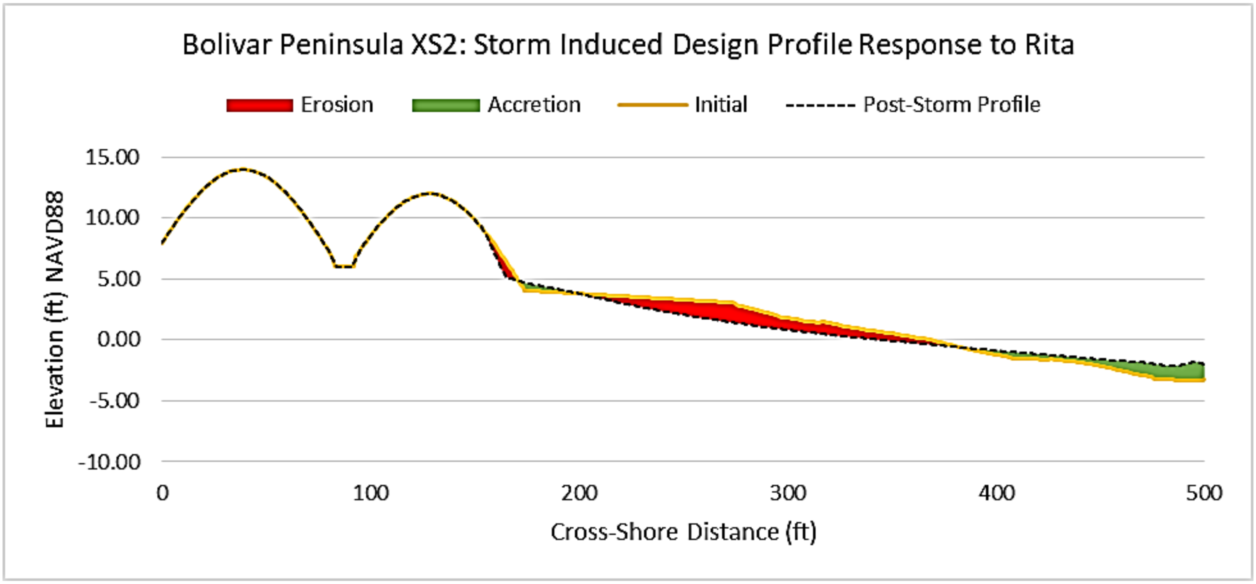
Beach Erosion (CSRM to MHHW= 0.61 ft): -6.71 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.53 cubic-feet per square foot (cft/sqft)



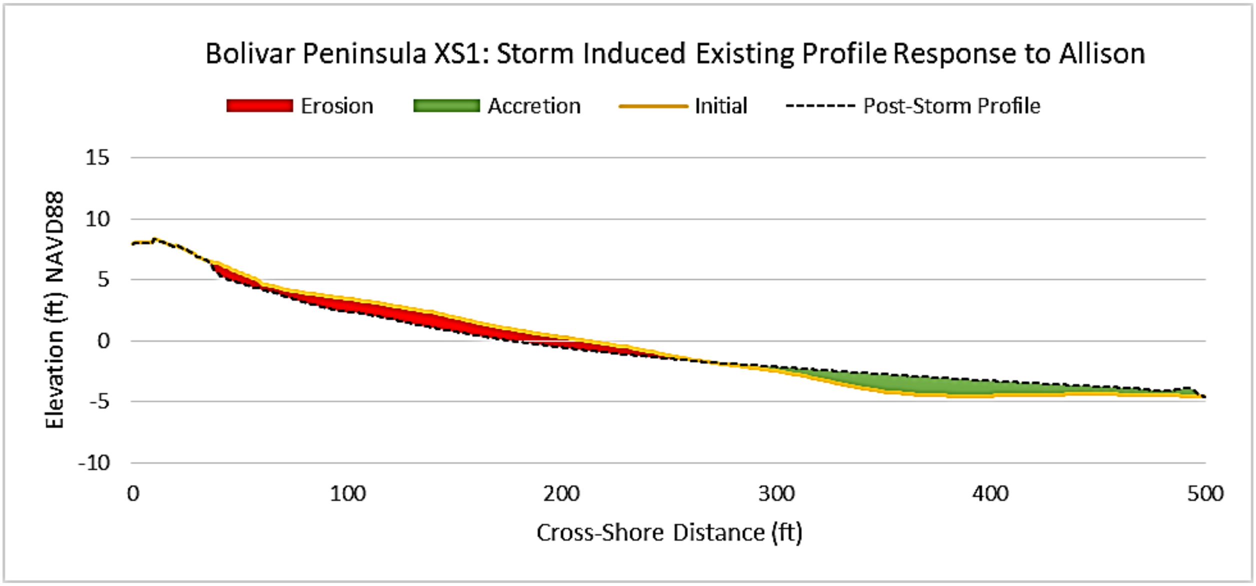
Beach Erosion (CSRM to MHHW= 0.61 ft): -5.24 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.7 cubic-feet per square foot (cft/sqft)



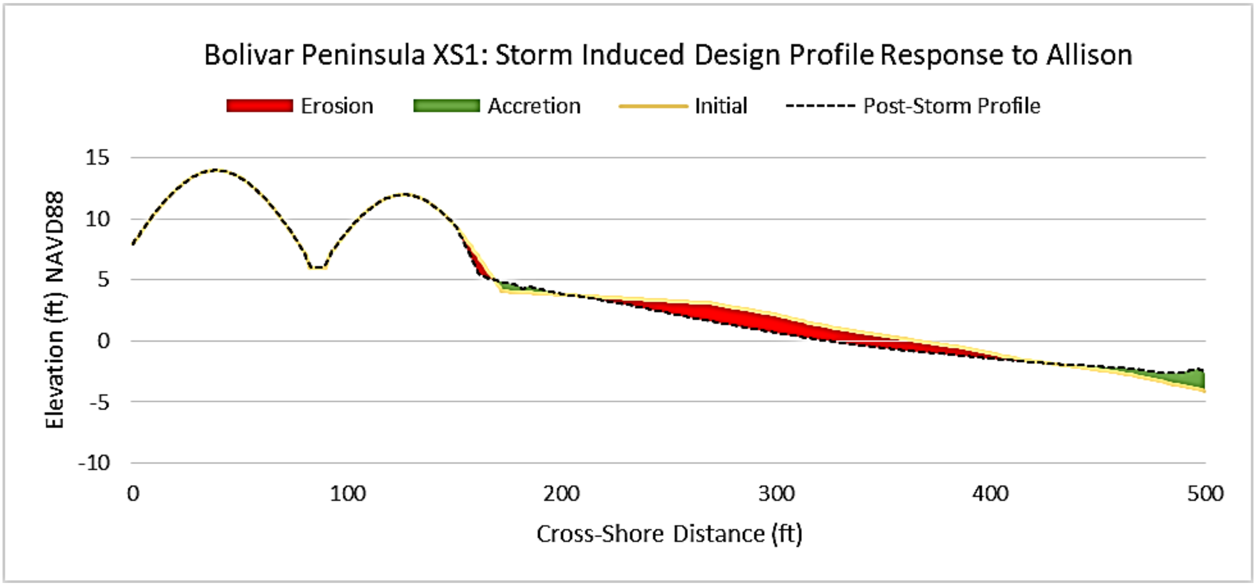
Beach Erosion (CSRM to MHHW= 0.61 ft): -5.27 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.41 cubic-feet per square foot (cft/sqft)



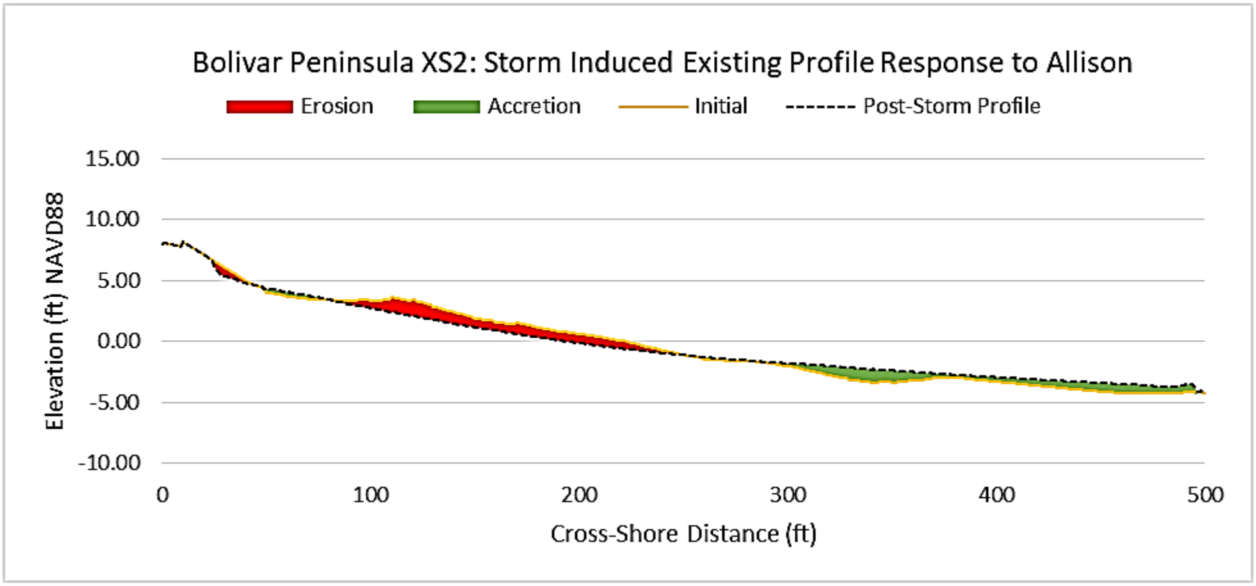
Beach Erosion (CSRM to MHHW= 0.61 ft): -5.46 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.78 cubic-feet per square foot (cft/sqft)



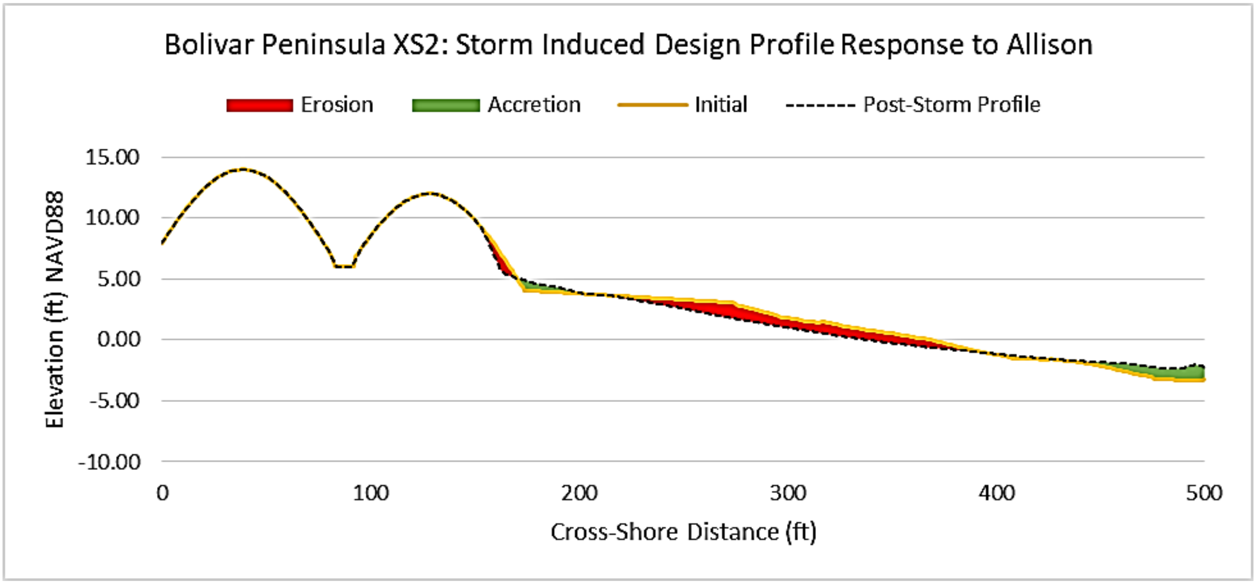
Beach Erosion (CSRM to MHHW= 0.61 ft): -5.34 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.42 cubic-feet per square foot (cft/sqft)



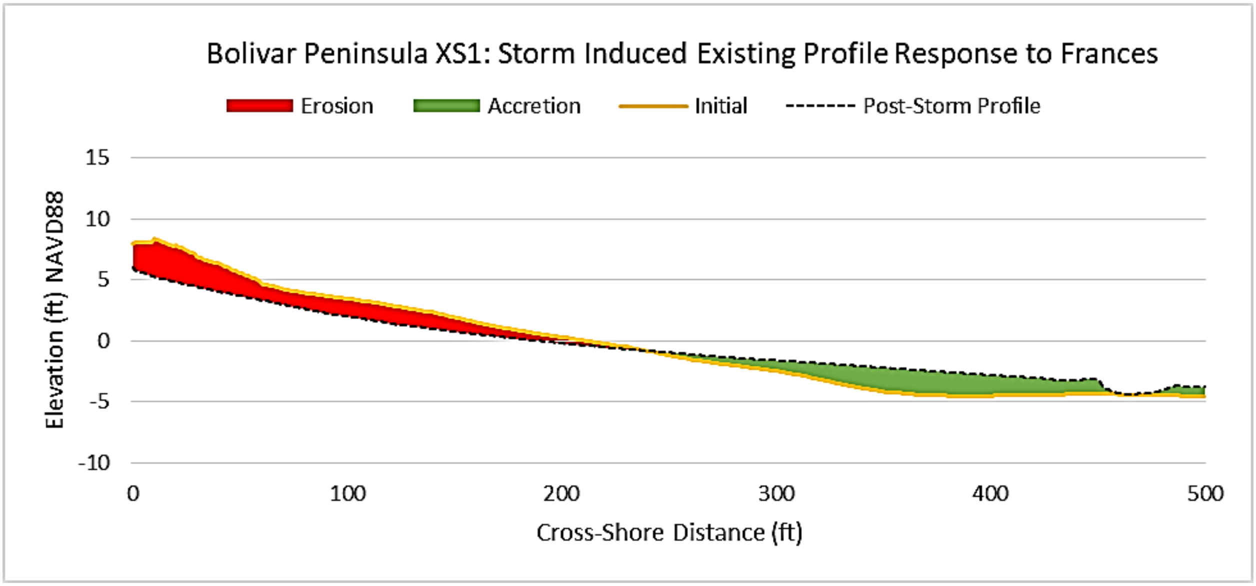
Beach Erosion (CSRM to MHHW= 0.61 ft): -3.7 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.49 cubic-feet per square foot (cft/sqft)



