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Galveston District

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Galveston 204 CAP – Beach Nourishment

GALVESTON, TX

Engineering Appendix

Hydrology and Hydraulics

April 2022

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PDT and Review Team

Name	Role	Signature
Jason Thies	Coastal Engineer	
Patrick C. Kerr, PhD, PE	Responsible Engineer Coastal Section Chief	
Coraggio Maglio, PE	DQC – H&H Branch Chief	
Reuben Trevino	Project Manager	
Shubhra Misra, PhD, PE	Peer Reviewer	

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Engineering Appendix

Hydrology and Hydraulics

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1 Introduction

Galveston Island experiences an average annual erosion rate of approximately 3 to 5 feet that negatively impacts hurricane protection, recreational activities, and local wildlife due to reduced nesting ground area. USACE has been contacted by the City of Galveston to perform a feasibility study to evaluate alternative solutions to mitigate ongoing erosion. Receding shorelines have generated local interest in evaluating nourishment options to increase beach width on the West End of Galveston Island. An estimated 500,000 cubic yards of dredged material is available from Galveston Harbor and Channel every dredge cycle. The dredge cycles occur every two years, or every odd fiscal year. The earliest dredge cycle available for this project area will be in fiscal year 2023. The project is under CAP section 204 of the Water Resources Development Act of 1992. This authorizes USACE to perform projects with the intent of the protection, restoration to reduced storm damage to property, in connection with dredging for the construction or operations and maintenance of an existing, authorized Federal navigation project. The feasibility phase is funded 100% federally and there is a $10.0 million federal project limit. The study sponsor is the Park Board of Trustees of the City of Galveston.

1.1 Geographic Setting

Galveston Island is located on the upper Texas Coast between the Galveston Ship Channel to the north and San Luis Pass to the south. The sandy barrier island is oriented at approximately 237° azimuth (assuming a bearing from NE to SW and cardinal north at 0°), measuring approximately 29 miles in length and 0.3 to 0.6 miles in width. The Project site located at the West End of Galveston Island is shown in Figure 1. For context throughout the remainder of the report the Project site is segmented and referred to in one of two manners: (1) per the PMP, the site is initially split into two sections, defined as “Project Area 1” and “Project Area 2”, (PA1 and PA2, respectively) or (2) per morphological similarities discovered during analyses, the site is later split into three sections, referred to as Reach 1, 2, & 3. The latter is distinguished by the yellow, purple/violet, and green polygons, respectively, as seen in Figure 1. Roughly speaking, Reach 1 includes Sunny Beach, Reach 2 covers Bermuda Beach, and Reach 3 covers Pirates Beach.

Similarly, the red to blue linework indicates PA 1 and PA2, respectively. Project Area 1 extends from 8-Mile Road to Pabst Road, covering Sunny Beach and much of Bermuda Beach. Project Area 2 extends from Pabst to 11-Mile Road, including Pirates Beach and a portion of Bermuda Beach. The line follows the same path as the Coastal Storm Risk Management (CSRM) line, established by the State of Texas’s Government Land Office (GLO) as the landward boundary for beach construction per the Coastal Texas Protect and Restore Feasibility Study (USACE, 2020). This line is the assumed landward limit of construction templates for the purposes of this project.