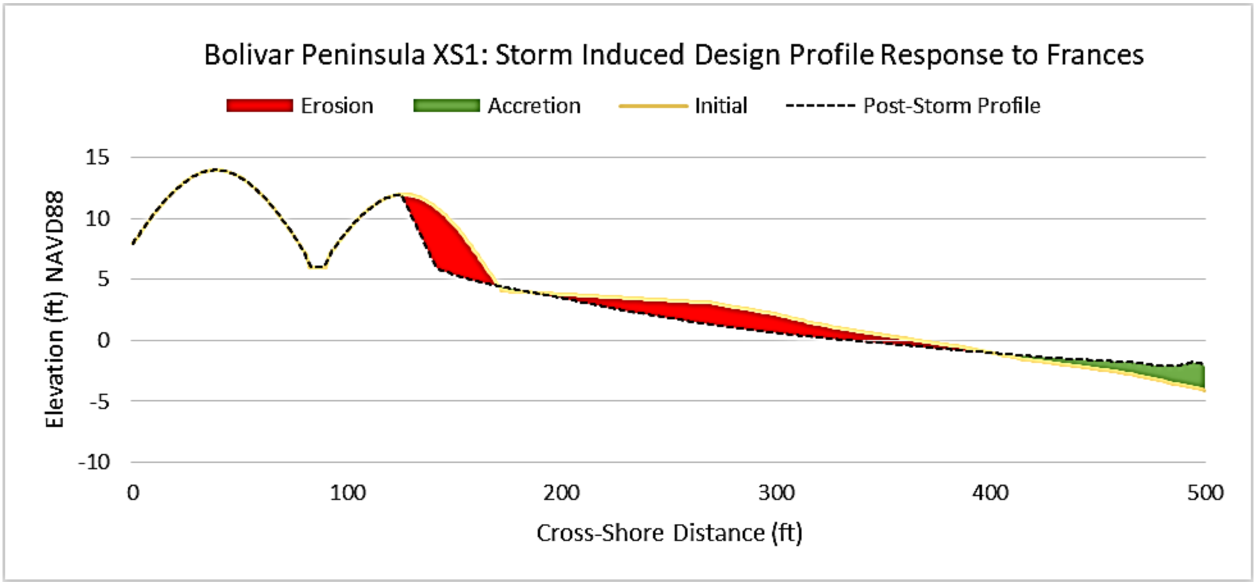
Beach Erosion (CSRM to MHHW= 0.61 ft): -3.7 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.29 cubic-feet per square foot (cft/sqft)



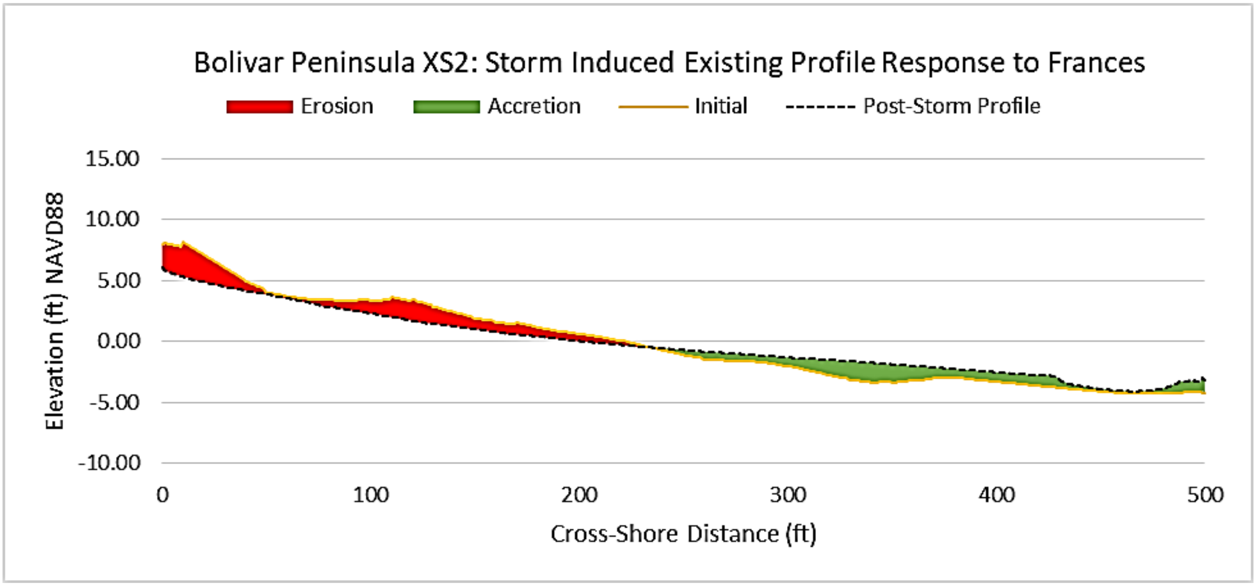
Beach Erosion (CSRM to MHHW= 0.61 ft): -11.27 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -1.6 cubic-feet per square foot (cft/sqft)



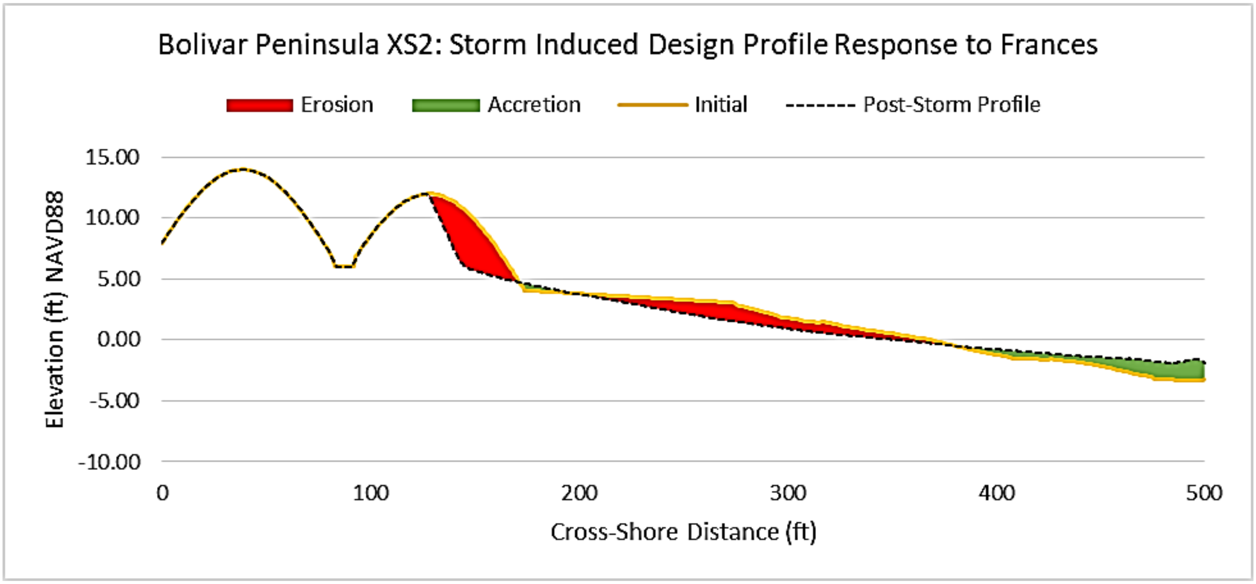
Beach Erosion (CSRM to MHHW= 0.61 ft): -11.24 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.88 cubic-feet per square foot (cft/sqft)



Beach Erosion (CSRM to MHHW= 0.61 ft): -8.19 cubic-yards per linear foot

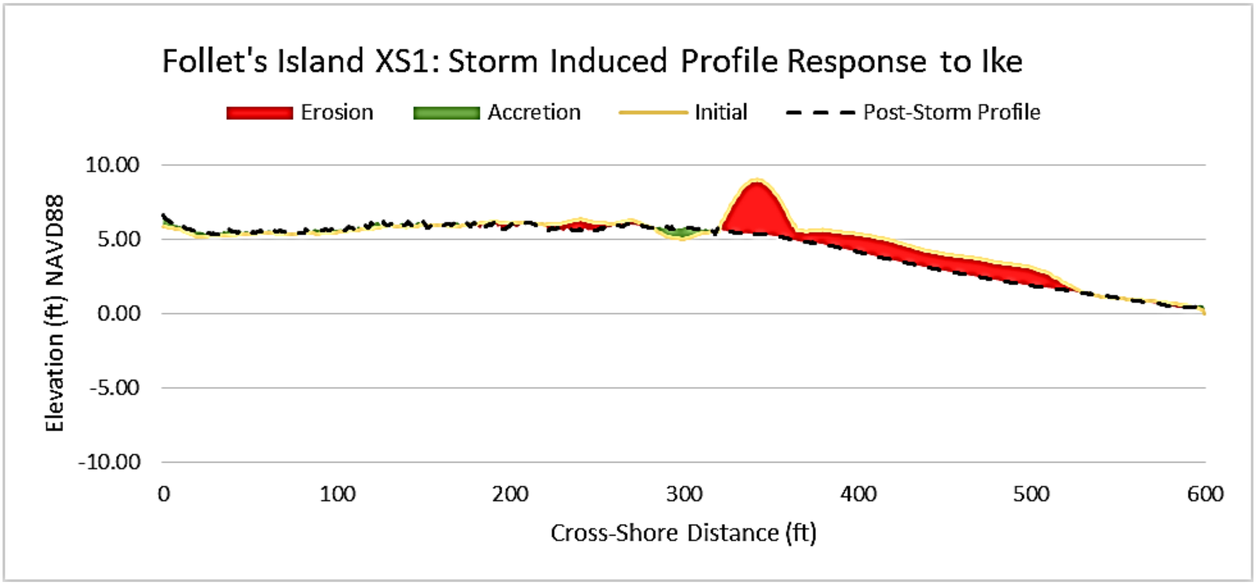
Normalized Erosion (CSRM to MHHW): -1.1 cubic-feet per square foot (cft/sqft)



Beach Erosion (CSRM to MHHW= 0.61 ft): -8.76 cubic-yards per linear foot

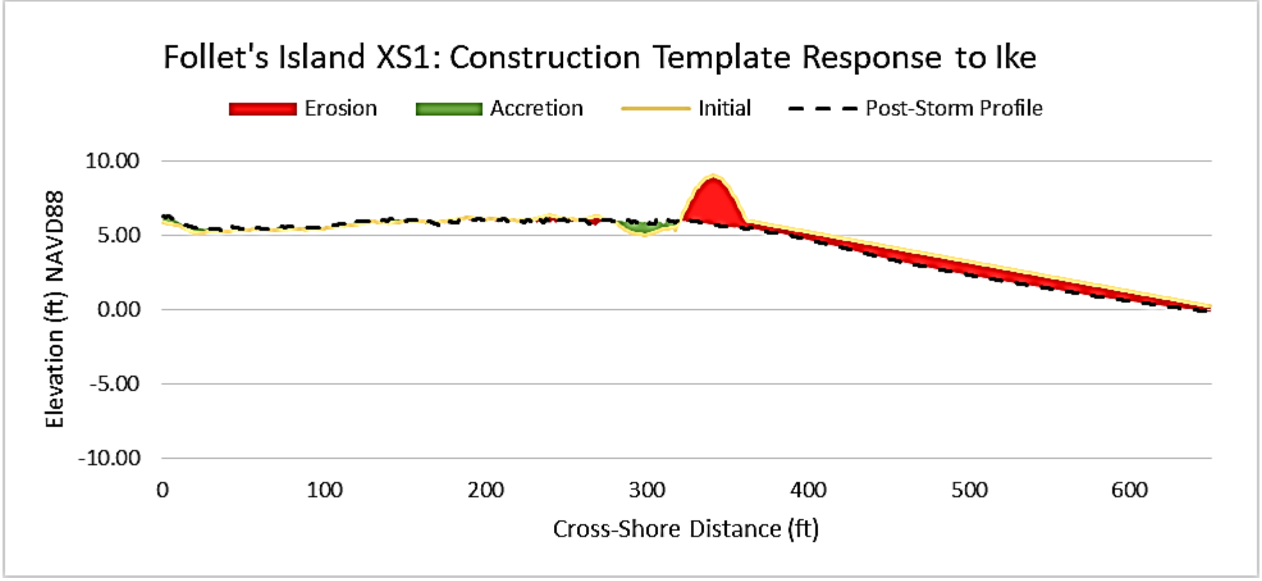
Normalized Erosion (CSRM to MHHW): -0.69 cubic-feet per square foot (cft/sqft)

APPENDIX C: ER STORM INDUCED RESPONSE DESIGN AND CONSTRUCTION PROFILES



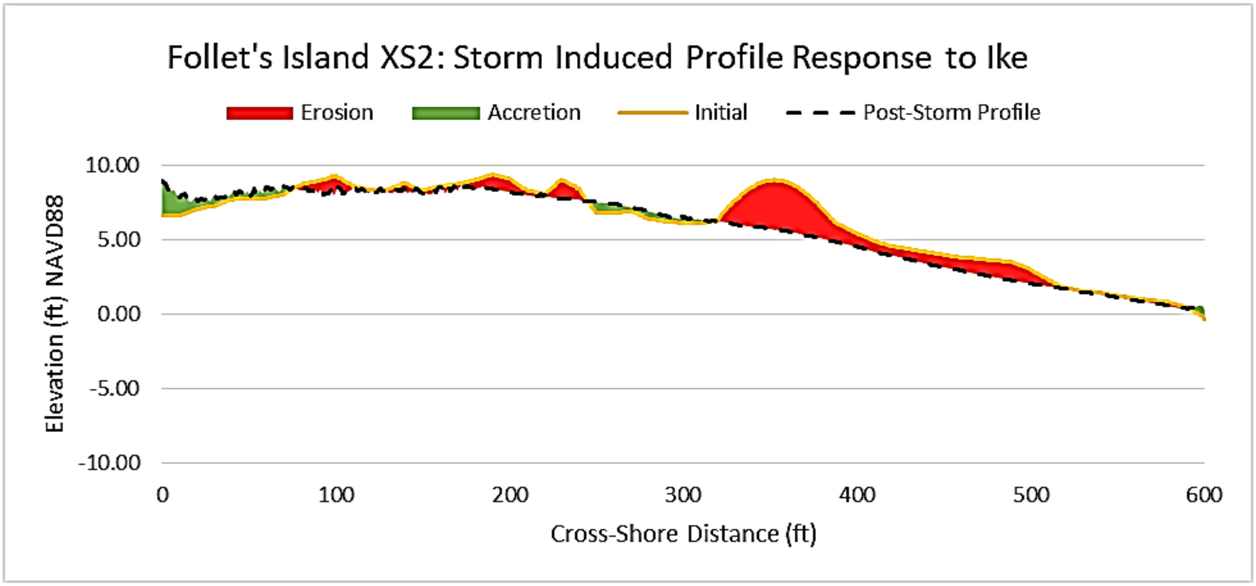
Beach Erosion (CSRM to MHHW= 0.85 ft): -9.0 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.46 cubic-feet per square foot (cft/sqft)