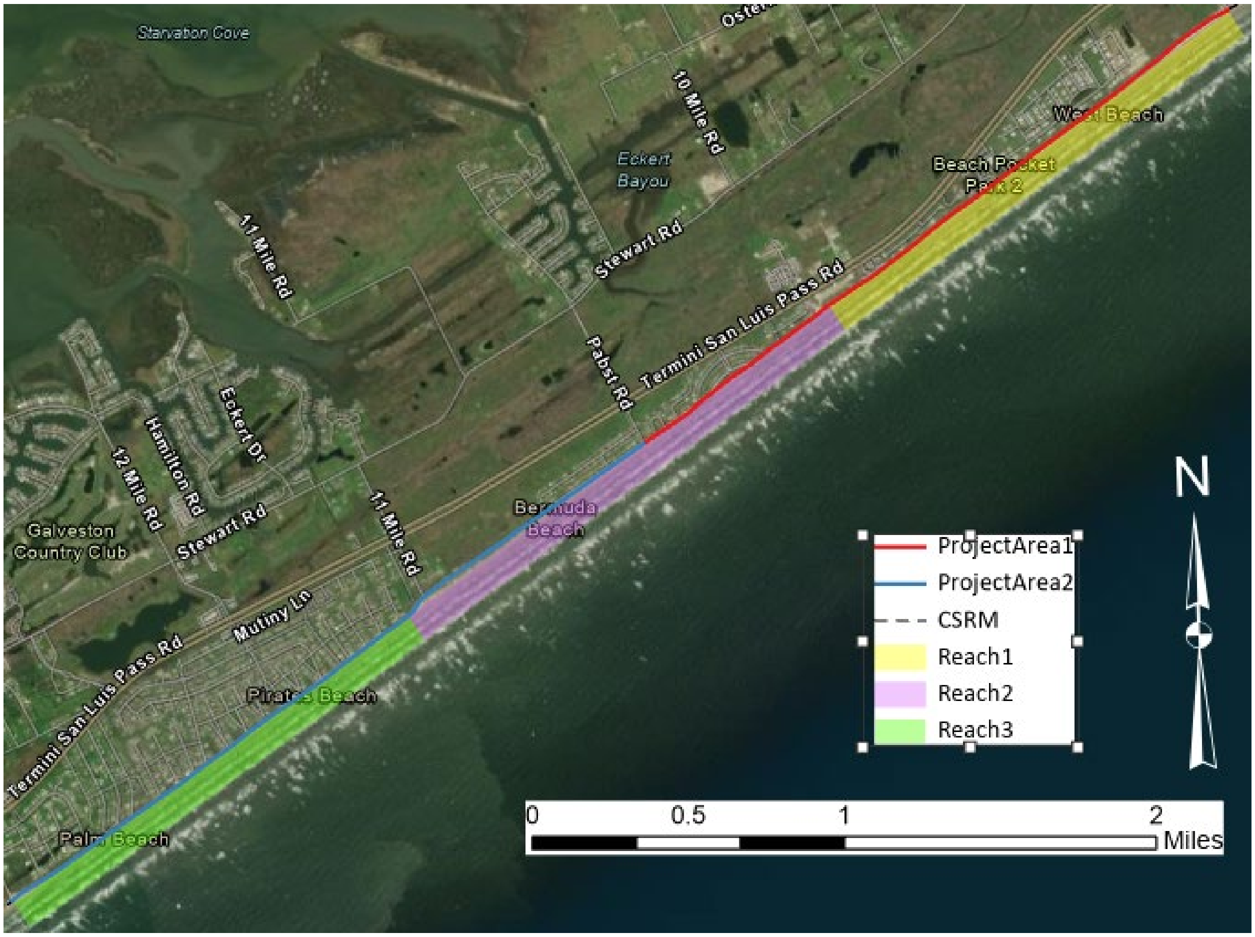

Figure 1: Project site on West Galveston; legend indicates various project-specific designations

1.2 Objectives

The intended purpose of this study is to evaluate the feasibility of five (5) alternative solutions that are intended to mitigate erosion within the West Galveston project area. The alternatives listed below must meet criteria within the Section 204 program, which is oriented towards the Beneficial Use (BU) of dredged material.

1. Alternative 1: No-Action – the FWOP (future without project) analysis serves as the baseline for evaluating other alternatives
2. Alternatives 2 & 3: Beneficial use of dredged material for coastal storm risk management, alternatives are differentiated by the location of targeted placement areas
3. Alternatives 4 & 5: Seawall extension from current end through Placement Area 1 and Placement Area 2, respectively.

Results from H&H analyses are used to screen alternatives and inform the economic analysis, which ultimately drives selection of the TSP (Tentatively Selected Plan). Additionally, PED (Preliminary Engineering Design) phase and general future work recommendations are provided in the final sections of this Appendix.

2 Site Conditions

The following sections will discuss the site conditions of the study area. Conditions to be discussed include the nourishment history, tides, historical storms, winds, currents, waves, and sea level rise.

2.1 Tidal Datums and Sea Level Change

Water level data was obtained from NOAA's Tides and Currents website for Station 8771450 located at Pier21 in Galveston, TX. Figure 2 shows the location of the Galveston Pier 21 station. The astronomical tides are diurnal along Galveston Island – there is one high and one low tide every lunar day.

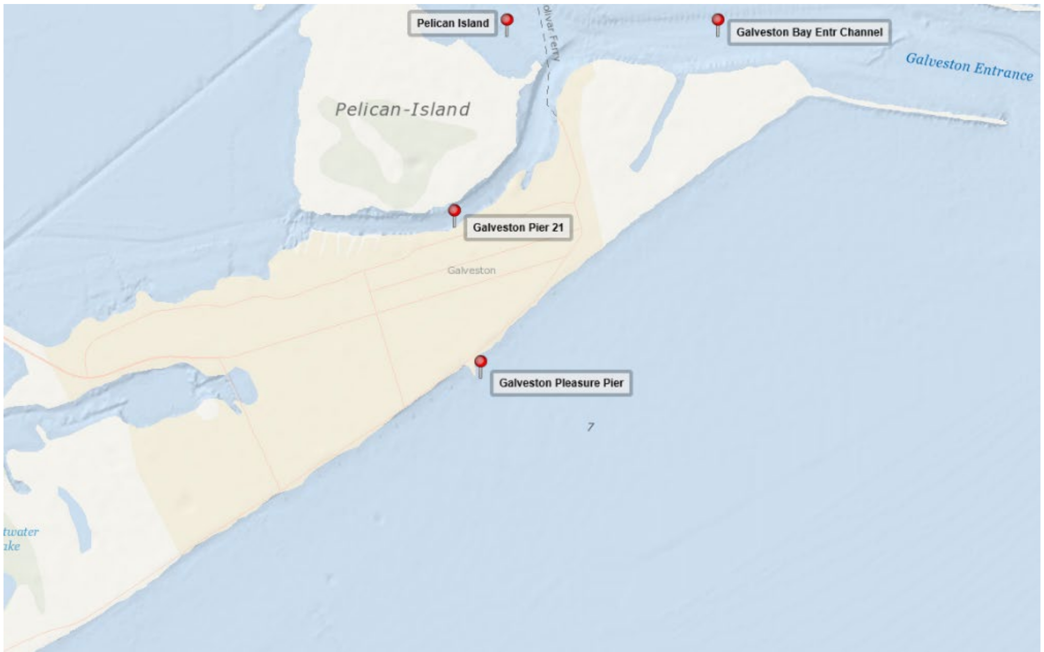

Figure 2: Location of NOAA Tide Station 8771450

The USACE Sea Level Change Curve Calculator (Version 2021.12) is used to project three local RSLC (relative sea level change) scenarios in accordance with ER 1100-2-8162 (USACE, 2013). The historic RSLC rate utilized (0.02106 ft/yr) reflects NOAA's regional rate at the Galveston, TX Pier 21 gauge (8771450). RSLC is projected out to year 2038, which is consistent with the FWOP analysis duration of 15-years (2023 to 2038). Projections are summarized for three scenarios (low, medium and high) in Table 1, along with station datums (on NAVD88) projected with intermediate RSLC in Table 1 and Figure 3. The mid-epoch analysis year (1992) is used as the starting year of RLSC projections according to the station's tidal datum analysis period.