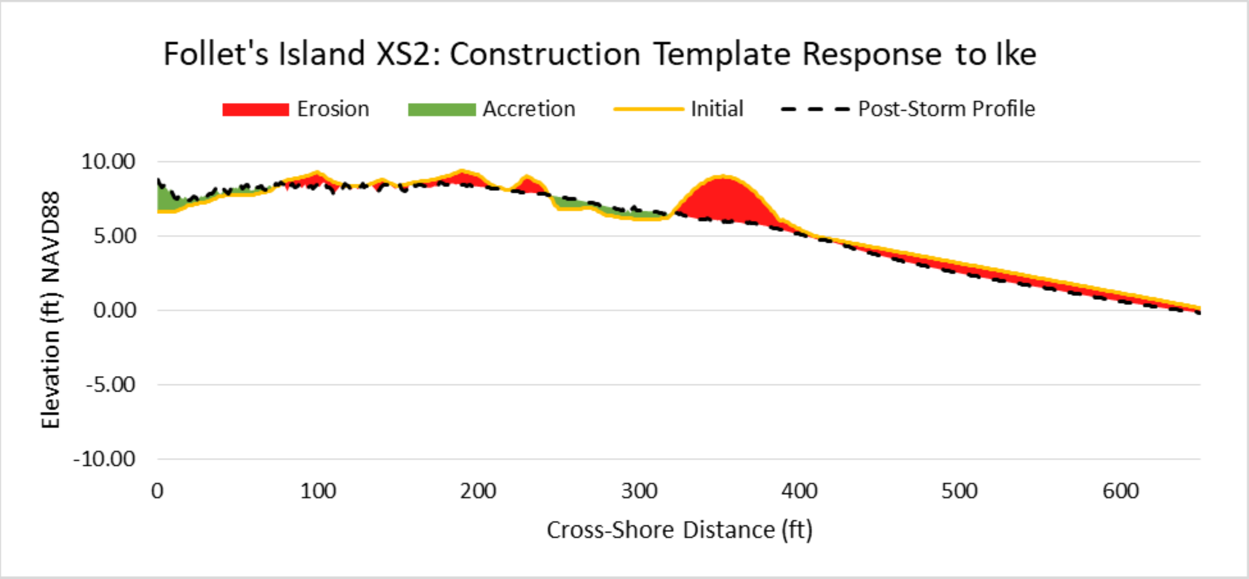
Beach Erosion (CSRM to MHHW= 0.85 ft): -9.06 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.39 cubic-feet per square foot (cft/sqft)



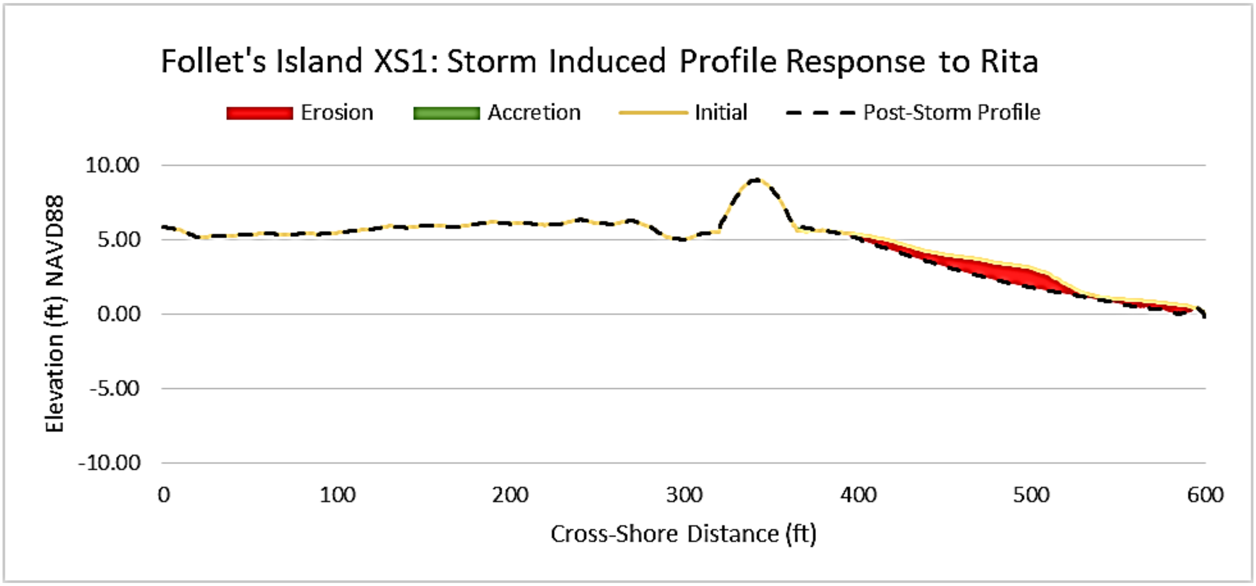
Beach Erosion (CSRM to MHHW= 0.85 ft): -10.43 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.49 cubic-feet per square foot (cft/sqft)



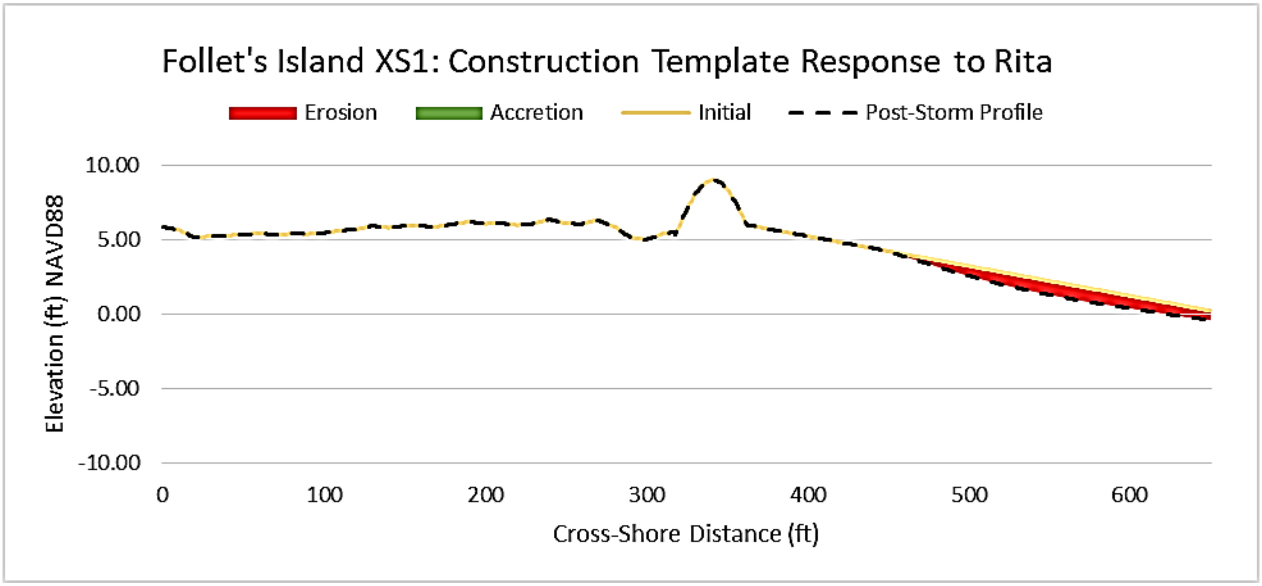
Beach Erosion (CSRM to MHHW= 0.85 ft): -9.04 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.4 cubic-feet per square foot (cft/sqft)



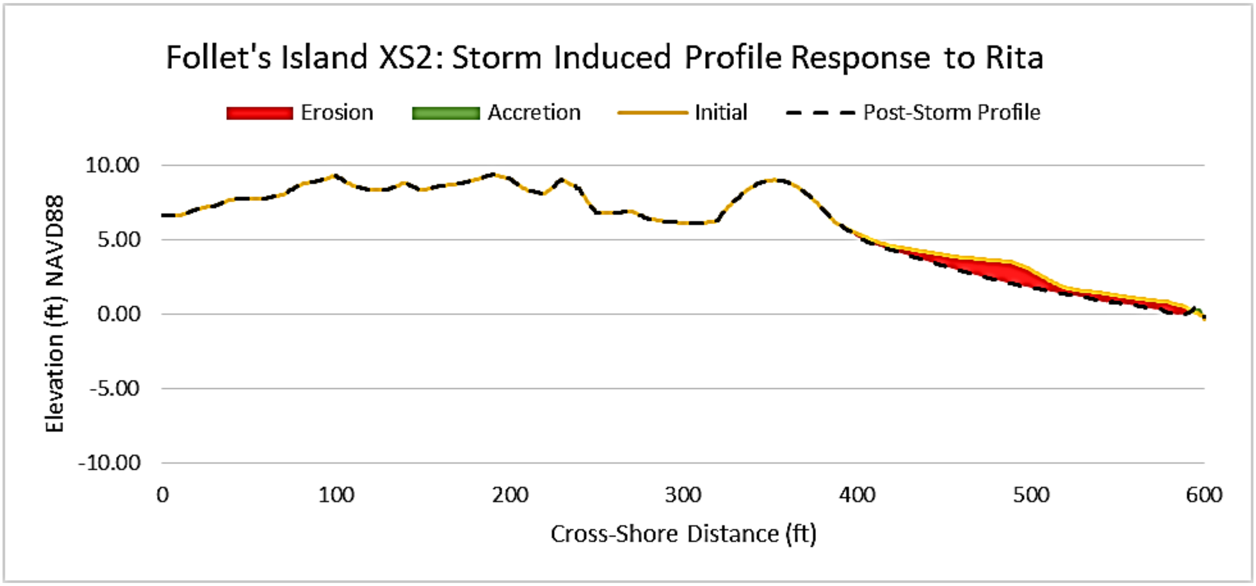
Beach Erosion (CSRM to MHHW= 0.85 ft): -4.61 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.22 cubic-feet per square foot (cft/sqft)



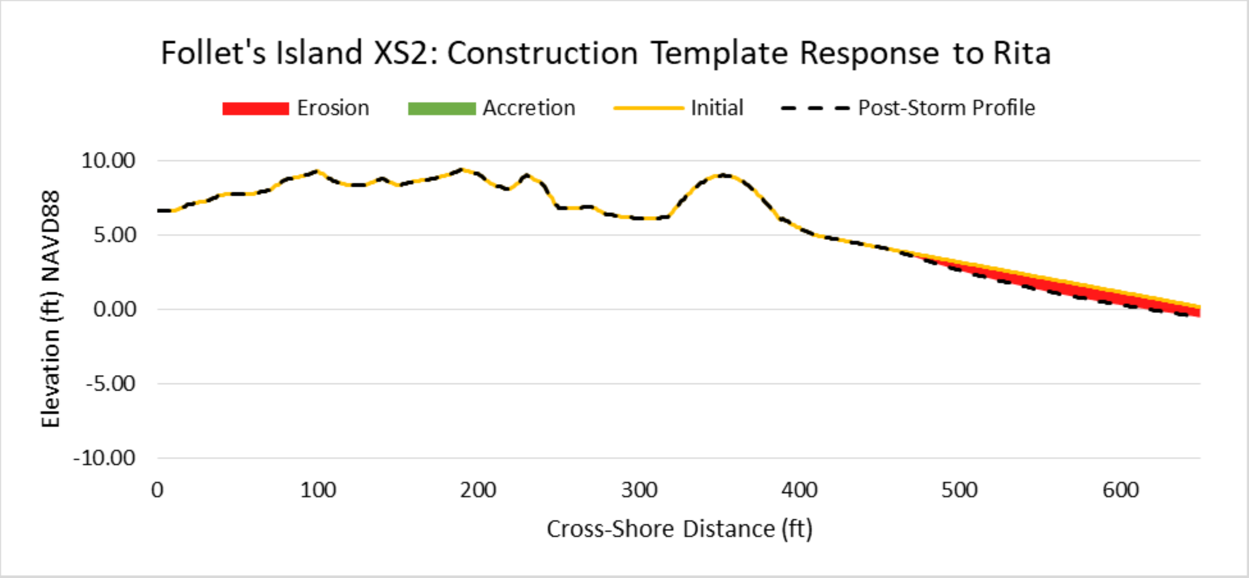
Beach Erosion (CSRM to MHHW= 0.85 ft): -4.45 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.19 cubic-feet per square foot (cft/sqft)



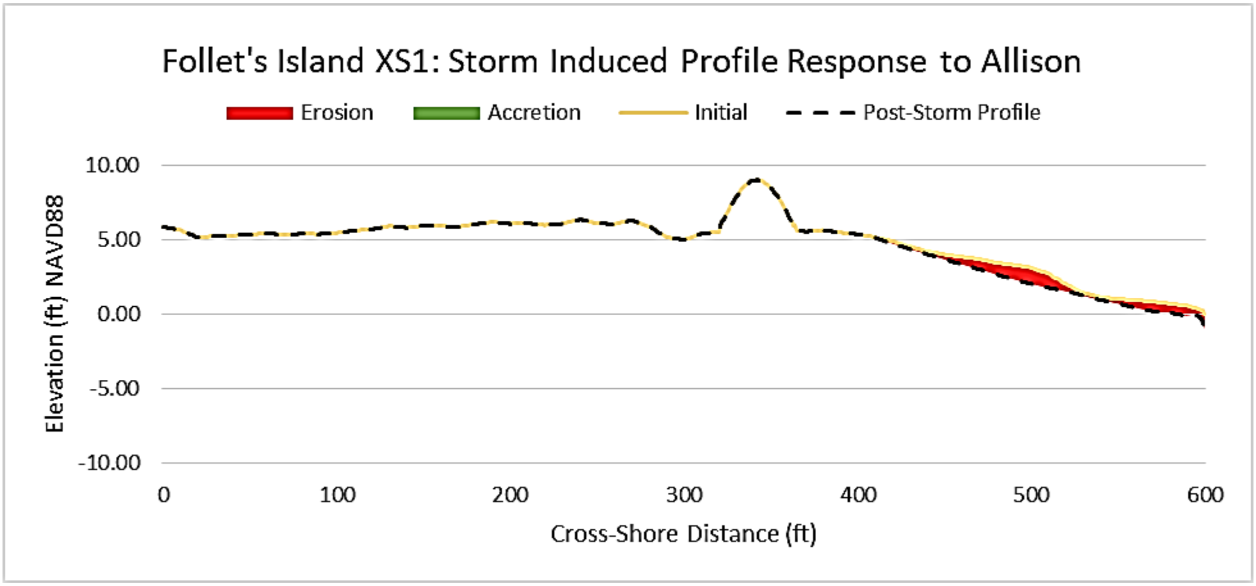
Beach Erosion (CSRM to MHHW= 0.85 ft): -4.6 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.21 cubic-feet per square foot (cft/sqft)



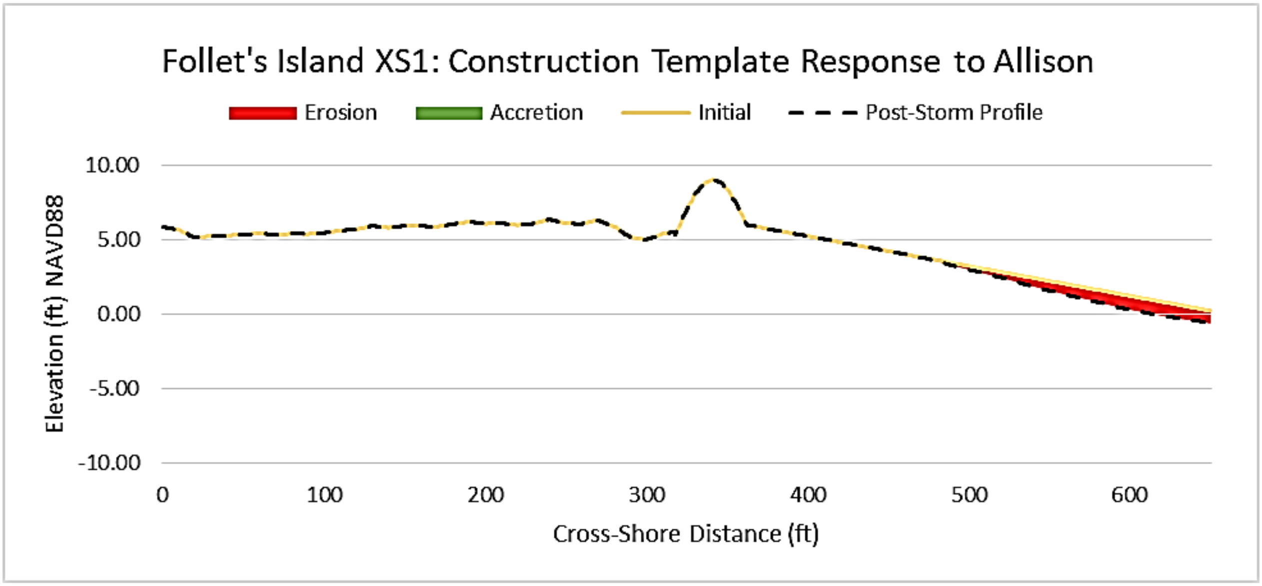
Beach Erosion (CSRM to MHHW= 0.85 ft): -3.94 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.17 cubic-feet per square foot (cft/sqft)



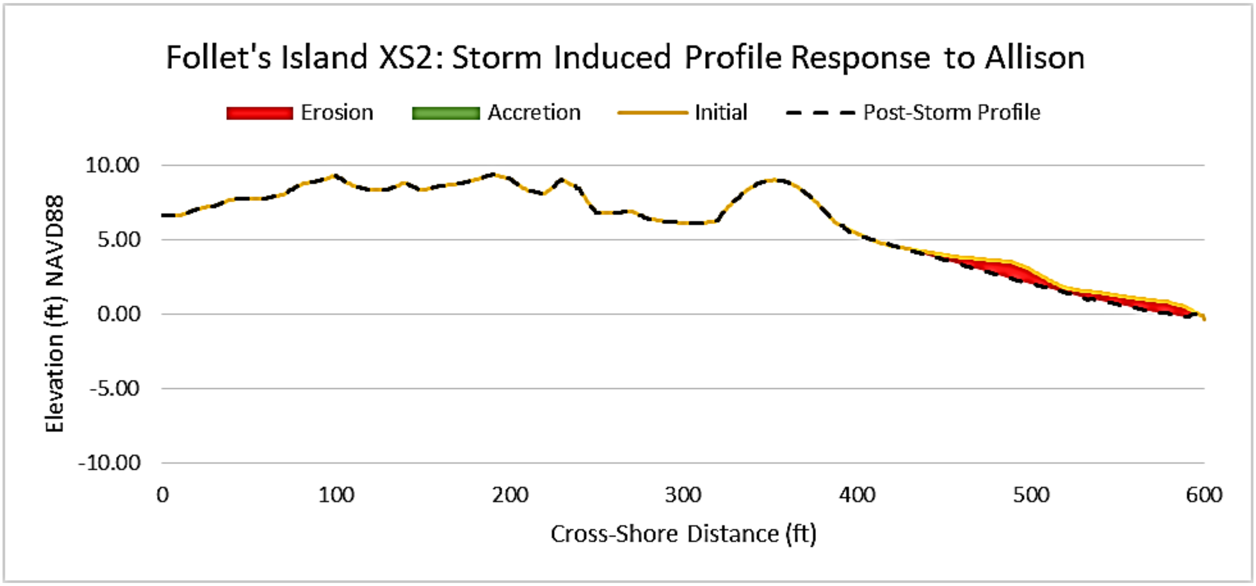
Beach Erosion (CSRM to MHHW= 0.85 ft): -2.91 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.14 cubic-feet per square foot (cft/sqft)



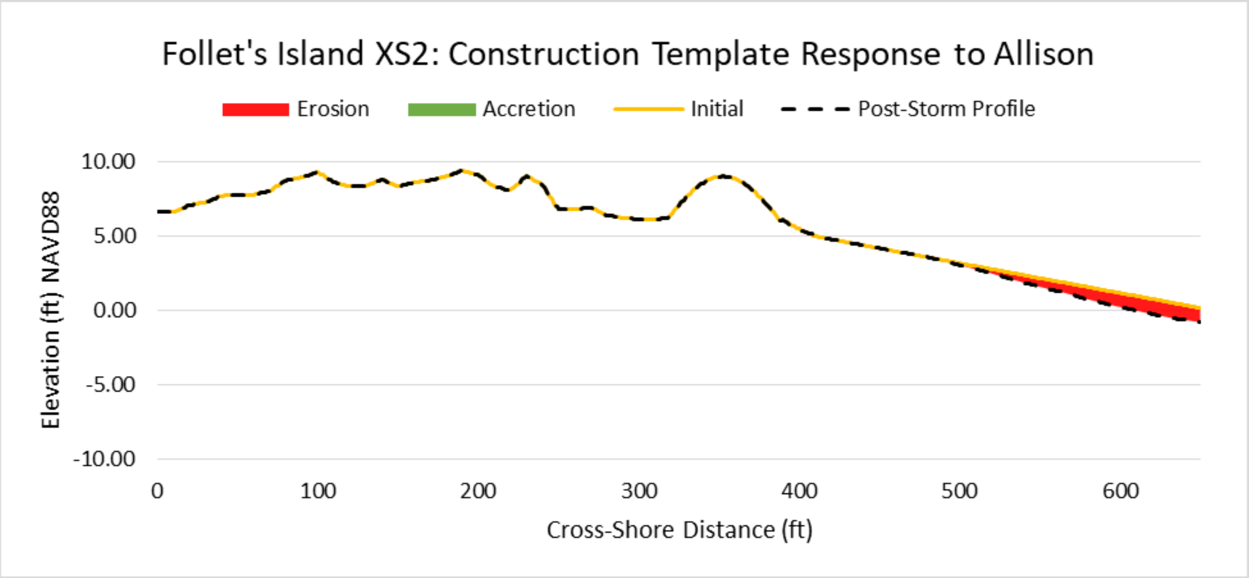
Beach Erosion (CSRM to MHHW= 0.85 ft): -3.09 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.13 cubic-feet per square foot (cft/sqft)



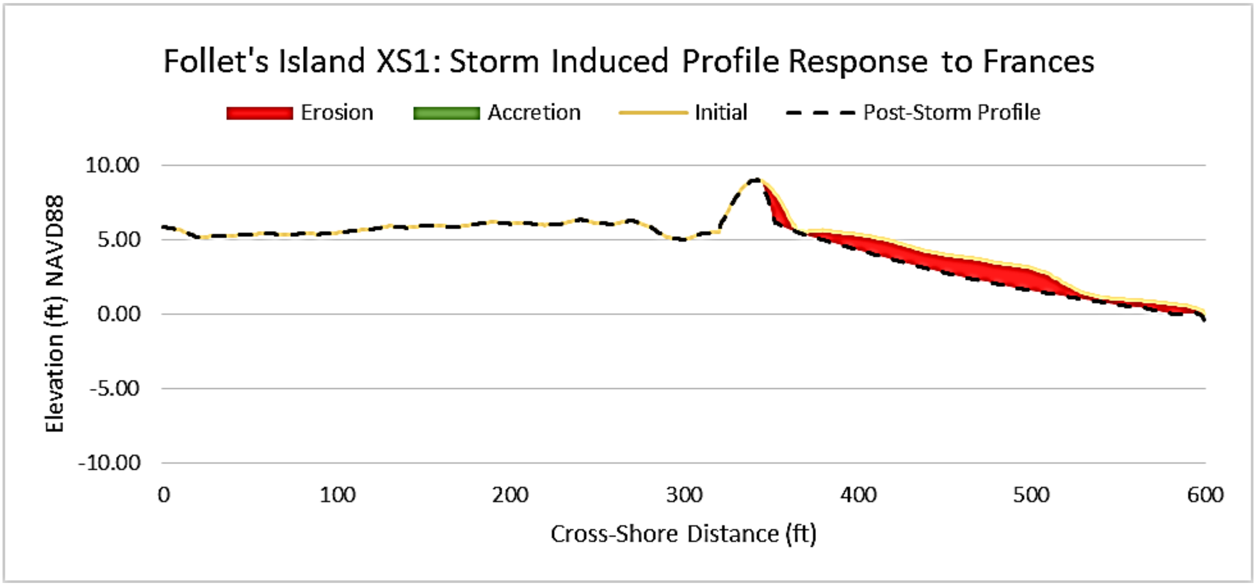
Beach Erosion (CSRM to MHHW= 0.85 ft): -3.3 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.15 cubic-feet per square foot (cft/sqft)



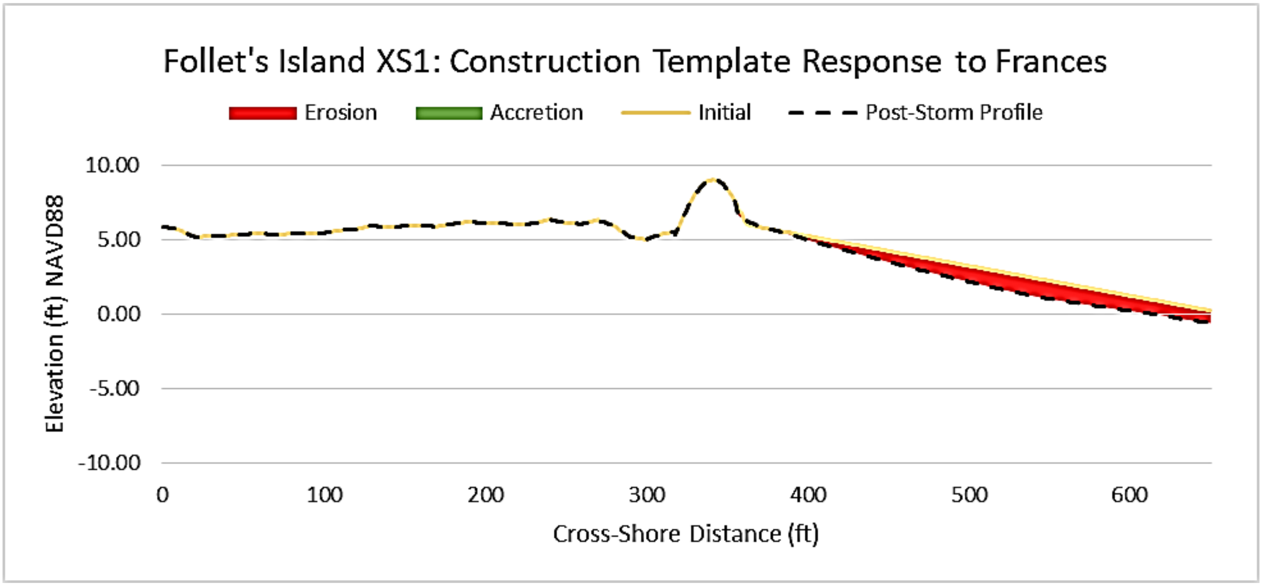
Beach Erosion (CSRM to MHHW= 0.85 ft): -2.69 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.12 cubic-feet per square foot (cft/sqft)



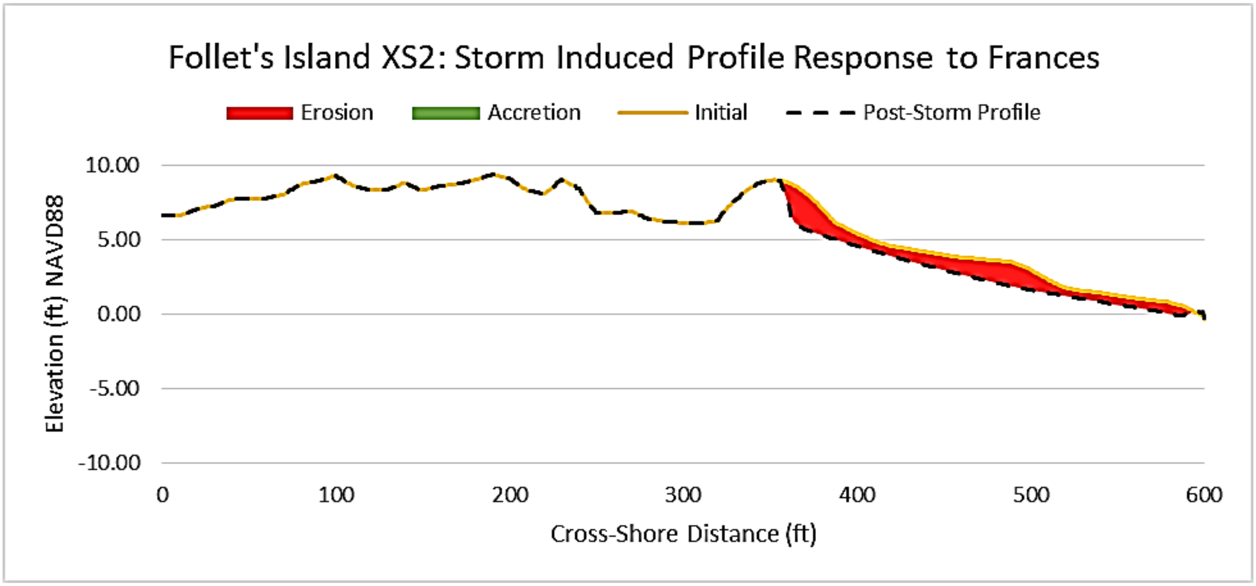
Beach Erosion (CSRM to MHHW= 0.85 ft): -8.17 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.39 cubic-feet per square foot (cft/sqft)