Table 1: Relative Sea Level Change (RSLC) projections for Pier 21 in Galveston, TX

Galveston Pier 21 (NOAA Gauge 8771450): Relative Sea Level Change Projections								
RSLC Projections (Low = 0.02106 ft/yr)				Datums on NAVD88 with Intermediate SLC (ft)				
Year	**Low**	**Int.**	**High**	**MLLW**	**MLW**	**MSL**	**MHW**	**MHHW**
1992	0.00	0.00	0.00	-0.31	-0.01	0.52	1.01	1.10
2023	0.65	0.74	1.01	0.43	0.73	1.26	1.75	1.84
2024	0.67	0.77	1.05	0.46	0.76	1.29	1.78	1.87
2025	0.69	0.78	1.09	0.47	0.77	1.30	1.79	1.88
2026	0.72	0.82	1.15	0.51	0.81	1.34	1.83	1.92
2027	0.74	0.85	1.19	0.54	0.84	1.37	1.86	1.95
2028	0.76	0.87	1.24	0.56	0.86	1.39	1.88	1.97
2029	0.78	0.90	1.29	0.59	0.89	1.42	1.91	2.00
2030	0.80	0.93	1.34	0.62	0.92	1.45	1.94	2.03
2031	0.82	0.96	1.39	0.65	0.95	1.48	1.97	2.06
2032	0.84	0.99	1.44	0.68	0.98	1.51	2.00	2.09
2033	0.86	1.01	1.49	0.70	1.00	1.53	2.02	2.11
2034	0.88	1.03	1.53	0.72	1.02	1.55	2.04	2.13
2035	0.91	1.07	1.59	0.76	1.06	1.59	2.08	2.17
2036	0.93	1.10	1.64	0.79	1.09	1.62	2.11	2.20
2037	0.95	1.13	1.70	0.82	1.12	1.65	2.14	2.23
2038	0.97	1.16	1.75	0.85	1.15	1.68	2.17	2.26
Note: All units are in feet								

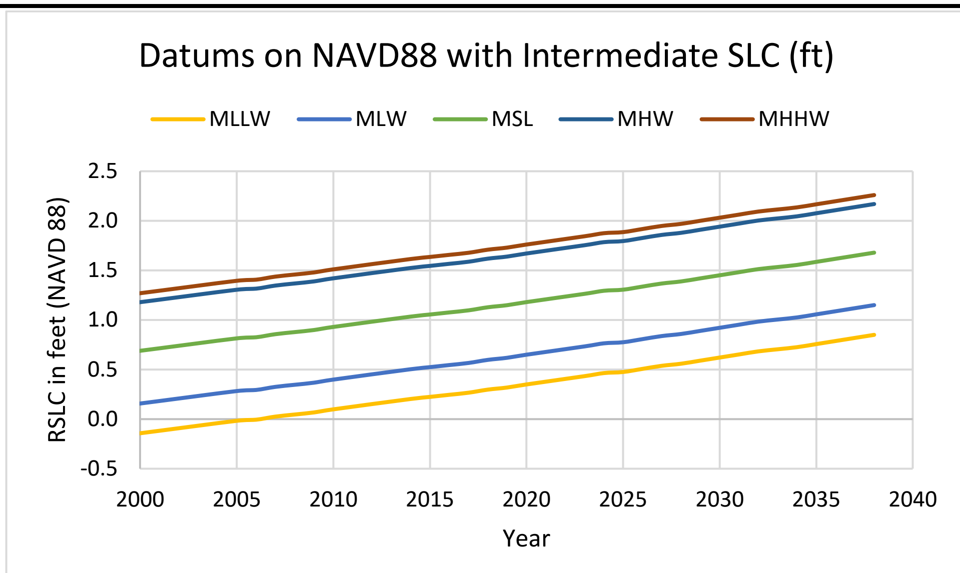

Figure 3: Pier 21 Datums adjusted for intermediate RSLR

2.2 Historic Storms

Figure 4 from NOAA's historical hurricane tracks website displays every major storm track within 100 miles of Galveston Island, between 2005 and 2020. Relevant storm data is summarized in Table 2, wherein peak surge water surface elevations (WSE) are based on time-series records from NOAA's Pier 21 gauge (8771450). The annual exceedance probability (AEP) values are similarly based on curves developed by NOAA according to the full period of record (from 1908 to present) at Pier 21 (NOAA, 2021). Time-series WSE records from individual events are compared against the station's AEP curves to determine the probability of occurrence (%) associated with each storm.

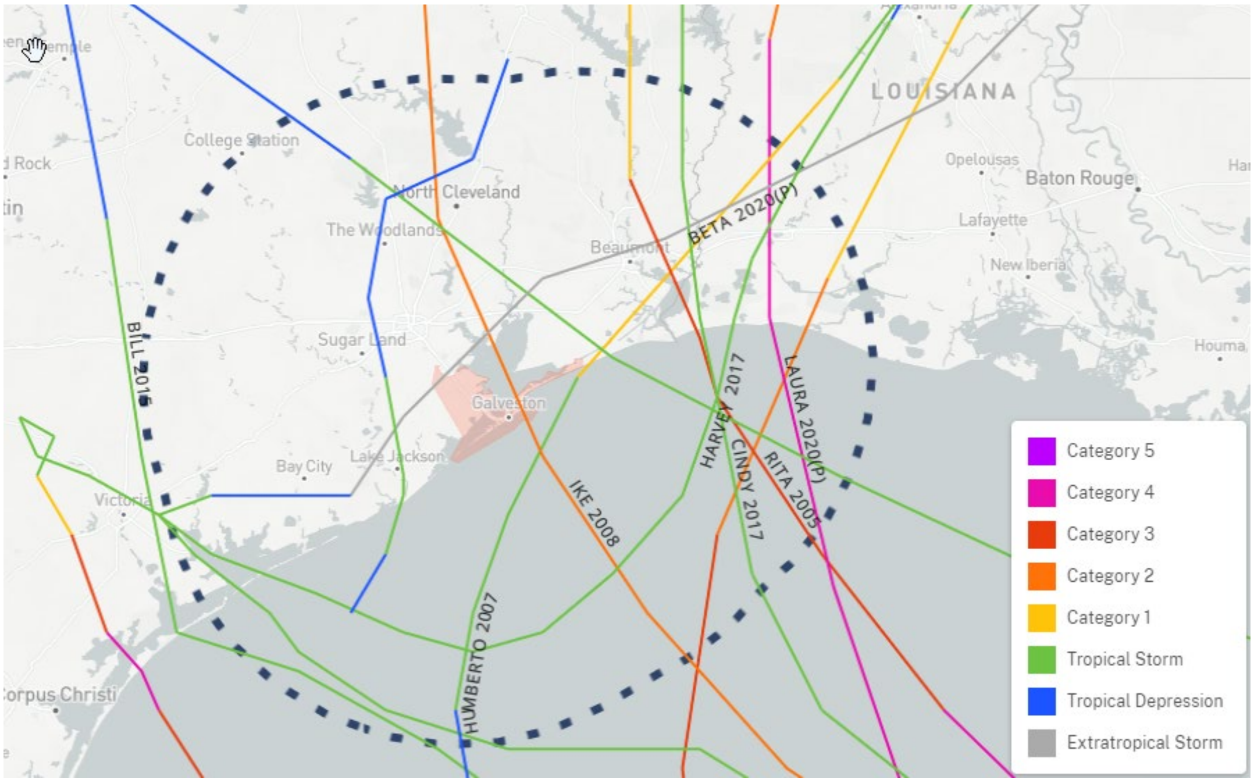

Figure 4: NOAA storm tracker (https://coast.noaa.gov/hurricanes/#map=4/32/-80)

Table 2: Summary of recent storms in Galveston area; peak surge and related AEP values are based on Pier 21 gauge records (NOAA, 2021)

Storm Name	Date	Peak Surge SWL (NAVD88 - ft)	Local AEP, Surge(%)
Hurricane Rita	Sept. 2005	3.47	26%
Humberto	Sept. 2007	2.72	56%
Edouard	Aug. 2008	1.61	> 99%
Ike	Sept. 2008	10.52*	< 1%
Bill	June 2015	3.58	28%
Cindy	June 2017	3.72	26%
Harvey	Aug. 2017	3.80	25%
Imelda	Sept. 2019	3.18	45%
Laura	Aug. 2020	5.08	12%
Beta	Sept. 2020	4.87	14%
Delta	Oct. 2020	3.65	29%
*Peak surge was not captured due to gauge malfunction			

2.3 Wind

Stations 73070 & 73071, displayed in Figure 5, are determined to be the closest WIS stations to the project location (USACE, 2010).