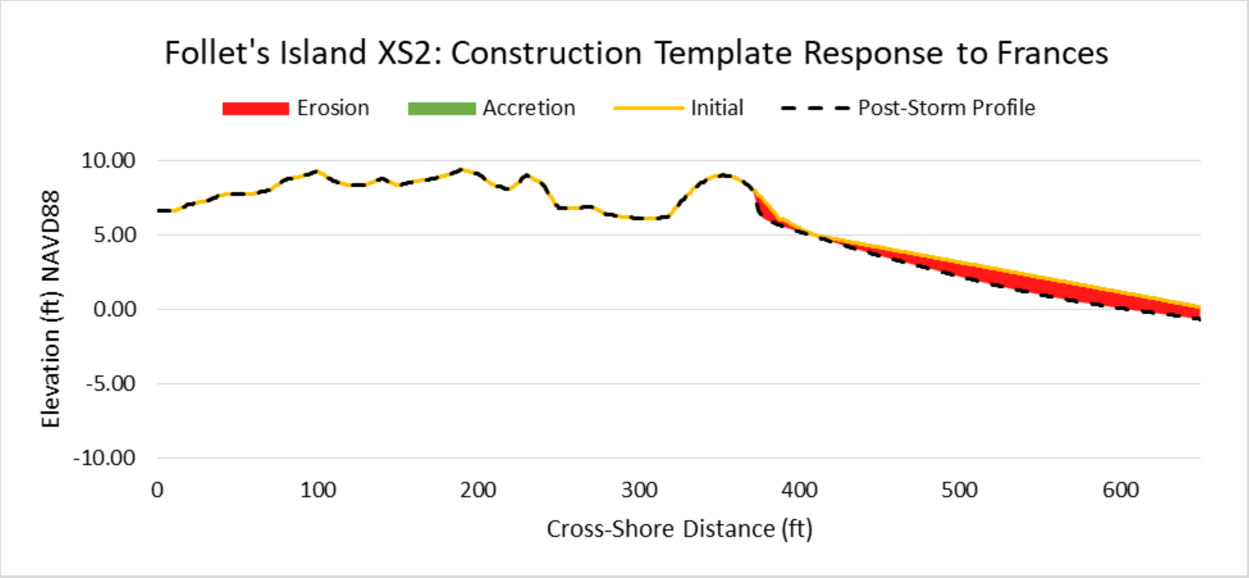
Beach Erosion (CSRM to MHHW= 0.85 ft): -7.65 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.33 cubic-feet per square foot (cft/sqft)



Beach Erosion (CSRM to MHHW= 0.85 ft): -8.62 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.4 cubic-feet per square foot (cft/sqft)



Beach Erosion (CSRM to MHHW= 0.85 ft): -7.43 cubic-yards per linear foot

Normalized Erosion (CSRM to MHHW): -0.33 cubic-feet per square foot (cft/sqft)

COASTAL TEXAS STUDY

Beach Drainage

Jason Thies, Paul Hamilton, & Himangshu Das SWG

10/1/2020

I. BACKGROUND

The purpose of this report is to review any interior drainage features that may impact, or be impacted by, Coastal Storm Risk Management (CSRM) recommendations if implemented, and to offer solutions to mitigate any potentially adverse impacts. The continuity of the coastal protection system is paramount to the efficacy and longevity of the design against storm surge. This is particularly true of natural components such as dunes that tend to fail at discontinuities, or breaches, which are weak points in an otherwise continuous dune system. Interior drainage that flows toward the beach tends to create breaches in a dune system over time if left to its own devices. Similarly, interior beach drainage areas will suffer adverse impacts if flow is restricted by CSRM features.

The study site is characterized by a sandy barrier island landscape with relatively uniform topography that generally slopes gently toward the bayside. The terrain accommodates natural drainage of runoff to the bayside throughout a majority of the region, however there are drainage areas that convey runoff to the beach. Stormwater runoff that presently outfalls on the beach, and intersects a CSRM feature, is the focal point of this study.

Recommendations within this report are limited by drainage and dune/beach protection regulations and by the scope of this study. The ideal alternative is to route all interior stormwater runoff toward the bayside, however this may require major drainage infrastructure changes due to topographic challenges, and will require a higher level of analysis to compare the cost and benefits. It is recommended that this alternative is explored in further detail during the Preliminary Engineering Design phase or in a separate study.

The objective at this level of the study is to offer recommendations to maintain the existing level of service (LOS) for beach drainage areas and simultaneously mitigate potential impacts that beach drainage may pose to a contiguous dune/levee system. Recommendations herein seek to route existing beach drainage through proposed CSRM features via culvert that is sized to maintain or improve the existing LOS, while preserving compliance with local drainage regulations.

II. LITERATURE REVIEW & DATA ACQUISITION

The focus of the literature review is to acquire information on any beach drainage areas that overlap with CSRM features. A summary of the most frequently referenced documents is included:

1. CITY OF GALVESTON MASTER DRAINAGE PLAN

The City of Galveston Master Drainage Plan (MDP) was prepared for the City of Galveston (excludes the City of Jamaica Beach) in 2003 by Dannenbaum Engineering Corporation. The MDP generally focuses on the storm sewer drainage system that exists throughout the more densely populated, eastern portion of the island (landward of the seawall). It also offers a cursory review of the west side of Galveston Island that concentrates on issues inherent in the open-channel drainage system, such as slow conveyance, sedimentation, ponding, etc. There is minimal attention to auxiliary issues created by the drainage, such as beach erosion.

The MDP does provide some insight into the location of several beach drainage areas, however the information generally lacks detail. It is made clear that beach drainage areas are local, somewhat isolated developments located exclusively south of FM 3005. These developments predate, and are exempt from, 1984 City of Galveston drainage regulations that prohibit discharge of stormwater onto the beach. The MDP indicates that portions of Indian Beach, Bermuda Beach, and Sunny Beach contribute to beach drainage on Galveston Island (Dannenbaum, 2003).

2. JAMAICA BEACH EROSION RESPONSE PLAN

The Jamaica Beach Erosion Response Plan was prepared by Peter A. Ravella Consulting, LLC in July, 2012 for the Texas General Land Office (GLO). The response plan provides a qualitative review of beach drainage inside city limits, which includes nearly all of the land south of FM 3005. The report also indicates the City's recognition of the beach drainage issue, and their intent to "…investigate, design and, if funds are available, construct a drainage system to redirect all rain and stormwater drainage to West Bay." (Ravella, 2012). Since then, the City has made some drainage improvements to reduce ponding in trouble areas, however no efforts have been made to alleviate the beach drainage related erosion issue. A City Council public hearing took place on October 1st, 2018 with a General Land Office (GLO) representative present to discuss the Jamaica Beach Dune Restoration Project. Within the meeting minutes, there is no mention of the drainage system described in the 2012 plan. Instead the discussion revolves around conveyance of drainage toward the beach via culvert, similar to recommendations within this report (City of Jamaica Beach, 2018).

3. GALVESTON COUNTY MASTER DRAINAGE PLAN

The Galveston County MDP was prepared by Klotz Associates in 2012 for Galveston County. It excludes all of Galveston Island, but offers an extensive review of Bolivar Peninsula drainage that will be referenced throughout this report. The MDP provides a comprehensive review and analysis of existing conditions, including an assessment of the level of service (LOS) for drainage structures. It also proposes recommendations for improvements based on a systematic review of the existing gravity drainage system in each drainage area. Each component of the existing drainage systems is reviewed to assess potential improvements, including review of drainage structures and potential land for storage areas. Recommendations are provided to maximize the LOS for each drainage area, assuming a gravity system remains in place, i.e.- no pumps. The maximum attainable LOS is generally limited by the flat topography, characteristic of the area, which limits available storage as well as the size and slope of recommended drainage structures. A new LOS is prescribed to each drainage area based on the implementation of proposed improvements. The maximum LOS is 5-years for drainage basins within the project area.

4. REGULATORY REVIEW

A review of legislation relevant to beach drainage was performed to look into any potential project implications. The following provides a summary of findings, however it should be noted that findings may not be exhaustive, it is possible that further regulations exist unbeknownst to the author.

1. Federal, State, County, and Municipal regulatory agencies all have regulations in place, intended to prevent erosion, protect dunes/beaches or waters, that are relevant to new construction of beach drainage.
    a. Federal: Clean Water Act Section 401
    b. State/County: Galveston County Dune Protection and Beach Access Plan (2006)
    c. Municipal:
        i. City of Galveston: Ordinance No. 84-40 (1984), integrated into City Building Code Chapter 10, Article I, Section 10-4
        ii. City of Jamaica Beach: Ordinance 93-4 & 93-5 (1993)

2. According to the review, the City of Galveston is the only relevant authority with regulatory language that outright prohibits drainage to the beach. Line number 11 of Ordinance No. 84-40 states that "… no drainage will be permitted into the Gulf of Mexico or onto the adjacent beach."

3. Language found within documents from the State/County and City of Jamaica Beach are oriented towards protection of the beach and dunes. The legislation is intended to limit beach construction that may have adverse impacts, which includes changes to the existing flow of beach drainage. However, there are provisions included that outline allowable mitigation measures to offset adverse impacts.

Based on the review, the spirit of regulations align well with project goals. The project seeks to improve the natural dune system, and the goal of drainage recommendations seeks to minimize changes to the existing system while preserving the dunes. Most regulations similarly seek to maintain or improve natural dunes. Ordinance No. 84-40, adopted by the City of Galveston in 1984, plainly prohibits beach drainage. This will effectively limit drainage recommendations to developments that predated the 1984 regulation, which are exempt according to the City of Galveston Master Drainage Plan (Dannenbaum, 2003). These older developments are highlighted in the following section of this report, wherein evidence of recent updates to drainage structures is indicative of provisions that allow for improvements to the existing system.

III. EXISTING CONDITIONS & FIELD OBSERVATIONS

1. GALVESTON ISLAND

The Galveston Island portion of this study focuses on the region west of the seawall, including Jamaica Beach, where CSRM features overlap with interior drainage areas. Interior drainage on the west end of Galveston is comprised of open channel drainage that primarily conveys runoff to the bayside of the island in compliance with City of Galveston drainage regulations found in Chapter 10, Article I, Section 10-4 of the City Codes, which references Ordinance No. 84-40, adopted in 1984. The City of Jamaica Beach (a separate municipality on Galveston Island) enacted Ordinances 93-4 & 93-5 in 1993 to provide general protections to dunes, including regulations regarding the disruption of "natural" drainage patterns. Other relevant regulations discovered include, but are not limited to the Galveston County Dune Protection and Beach Access Plan, established in September 2006.

There is a 17- year time lapse since the City of Galveston MDP was prepared, which, along with reasons discussed in the *Literature Review & Data Acquisition* section, warranted a field review of site conditions. A field review conducted on 10/03/2019, which focused on regions where beach drainage was purported to exist, however an overview of the remainder of the beach is performed as well. Two follow-up field reviews were conducted on 10/25/2019 and 01/03/2020 to observe drainage conditions after a precipitation event and to gather additional information on existing drainage structures. The regions that were ultimately confirmed positive for beach drainage include portions of Sunny Beach, Bermuda Beach, Jamaica Beach, Gulf Palms, Karankawa, Acapulco and Indian Beach. For the purposes of this report, and due to a conveniently located geographic divide, Gulf Palms is lumped into Jamaica Beach, while Karankawa and Acapulco are considered a continuation of Indian Beach. Further details are documented in the following:

1.1 SUNNY BEACH

Just west of the seawall a perimeter is formed by 7-Mile Rd, 8 Mile Rd, FM 3005 and the beach that envelopes the two Sunny Beach basins. The subbasins are defined by 7-1/2 Mile Rd., each with a retention pond that collects stormwater runoff. The 2003 City of Galveston MDP reports that discharge from these ponds has formed breaches in the existing dune system (Dannenbaum, 2003).

The claim was substantiated during the field investigation, however recent improvements provide bayside conveyance via culverts under FM 3005. The bayside drainage was actively conveying stormwater, while beachside discharge was inactive during the site visit. The ponds still actively convey discharge to the beach, which has created large breaches in the dunes.

1.2 BERMUDA BEACH

The City of Galveston MDP reports an overland sheet flow problem in the subdivision located at Pabst Rd. and Bermuda Beach Road, as well as ponding issues on John Reynolds Circle, however the extent of beach discharge is not made clear in the report (Dannenbaum, 2003). A field review on 10/25/2019 substantiated reported sheet flow and ponding issues, though recent storm drain installation appears to have resolved some local ponding issues on John Reynolds Circle.

Drainage structures collect much of the stormwater north of West Bermuda Beach Road, where it is conveyed to the bayside, however runoff from the row of homes directly adjacent to the street tends to flow toward the beach. The beach drainage area east of Pabst Road, extends further north, encompassing most of the region between FM 3005 and East Bermuda Beach Road.

On both sides of Pabst Road runoff flows overland to Bermuda Beach Road, where it collects on the vegetated south side of the dirt road. The stormwater eventually outfalls onto Bermuda Beach through multiple channels formed by concentrated flow. Several channels were observed at the end of Pabst Rd, and along Bermuda Beach Rd where flow concentrates at low points on the south side of the road and forms outfalls through the small dune system.

1.3 JAMAICA BEACH

Three distinct, adjacent beach drainage areas exist south of FM 3005, in Jamaica Beach and surrounding area. The subbasins are referenced according to the main street name in each of the respective subdivisions, which include Buccaneer Drive, Beachcomber Road, and 16-Mile Road.