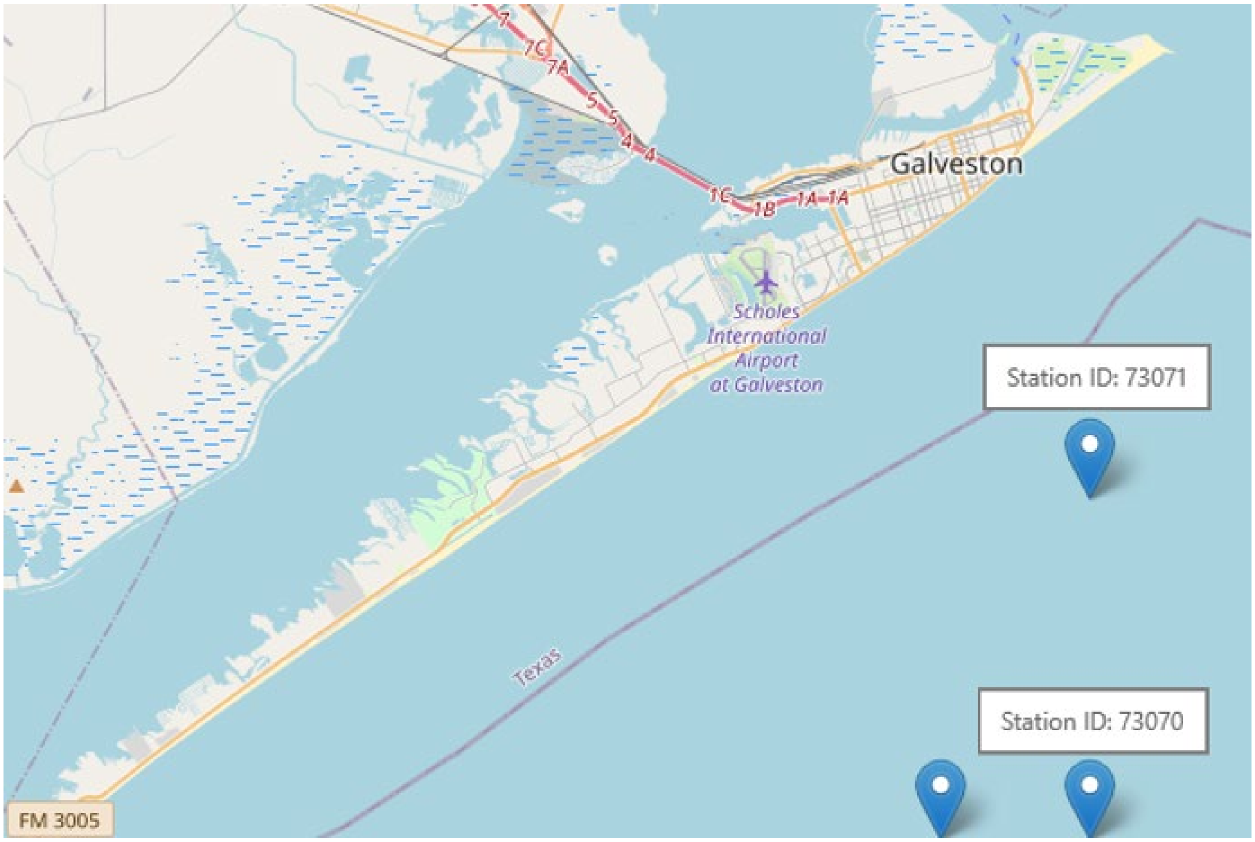

Figure 5: Location of USACE WIS Station 73071

The wind rose displayed in Figure 6 shows 34 years of hindcast data per Station 73071. The dominant wind direction for lower wind speeds (0-5 m/s and 5-10 m/s) comes predominantly from the southeast, while northerly winds tend to occur at lower frequency and higher magnitudes.

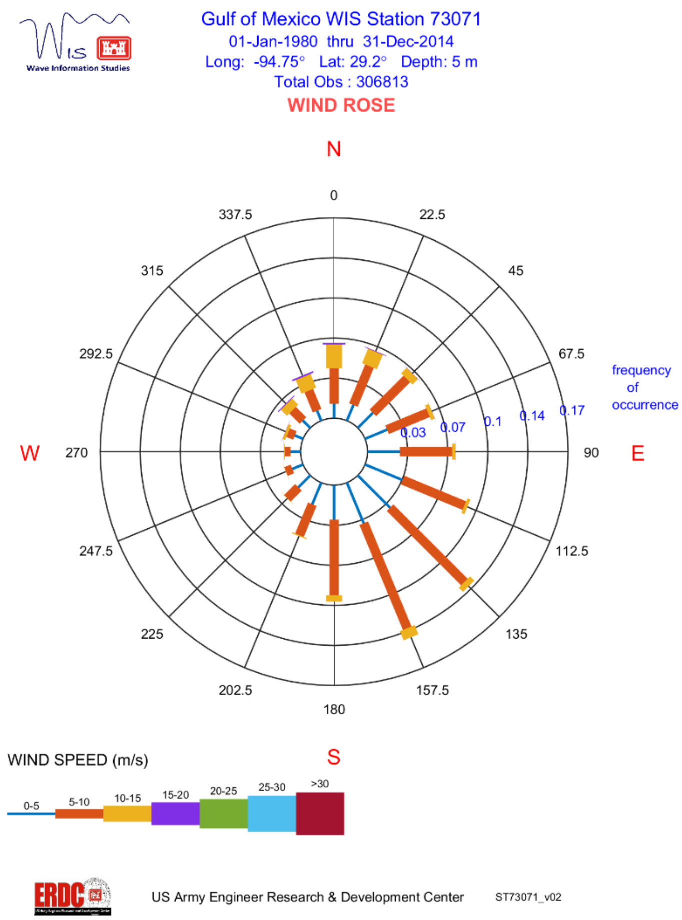

Figure 6: Wind Rose from WIS Station 73071; units are in meters per second

2.4 Waves

Predictably, the predominant wave direction is also from the southeast, according to the wave rose for WIS Station 73071 seen in Figure 7. The shore-normal direction for waves approaching Galveston Island is approximately 147 degrees azimuth, which is roughly midway between the two most frequent direction bins per the wave rose. For this reason, there is a fairly even split in the directional frequency of wave driven longshore currents. However, seasonal variations in wave magnitude and direction ultimately yield a net longshore transport direction to the southwest.

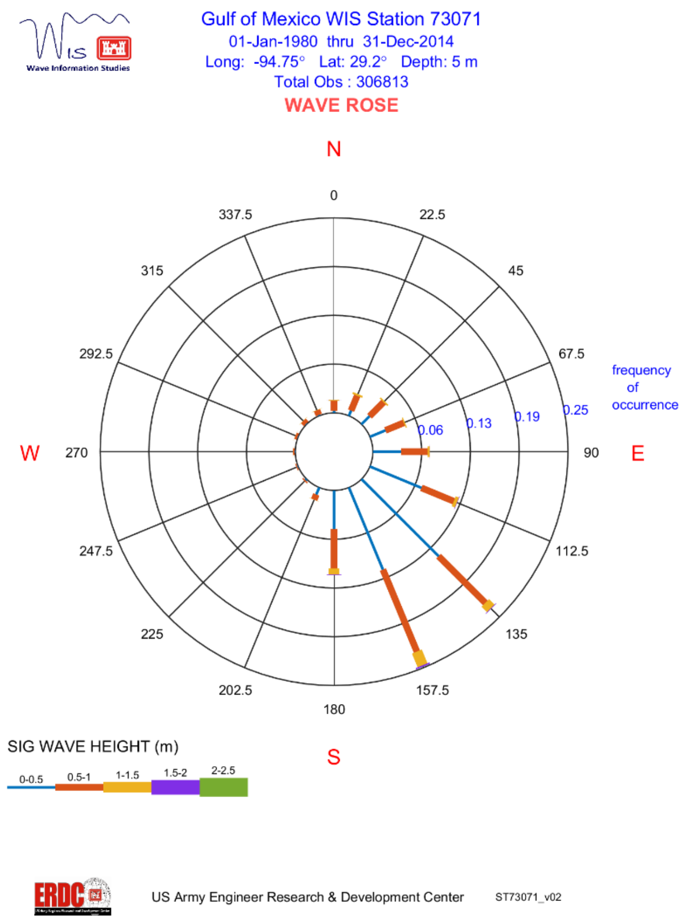

Figure 7: Wave Rose for USACE WIS Station 73071; units are in meters

2.5 Currents

Currents are affected by many different factors including wind, waves, thermohalines, tides, and the Coriolis effect. NOAA's Atlantic Oceanographic and Meteorological Laboratory records daily geostrophic current fields for the Gulf of Mexico. During non-summer months the current along Galveston moves in same direction as the net longshore current (southwest) at higher magnitudes than in summer months when it shifts to the opposite direction, as seen in Figure 8 and Figure 9, respectively (Johnson, 2008).

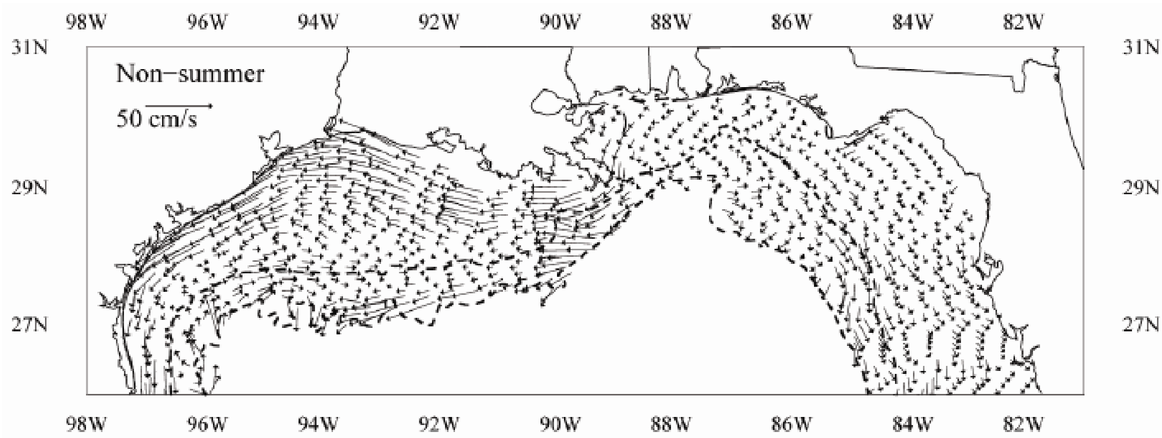

Figure 8: September-May Surface Current Climatology

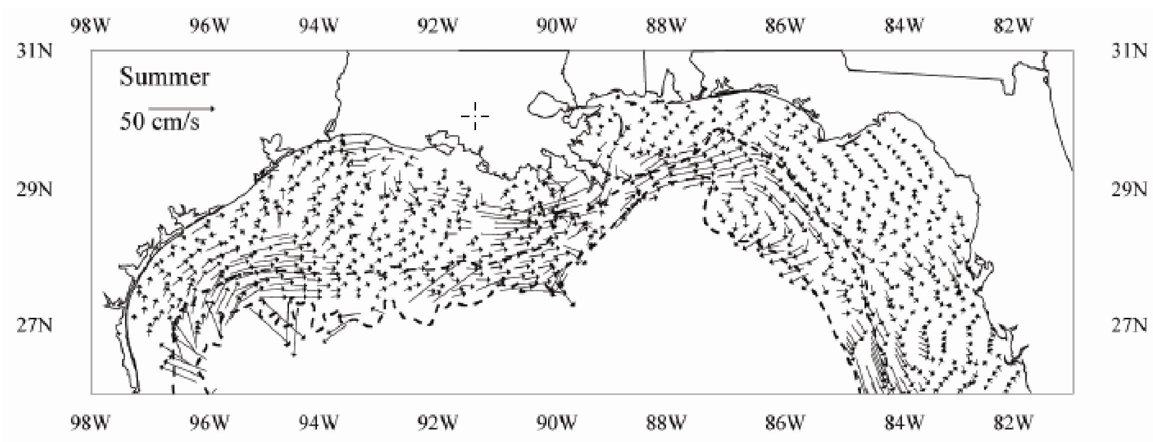

Figure 9: June-August Surface Current Climatology

2.6 Sediment & Morphology

2.6.1 Native Sediment Properties

Sediment samples from the Texas Coastal Sediment Geodatabase (TxSed), compiled by the Texas Government Land Office (TXGLO), were analyzed to review spatial variation, and estimate median grain size (D_{50}) of native sediment. A total of 42 samples with sieve data are identified along West Galveston (Figure 10), including 18 beach samples collected by HDR in 2003 and 22 nearshore samples collected by TAMUG in 2005, between depths of 14 and 26 feet (datum unverified) (HDR, 2003; TAMUG, 2005).