Buccaneer Drive serves as the entry into the Jamaica Beach subdivision south of FM 3005. The entire subdivision south of FM 3005 drains stormwater to the beach through a series of driveway culverts along a drainage ditch that leads to a single outfall channel at the end of Buccaneer Drive. The outfall forces runoff to cut through the dune system as it exits toward the Gulf of Mexico. The Jamaica Beach Erosion Response Plan (JBERP) reports that "…the shallow drainage gradient to the beach causes rainwater to collect in the ditches for days after a heavy rain." (Ravella, 2012). Beach drainage issues highlighted in the 2012 JBERP were substantiated by field observations. Despite minimal precipitation surrounding the 10/03/19 field investigation the drainage ditch was nearly at capacity, and was not actively discharging into the Gulf. The water surface elevation had visibly decreased following the 10/25/2019 precipitation event, but a flow path had been carved through the beach allowing discharge into the Gulf. The ditch essentially acts as storage between precipitation events, until the flow rate reaches a threshold at which it is able to cut a path through the beach and exit to the Gulf.

Beachcomber Drive is a paved road that forms a horseshoe shaped subdivision south of FM 3005. The subdivision has no drainage structures, so runoff concentrates along curbs, until it reaches the ends of the "horseshoe" street, where concentrated flow has carved narrow flow paths through the dune system to reach the beach. The Beachcomber subbasin also includes the southern portion of the empty lot to the west, which ends at 16-Mile Road.

16-Mile Road is a beach access road that spans Gulf Palms Beach, but is included with adjacent Jamaica Beach subbasins for the purposes of this report. The 2003 City of Galveston MDP reports that all drainage in this region is routed toward the Gulf of Mexico via 16-mile road

(Dannenbaum, 2003). Field observations from 10/25/19 support this conclusion. 16-Mile Road facilitates overland sheet flow toward the beach, however a majority of beach runoff flows via a drainage swale parallel to the road. Runoff has created a washout at the end of the asphalt pavement, where it interfaces with the beach.

1.4 INDIAN BEACH

Antigua/Vera Cruz Drive is an unpaved road that forms the entrance to the small subdivision south of FM 3005. The subdivision has one main swale formed by concentrated flow that conveys runoff to a single beach discharge point where a breach in the dune is observed.

Gulf Blvd. and Captain Hook are the unpaved roads that form the intersection of this RV/mobile home community south of FM 3005. No drainage structures were observed. It appears that runoff flows overland to three distinct points along Ocean View Drive where it is discharged onto the beach. The southwest corner of the subdivision appears to be where flow is most concentrated.

East DeVaca Lane is accessed via Indian Beach Drive and spans the length of another development south of FM 3005 that drains to the beach. From field observations it appears that a majority of runoff flows toward the Gulf through drainage swales and a reinforced concrete culvert that crosses East DeVaca Lane. Stormwater outfalls onto the beach through a 24” corrugated high-density polyethylene (HDPE) outlet pipe, which was filled with sand during field investigations. The blockage appears to have diverted runoff, causing ponding to concentrate near the pipe before discharging onto the beach.

West DeVaca Lane is accessed via Kiva Road, and is laid out similarly to the East DeVaca development. Stormwater collects in swales that are routed to a single 24 inch reinforced concrete wing-wall outfall that discharges onto the beach. The outfall is not as obstructed as the East DeVaca Lane outfall, however scour and ponding were observed at the outlet pipe location.

1.5 OTHER

Habla Drive is located between the 16-Mile Road and Antigua Drive developments. The 2003 City of Galveston MDP reported ponding issues in this region due to low elevation and drainage regulations, which prohibit the development from draining toward the beach. The area was investigated due to its location relative to other beach drainage areas.

The entire subdivision experiences flooding during mild precipitation events. The water surface elevation was observed at approximately 1-foot above Glei Road during the 10/25/2019 field review. Flooding issues may have been exacerbated by recently installed drainage structures that connect FM 3005 drainage ditches to the low-lying subdivision, presumably in an attempt to alleviate flooding. However there was no evidence of runoff toward the beach while on site, suggesting that the subdivision has maintained compliance with drainage regulations. Improvements to this area are outside the scope of this report, and must be avoided despite its location relative to locations in this report.

2. BOLIVAR PENINSULA

Bolivar Peninsula beach drainage spans from wetlands near Fort Travis to the more developed Crystal Beach area. Drainage on the low-lying peninsula is conveyed to six open-channel beachside outfalls via a system of sloughs, drainage ditches, and open-channels. The sloughs and many of the drainage ditches hold water during typical conditions due to topographic challenges and sedimentation of the channels. Beach discharge has created large breaches in the dunes at outfall locations.

Throughout this report, outfalls are referenced according to nomenclature adopted from the Galveston County MDP, prepared by Klotz Associates in April 2012. Outfalls on the beach side are referred to as “Gulf” outfalls, followed by a number assigned in chronological order increasing numerically from East to West alongshore.

A drainage related field visit to the site was not deemed necessary due to the relatively straight-forward nature of beach drainage on Bolivar Peninsula and the detail provided by the Galveston County MDP. Further, a field visit was conducted months prior to review beach access points, from which several images of existing drainage outfalls were collected. Oblique aerial imagery used in this report is from a post-Tropical Storm Imelda USACE flyover. The following provides a review of beach outfall existing conditions on Bolivar Peninsula:

2.1 GULF 01 – S. MONKHOUSE DRIVE

Gulf 01 is the furthest eastern beach outfall on Bolivar Peninsula. The area immediately adjacent to the outfall channel is undeveloped wetland, however it services much of the residentially developed Crystal Beach area. A single outfall channel, that roughly parallels Monkhouse Drive, drains a large portion of the main slough and north slough on Bolivar Peninsula (Klotz Associates, 2012). It is the second largest and most developed drainage area on Bolivar.

2.2 GULF 02 – ALMA ROAD

Gulf 02 drains a portion of the main slough toward a single, open-channel beach outfall. The region immediately adjacent to the outfall channel is undeveloped to Alma Road, which roughly parallels the channel at an offset distance of approximately 800 feet.

2.3 GULF 03 – RANCHO CARIBE DRIVE

The Gulf 03 drainage area is largely undeveloped, save the sparsely populated residential gated community called Rancho Caribe. The drainage area outfalls onto the beach via an open channel system.

2.4 GULF 04 – HONEYSUCKLE

The Gulf 04 outfall services the smallest beach drainage area on Bolivar Peninsula. The 2012 Galveston County MDP reports that it outfalls onto the beach via a 24-inch reinforced concrete pipe culvert, however field observations could not confirm the existence of a culvert. The beach outfall appeared to be an open-channel, similar all other beach outfalls on the peninsula.

2.5 GULF 05 – JOHNSON BAYOU

The Gulf 05 open-channel is commonly known as Johnson Bayou. The channel flows north to south, forming a diagonal approach relative to the beach and pronounced beach erosion at the outfall location.

2.6 GULF 06 – BEACON BAYOU

Located on a marshy wetland area between Biscayne Beach to the east and Rettilion Road at the west, Beacon Bayou is an open channel that outfalls to Gulf 06. Beacon Bayou services the largest, and least developed beach drainage area on Bolivar Peninsula, including a large watershed northwest of HWY 87.

The region will be subjected to significant changes if CSRM measures are implemented, which include a levee that will follow an offset alignment of Highway 87 until it makes a southeast turn toward the beach, bisecting the drainage area to tie into the dune alignment.

IV. HYDROLOGIC ANALYSIS

1. DATA ACQUISITION AND PREPROCESSING

Esri Geospatial Information System (GIS) software, ArcMap, and the HEC-GeoHMS extension is used to preprocess physical data and extract key hydrologic information. The HEC-GeoHMS extension is a toolbox that is typically used to prepare HEC-HMS basin models based on topographic survey data. Before setting up a basin model, a topographic raster surface, or raw digital elevation model (Raw-DEM), is preprocessed with a set of tools that are used to prepare a hydraulic digital elevation model (Hydro-DEM) with geographic information about hydrologic elements. Standard HEC-GeoHMS preprocessing toolbox steps were followed to delineate subbasins, determine flow paths, and automatically generate output that characterizes these physical characteristics. This data was used not only for HMS hydrologic models, but also to inform rational method calculations such as time of concentration. For the Beacon Bayou basin in Bolivar, the proposed levee had to be burned into the existing terrain, using a standard tool in the HEC-GeoHMS toolbox, called "Build Walls", however gaps/breaches in the levee are left where natural flow paths intersect the proposed levee to determine peak flow at those intersections and properly size culverts.

The preprocessing toolbox is used to create an existing conditions hydrologic digital elevation model, or Hydro-DEM, from a 2018 LiDAR raster file. Preprocessing tools are used to delineate drainage basins and determine flow paths for the entire study site. Drainage basin delineations are cross-referenced with those developed in respective MDPs, wherever applicable. The drainage lines are used to identify proper placement of proposed culvert locations. The beach drainage maps are available in **Appendix __.**

Survey data used for this study is 2018 topographic LiDAR data, from the Texas Water Development Board (TWDB), accessed and downloaded via the NOAA: Data Access Viewer website. Precipitation frequency data, used for the hydrologic analysis was downloaded from the NOAA: Atlas 14 Precipitation Frequency Data Server.

A shape file with parcel land-use information from the Houston-Galveston Area Council (HGAC) is used to determine runoff coefficients (C-values), development (%), and imperviousness (%) for drainage areas within the study site. Composite values are calculated inside ArcMap. ArcMap tools are used to measure or extract geospatial-related physical parameters from the raster data.

2. RATIONAL METHOD

For the purposes of this study, the rational method is used to determine the peak discharge for drainage areas of approximately 200 acres or less. This method is applicable for a majority of the study site due to the limited size of drainage areas inherit in the topology of the barrier island landscape. It is used for all of Galveston Island's and half of Bolivar Peninsula's drainage areas of interest. The procedure outlined in the Galveston County Drainage District Number One (GDD1) Drainage Criteria Manual was followed closely. The peak discharge Q_P in cubic-feet per second is found with the following:

$$Q_P = C_f \cdot C \cdot I \cdot A$$

Where C is a runoff coefficient that is determined by the type of local land cover, A is the acreage of the drainage area, and I is the precipitation intensity (inches/hour) for the time of concentration T_C. C_f is an empirically derived frequency factor used to scale the magnitude of the peak runoff in relationship to the return interval of the storm (GDD1, 2020, pg. 15). Frequency factor (C_f) values are summarized in Table 1.

Table 1: Frequency Factor per GDD1 pg. 15

Storm Frequency (years)	Frequency Factor (C_F)
10	1.0
25	1.1
100	1.25

For applicable Bolivar drainage basins, the runoff coefficient ‘C-values’ are adopted from Table J.6 of the Galveston County MDP, which originate from the GDD1 Drainage Criteria Manual. For Galveston Island drainage basins, runoff coefficients are derived directly from the GDD1 Drainage Criteria Manual, and methodologies from the Galveston County MDP are employed to develop the composite value used for each basin (GDD1, 2020, pg. 15).

Table 2: GDD1 Derived Runoff Coefficients

Land Use Type	**Runoff Coefficient**
Raw, undeveloped	0.2
Improved, undeveloped	0.25
Residential Districts	
Lots more than 1 Acre	0.35
Lots 1/2-1 acre	0.45
Lots less than 1/2 acre	0.55
Open Water*	0.8
Notes	
*Open water value C-value is from Galveston County MDP, Appendix J, Table J.5; value is applied to Sunny Beach reservoir ponds only	

A shapefile with Galveston parcel data is downloaded from TNRIS, clipped to the drainage areas of interest, and spatially joined to the land use polygons. The attribute table, with land use codes, lot acreage, and respective drainage basin ID is exported to Excel where the data is post-processed to develop weighted runoff coefficients. An Excel formula is used to identify any land use code that signifies undeveloped land and applies a value of 0.2 or 0.25 depending on if the land is considered improved or not. The majority of parcels are residential lots, therefore the C-values are based directly on the parcel acreage. For each drainage basin a composite c-value is developed based on the weighted average of individual parcel size and assigned runoff coefficients. The C-values, and other parameters assigned to Galveston drainage areas for Rational Method calculations are seen in Table 3.

The time of concentration is the amount of time that it takes a drop of water to travel from the furthest upstream point of a drainage basin to the outlet. The equation on page 14 of the GDD1 Drainage Criteria Manual is used to determine time of concentration:

$$T_C = \frac{\text{Length}}{\text{Velocity} * 60} + 10$$

Where length is in feet, and velocity is in feet per second. T_C takes into account both overland flow and concentrated flow, and velocities for each are from values suggested on page 15 the GDD1 Manual.

Table 3: Parameters Assigned to Galveston Island Drainage Basins for Rational Method analyses

Drainage Basins		**Flow Length**		**Flow Velocity**		**Time of Concentration**			**C**
Name	Area	Ditch	Overland	Ditch	Overland	Ditch	Overland	**Tc**	
	(acres)	(ft)	(ft)	(ft/s)	(ft/s)	(min)	(min)	(min)	
Sunny Beach East	28.95	0	1300	1.5	0.5	0	43.33	53.33	0.58
Sunny Beach West	38.79	0	1500	1.5	0.5	0	50	60	0.51
Bermuda Beach East	34.12	0	2126.3	1.5	0.5	0	70.88	80.88	0.54
Bermuda Beach West	11.14	0	914.11	1.5	0.5	0	30.47	40.47	0.54
Jamaica Beach	23.76	1600	718	1.5	0.5	17.8	23.93	51.71	0.51
Jamaica Beach	27.93	0	1400	1.5	0.5	0	46.67	56.67	0.47
Jamaica Beach	8.78	1235.79	660	1.5	0.5	13.7	22.00	45.73	0.52
Indian Beach	4.83	0	702	1.5	0.5	0	23.40	33.40	0.55
Indian Beach	6.60	0	778	1.5	0.5	0	25.93	35.93	0.55
Indian Beach	33.47	1288	600	1.5	0.5	14.3	20	44.31	0.55
Indian Beach	11.22	1137	600	1.5	0.5	12.6	20	42.63	0.55

Local Atlas 14 precipitation frequency data tables from NOAA's Hydrometeorological Design Studies Center are used to determine rainfall intensity 'I' for storms with annual return intervals including 1-years, 2-years, 5-years, 10-years, 25-years, 50-years, and 100-years. The intensity is interpolated from the tables, based on the time of concentration determined for each drainage area.