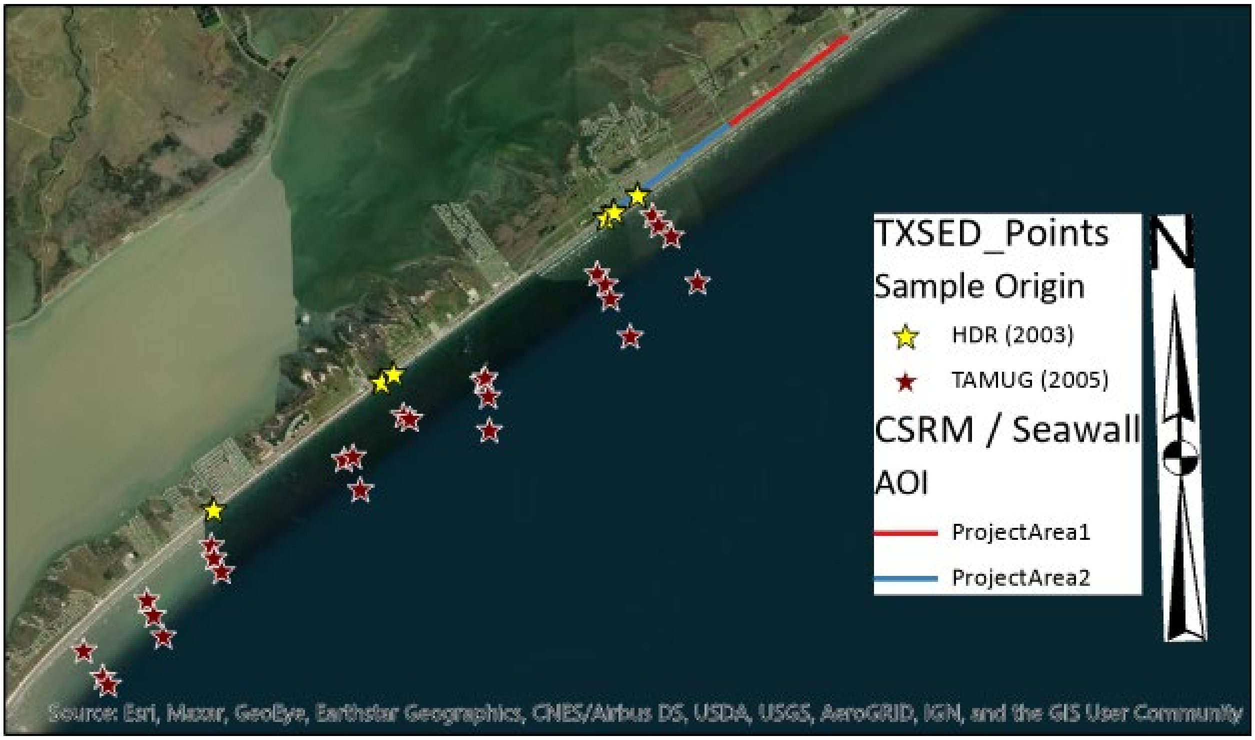

Figure 10: Effective sediment sample locations, mined from TxGLO's TxSed database

The data are manually recorded in Excel, reviewed for consistency, and particle size distribution curves are developed for each sample to evaluate gradation, estimate D_{50}, and review spatial variation. Table 3 summarizes D_{50} estimates, relative to depth and collection date.

Table 3: Median grain size estimates, values averaged according to depth

Sampled D_{50} Grain Size (mm) Relative to Depth					
Collected by:	TAMUG (2005)				HDR (2003)
Depth (ft):	> 25'	20' > x > 25'	15' > x > 10'	<= 15	Beach
D50 (mm):	0.075	0.103	0.104	0.100	0.156
Note:	Data accessed via <https://cgis.glo.texas.gov/txsed/index.html>				

The calculated average D_{50} is 0.156 mm for samples collected along the beach, while nearshore samples collected by TAMUG yield an average D_{50} at 0.094 mm.

Alongshore consistency is observed in sampled D_{50} values collected at similar depths and is assumed for the purposes of this study. Similarly, the particle size distribution curves consistently indicate poorly graded (well sorted) sediment at any given sample location. This is attributed to coastal processes that naturally distribute/sort sediment to varying distances/depths along the cross-shore profile. This natural sorting process is driven by the fall velocity of sand particles, which is largely controlled by the respective grain size. The coarsest sand is concentrated along the surf/swash zone of the beach, where samples are often collected, while finer sand is distributed seaward by waves/current, or landward to dunes via aeolian processes (Benedet, 2004).

According to beach equilibrium profile theory, discussed further in Section 3.4.3, the shape of existing cross-shore (depth of closure) profiles in the project area indicate a theoretical equivalent D_{50} range of 0.07 - 0.1 mm, in good agreement with TAMUG samples. It should be noted that many past studies have used a coarser D_{50}, consistent with samples collected on the beach, to represent the effective native fill. However, the portion of the active profile that consists of coarser material is relatively small. To represent the entire active profile and to maintain consistency with equilibrium profile concepts, the native beach is assigned an effective D_{50} = 0.09 mm.

2.6.2 Historic Erosion

The University of Texas BEG (Bureau of Economic Geology) reports shoreline change rates in Galveston that range from -5.1 to +24.9 meters per year (-16.7 to +81.7 ft/yr; negative indicating erosion/loss and positive indicating accretion/gain), and a net rate of +0.98 m/yr (+3.2 ft/yr) between the years 2000 and 2012 (Paine, 2014). Between 2000 and 2019 the updated change rates reportedly range from -2 to +11 meters per year (-6.6 to +36.1 ft/yr), and a net rate of +0.77 m/yr (+2.5 ft/yr), as seen in Figure 11 (Paine, 2020). Rates are not specifically reported for the period between 2012 and 2019, however min/max values reduced significantly between available periods indicating a stabilizing trend in recent history.