3. HEC-HMS

HEC-HMS is used to model larger drainage areas on Bolivar Peninsula that discharge to Gulf 01, 05, and 06 outfalls, respectively. HEC-HMS required inputs include a basin model, a meteorological model, and control specifications. The meteorological model is set up as a "frequency storm" with local Atlas 14 precipitation frequency data,. The precipitation frequency data is applied homogenously across all subbasins. The control specifications simply control the model run time. A 24-hour run time is used for all models, with a 5-minute time interval step size.

The basin model is essentially a schematic of nodes and connections, which represent drainage elements including subbasins, junctions, inlets and outlets. Subbasin elements contain information about transform and loss parameters. The following Green and Ampt loss parameters are uniformly applied across all model basins, except for the impervious parameter, which is sub-basin specific:

- Initial Content (%) = 0.075
- Saturated Content (%) = 0.46
- Suction (IN) = 12.45
- Conductivity (IN/HR) = 0.024

To minimize duplicate efforts, TC&R Clark Unit Hydrograph transform parameters are adopted from the Galveston County MDP, and basin delineations are used for setup of Gulf 01 and Gulf 05 basin models.

The GIS extension, HEC-GeoHMS is used to prepare the Beacon Bayou (Gulf 06) basin model for HEC-HMS. Setup of the Beacon Bayou basin model requires additional preprocessing due to the proposed levee alignment, which must be physically represented in the basin model. A preprocessing tool in the program allows for modeling of interior and exterior walls, which are "burnt" into the surface of the Hydro-DEM. The interior wall option is used to define the levee with breaches at points of intersection with drainage lines, which are identified as the proper culvert locations. Nodes are set up at the breach points to monitor discharge in the HMS model.

V. HYDRAULIC ANALYSIS

1. HYDRAULIC CALCULATIONS

The Chezy-Manning equation is used to calculate the capacity required for open-channel drainage ditches, and culverts. Peak discharge rates are used to size culvert capacity, while a reduced discharge rate is used to size drainage ditches. Culverts are intended to convey drainage through CSRM features, namely dunes, to an outfall on the beach. The average difference in elevation, and cross-shore distance, between the CSRM alignment and toe of proposed dune features is used to determine the depth available for a culvert that maintains a 1:100 slope.

2. LEVEL OF SERVICE (LOS) FREQUENCY CRITERIA

Galveston Island outfalls are sized for a 100-year LOS, Beacon Bayou outfalls have a 25-year LOS, and remaining Bolivar Peninsula have a 5-year LOS. Culvert capacity recommendations are developed according to the level of service (LOS) that could be achieved if improvements to optimize the existing drainage system were implemented. The criteria was based on the Galveston County MDP LOS assessment of existing conditions and proposed improvements on Bolivar Peninsula.

1.1 BOLIVAR PENINSULA

An excerpt from the 2012 Galveston County Master Drainage Plan explains the criteria used to evaluate proposed channels:

> *"Proposed channels were evaluated subject to the following conditions: 1) freeboard of 1 ft, 2)channel side slopes of 4H: 1V, 3) maximum velocities not to exceed an eroding velocity, selected as 8 fps, 4) a flow line drop of 1 ft at confluences of two or more channels, 5) minimum bottom slopes of 0.05%, and 6) a minimum channel depth (if feasible) of 8 ft to allow discharge of existing or future sewer outfalls to the channel reach." (Klotz Associates, 2012).*

Improvements/replacements of culverts and bridges were sized to handle the maximum capacity of the proposed channel. In other words, channels were hydraulically optimized within physical limitations inherit in the landscape, and other components were sized accordingly to handle the capacity.

According to the Galveston County MDP, Gulf outfalls 01-05 have an existing LOS frequency below 2-years and a maximum attainable LOS frequency between 2 and 5 years with proposed improvements (Klotz Associates, 2012). The maximum LOS limit is a result of topography and limited storage onsite. Therefore a 5-year LOS is the criteria used to size all outfalls on Bolivar Peninsula, except for the Beacon Bayou drainage area. The proposed levee alignment eliminates the need for a culvert at the existing Gulf 06 outfall location in favor of 4 new outfalls located at points of intersection with drainage lines. These outfalls service smaller subbasins, and culverts are sized to a 25-year LOS.

1.2 GALVESTON ISLAND

Galveston Island drainage areas, and associated discharge rates, are significantly smaller than those on Bolivar Peninsula. As a result, an increased LOS of 100-years is the criteria used to develop culvert size recommendations for Galveston.

The size and location of proposed culverts is intended to handle the full capacity of the 100-year event for each basin. Therefore, the proposed drainage swales are intended as a safety net that will capture and distribute overland runoff that may not be conveyed by the primary natural paths. Since drainage channels connect adjacent drainage areas, the drainage channel dimensions were assumed to remain constant throughout Galveston Island. Physical constraints limit the improved maximum channel width to 14-feet with a 3-foot depth and a maximum flow velocity of 5 feet per second is selected to remain below the erosion threshold, assuming a Mannings n-value of 0.03.

If Manning's equation is used with a slope of 1/1000 (based on hydraulic gradient), the ditch will provide a capacity of approximately 50.5 CFS. The slope is based on the elevation difference (1') between the max depth in the ditch (3') and the max depth at the culvert (2'), over a distance of 1000', which is roughly equal to the distance between any two outfalls.

VI. STUDY RESULTS

The following tables provide a summary of culvert type and quantity recommendations. Location information is provided in drainage maps, located in the Appendix that follows the References section of this report.

1. GALVESTON ISLAND

Galveston drainage areas are grouped according to their location relative to each other. Adjacent drainage areas are connected by a proposed drainage ditch to improve storage and distribution of runoff. Galveston Island culvert recommendations do not exceed a 24-inch diameter to accommodate one foot of fill coverage and the 3-foot drainage ditch depth.

Table 4: Galveston Island Beach DAs – Results & Recommendations

ID	**DA (Beach Name)**	**Common Subbasin Name (Nearby Street Name)**	**Area**	**100-Year LOS**		**Culvert Qty.**
				Precipitation	**Peak Discharge**	**24 inch RCP***
			(Acres)	(in/hr)	(cfs)	(#)
1	Sunny Beach	7 1/2 Mile	28.95	5.58	117.95	0 (6)**
2	Sunny Beach	8 Mile	38.79	5.07	126.59	0 (6)**
3	Bermuda Beach	East Bermuda Beach	34.12	4.59	105.06	5
4	Bermuda Beach	West Bermuda Beach	11.14	6.57	49.17	2
5	Jamaica Beach	Buccaneer	23.76	5.71	87.07	4
6	Jamaica Beach	Beachcomber	27.93	5.33	87.19	4
7	Jamaica Beach	16 Mile	8.78	6.17	35.47	2
8	Indian Beach	Antigua	4.83	7.12	23.65	1
9	Indian Beach	Captain Hook	6.6	6.92	31.39	2
10	Indian Beach	East DeVaca	33.47	6.28	143.64	6
11	Indian Beach	West DeVaca	11.22	6.41	49.42	2

Notes:

* 24 inch dimension refers to the diameter; RCP = Reinforced Concrete Pipe

* *Official recommendation is to eliminate beach outfall in favor of existing bayside conveyance (0 culverts recommended); culvert quantity in parenthesis assumes no bayside conveyance, only beach discharge, thus results are very conservative

The Sunny Beach drainage area presents an ideal opportunity to eliminate discharge to the beach, provided that bayside drainage structures are capable of maintaining the capacity. The current recommendation is to eliminate beachside discharge, however recommendations resulting from the hydraulic analysis are included in parenthesis within the results below. Further investigation is required to ensure that bayside drainage structures have adequate capacity to eliminate beachside discharge.

2. BOLIVAR PENINSULA

Bolivar Peninsula topography allows for a maximum diameter/depth of 36-inches, which is corroborated in Appendix K of the Galveston County MDP. All recommendations are sized to accommodate a 5-year LOS capacity, except for the Gulf 06 levee outfalls, which have a 25-year LOS.

Table 5: Bolivar Peninsula Beach DAs - Results & Recommendations

DA ID	Outfall Location	Name (Prominent Street or Bayou)	Area	Peak Discharge*	Proposed Outfalls		
					Type**	Size	Qty.
			(Acres)	(cfs)			(#)
Gulf 01	Beach (Existing)	S Monkhouse	797.50	987.1	RCB	3' x 6'	5
Gulf 02	Beach (Existing)	Alma Rd	151.40	122	RCB	3' x 6'	1
Gulf 03	Beach (Existing)	Rancho Caribe	208.10	158.77	RCB	3' x 6'	2
Gulf 04	Beach (Existing)	Honeysuckle	17.20	33.5	RCP	36" Ø	1
Gulf 05	Beach (Existing)	Johnson Bayou	453.30	351.7	RCB	3' x 6'	3
Gulf 06	Hwy 87	Beacon Bayou	271.07	391.2	RCB	3' x 6'	2
Gulf 06	N Levee	Beacon Bayou	132.45	108.4	RCP	36" Ø	2
Gulf 06	Mid Levee	Beacon Bayou	77.42	63.5	RCP	36" Ø	1
Gulf 06	S Levee	Beacon Bayou	14.10	11.7	RCP	24" Ø	1

Notes:

* The peak discharge result is for a 5-year event EXCEPT for the Gulf 06 DA, which is for 25-years

** RCP = Reinforced Concrete Pipe; RCB = Reinforced Concrete Box

Peak discharge calculations compare well to the 2012 Galveston County MDP. Study results show a peak discharge magnitude increase at approximately 25% in comparison to MDP results, which is closely correlated to the increase in the magnitude of precipitation frequency values used.

VII. RECOMMENDATIONS FOR PED PHASE

Though outside the scope of this report, the following considerations should be addressed in the Preliminary Engineering Development phase:

The beach is a highly dynamic environment that demands detailed consideration of the design/installation of any structure. Survivability, operations/maintenance requirements, and fulfillment of the intended purpose without creating or worsening existing issues are key considerations that are made more difficult by the dynamic nature of the beach. Sedimentation of drainage systems from aeolian (wind-driven sediment transport) processes will require routine maintenance, which worsens with proximity to the beach.

Open channel drainage ditches, recommended for certain regions of Galveston, are of primary concern due to their location relative to the leeward toe of the sand dune. Sand tends to deposit on the leeward side of the dune as a result of aeolian processes, creating a slip-face that increases the likelihood of sedimentation of the drainage ditch. In addition, severe storm surge events will require closure of flap gates on culvert outlets, which will increase precipitation-related flooding leeward of dunes. Increased flooding will increase hydrostatic pressure and soil saturation, thereby increasing the risk of local dune failure near outlet pipes during such storm-surge events.

Further, runoff conveyed toward the beach has detrimental impacts on the beach itself, which will require design of scour protection at the outfall location. The location of the outfall is currently assumed at the seaward toe of the design dune, however this requires a culvert length of roughly 200-feet and subjects the design berm to scour. Maintaining adequate structural support and coverage of the culvert in such a dynamic environment may pose challenging maintenance concerns, which are further exacerbated if outfalls are clogged by sediment and/or debris.

Although initial cost is inevitably higher, conveyance of runoff to bayside outfalls would alleviate many of the above concerns and may reduce cost over the life of the project. A detailed risk-benefit analysis should be performed to review the cost of alternatives and to explore the potential for funding from local sponsors that may offset additional costs.

VIII. REFERENCES

i. CITY OF JAMAICA BEACH. (2018, OCTOBER 1ST). CITY COUNCIL WORKSHOP MEETING MINUTES. CITY COUNCIL CHAMBERS, 5624 JAMAICA BEACH, JAMAICA BEACH, TX 77554. (PP. 1-2)

ii. DANNENBAUM ENGINEERING CORPORATION (PRIME), 2003. CITY OF GALVESTON MASTER DRAINAGE PLAN. SUBMITTED TO THE CITY OF GALVESTON. IN ASSOCIATION WITH: BERG OLIVER ASSOCIATES, INC., DODSON & ASSOCIATES, INC., KATHY THOMAS BARR, TERRAPOINT.

iii. GDD1, 2020. GALVESTON DRAINAGE DISTRICT #1 DRAINAGE CRITERIA MANUAL. JANUARY, 2020. 3722 AVE J – P.O. BOX 591 SANTA FE, TX 775517

iv. KLOTZ ASSOCIATES, 2012. MASTER DRAINAGE PLAN FOR GALVESTON COUNTY, TEXAS, BY KLOTZ ASSOCIATES, INC., HOUSTON, TEXAS, APRIL, 2012

v. NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION. NATIONAL WEATHER SERVICE. HYDROMETEOROLOGICAL DESIGN STUDIES CENTER. PRECIPITATION FREQUENCY DATA SERVER: NOAA ATLAS 14, VOLUME 11, VERSION 2.

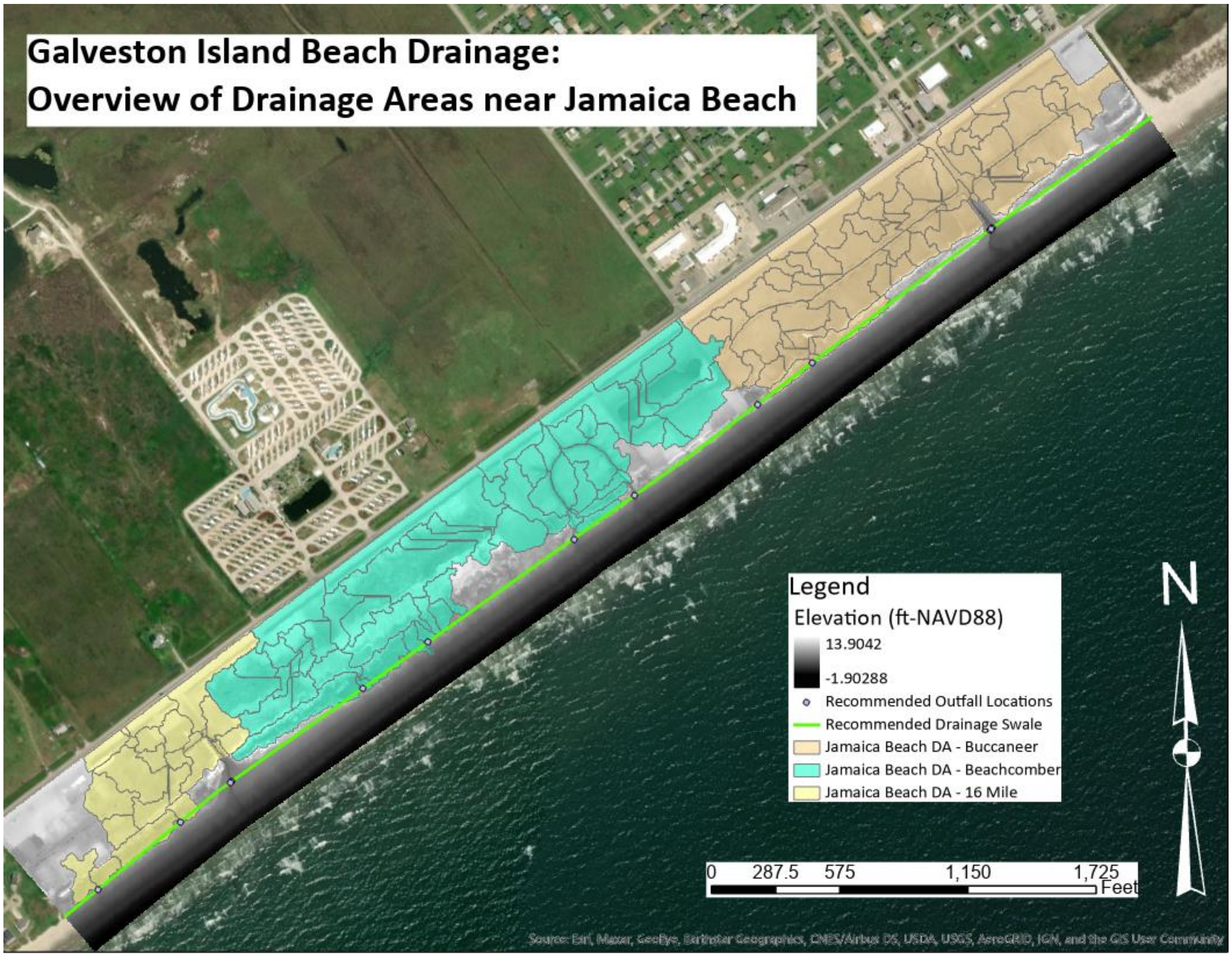
vi. RAVELLA, PETER A., WORSHAM, B. 2012. JAMAICA BEACH EROSION RESPONSE PLAN. SUBMITTED TO THE TEXAS GENERAL LAND OFFICE. PETER A. RAVELLA CONSULTING, LLC & LJA ENGINEERING, INC.

vii. STRATEGIC MAPPING PROGRAM (STRATMAP). LAND PARCELS, 2019-03-01. WEB. 2020-08-21.

viii. TEXAS WATER DEVELOPMENT BOARD. 2018 TWDB LIDAR: COASTAL TEXAS. NOAA: DATA ACCESS VIEWER. TEXAS NATURAL RESOURCES INFORMATION SYSTEM. 2018

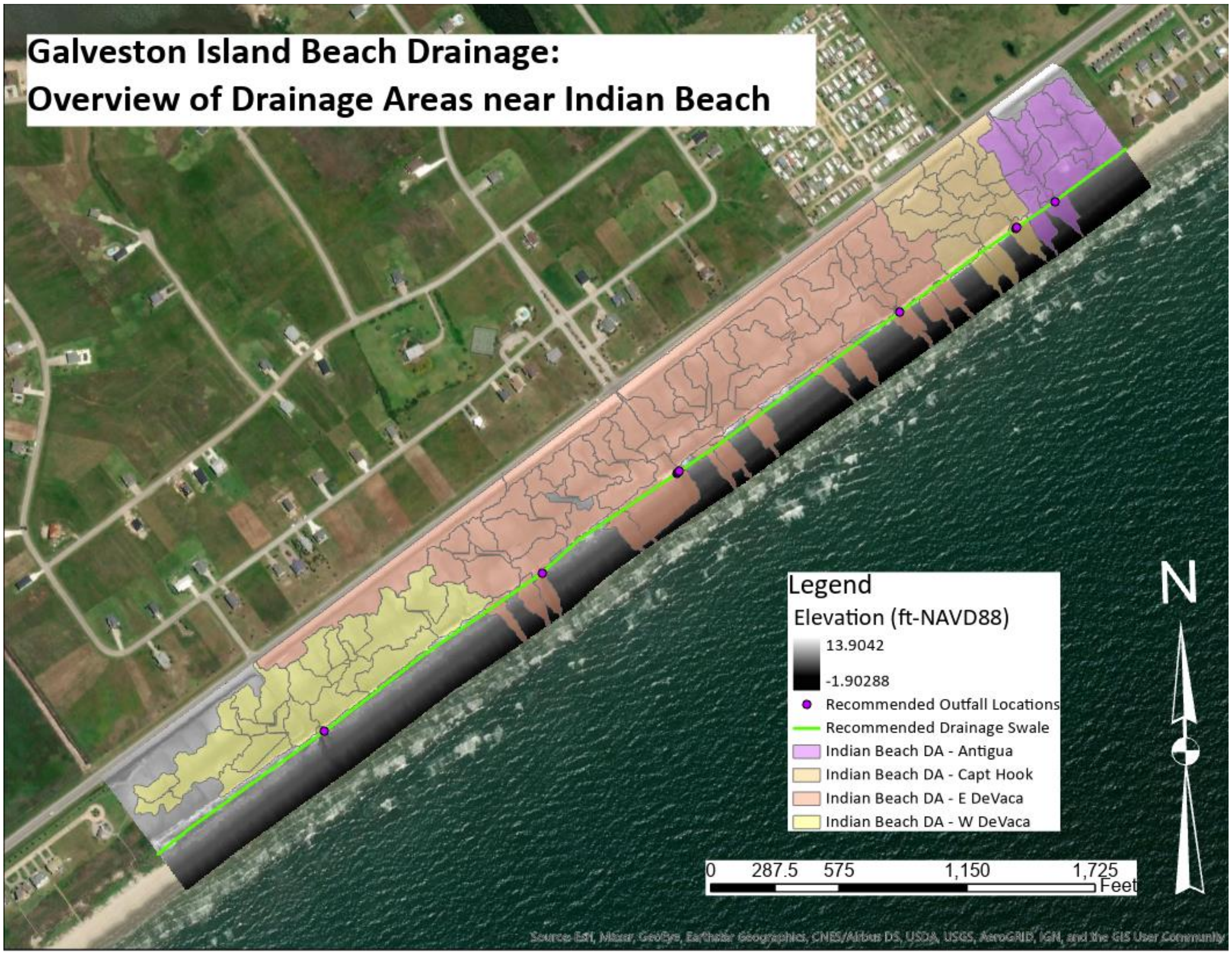
APPENDIX


Galveston Island Beach Drainage: Bermuda Beach
N
Proposed Outfalls
Proposed Ditch
CSRM
Drainage Lines
DA_Bermuda Beach East
DA_Bermuda Beach West
0 200 400 800 1,200 1,600
Feet
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

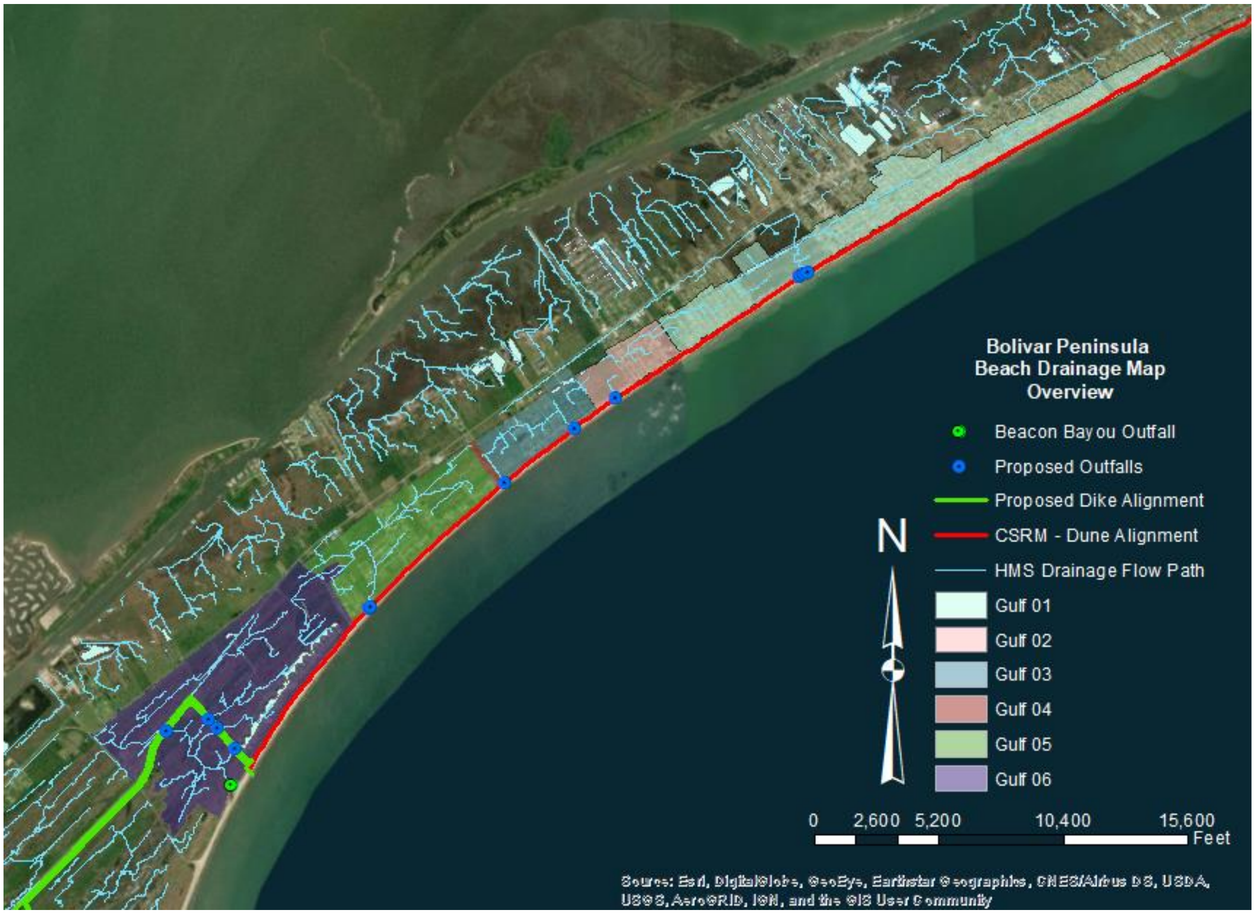


Galveston Island Beach Drainage:
Overview of Drainage Areas near Jamaica Beach

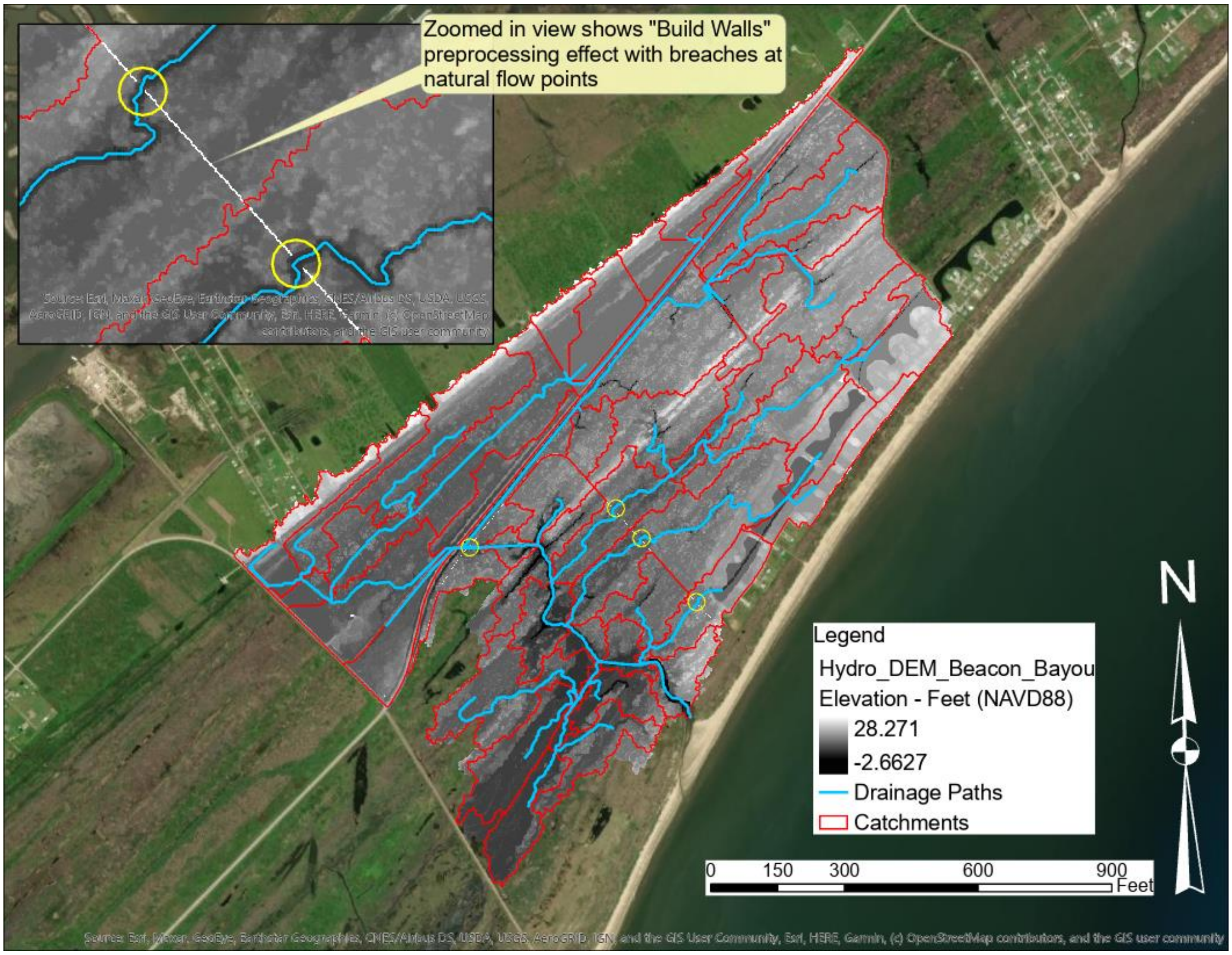
Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community


Zoomed in view shows "Build Walls" preprocessing effect with breaches at natural flow points
Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community, Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community
Legend
Hydro_DEM_Beacon_Bayou
Elevation - Feet (NAVD88)
28.271
-2.6627
Drainage Paths
Catchments
0
150
300
600
900
Feet
N
Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community, Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community