The BEG reports long-term (1930s-2019) historic retreat rates that range from -4.5 to -8 ft/yr (rounded) at the Project site (Paine, 2019). PA 1 long-term rates range from -7 to -8 ft/yr and PA 2 rates range from -4.5 to -7 ft/yr (west to east). Recent trends (2000-2019) show a reduction to shoreline retreat at the Project site, with rates that range from -3.5 to -5 ft/yr (rounded) (Paine, 2019). Interestingly, long-term historic alongshore trends (increased erosion from west to east) are not reflected in recent trends. Instead, peak retreat rates are somewhat sporadic with less consistency between transects and tend to exist in the western third of PA1, on the east side of Bermuda Beach.

Long-term erosion trends documented within the project area indicate that shoreline retreat rates generally increase with proximity to the erosional hotspot located at the end of the seawall. This has been mitigated partially due to regular nourishments that have occurred in recent history.

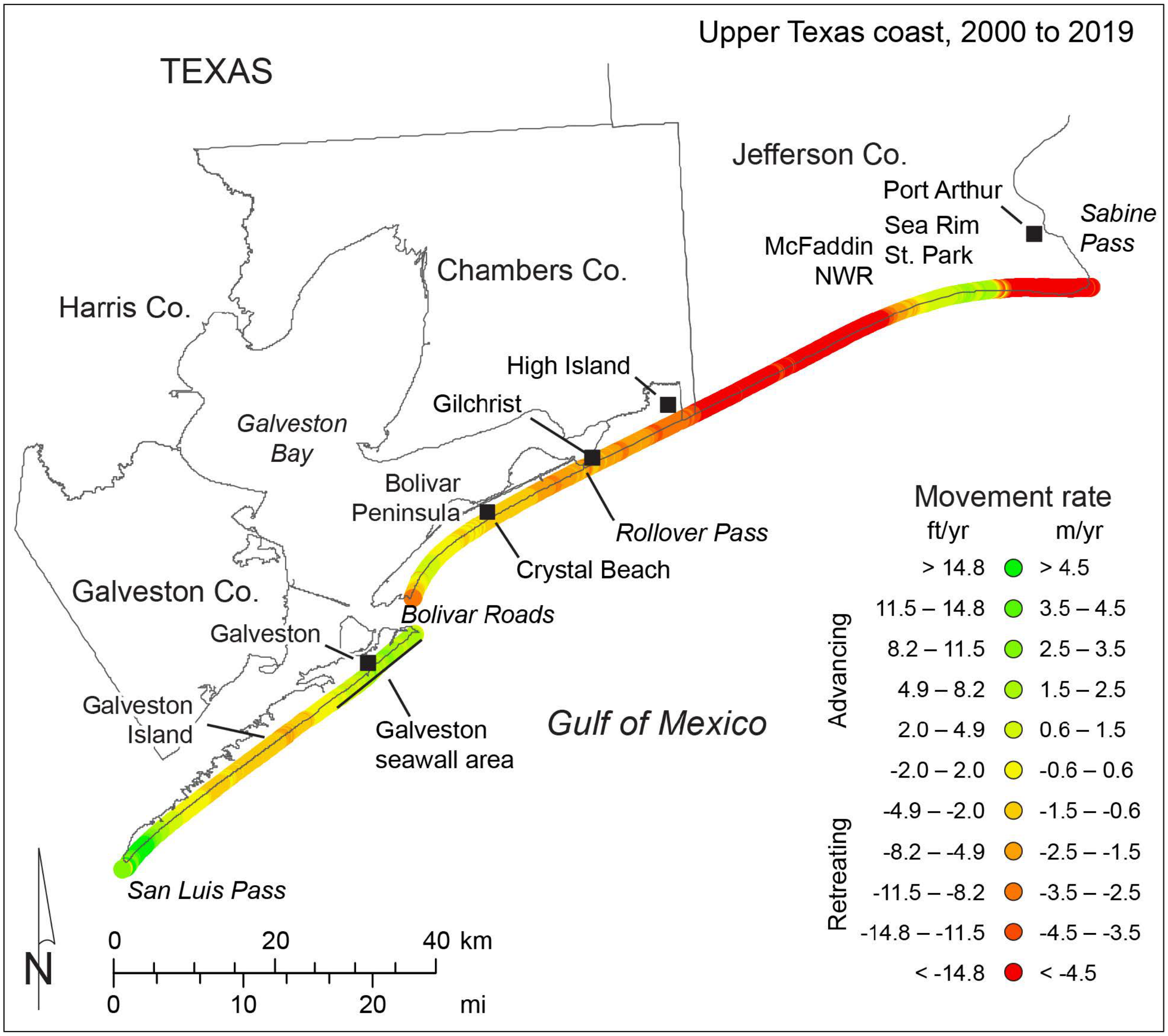

Figure 11: BEG shoreline change rates between 2000 and 2019 (Paine, 2020)

2.6.3 Recent Nourishment

Beach nourishment on Galveston Island has historically been in response to severe storm events. However, in recent history regular nourishments have been placed in front of the seawall, along Babe's Beach (61st street to west end of seawall). Recent nourishments are provided in Table 4, courtesy of the American Shore and Beach Preservation Association (ASBPA) nourishment database online.

Table 4: ASBPA Nourishment Records for Galveston Island

Galveston, TX Nourishment Events

Year	Length (ft)	Volume (cy)	Cost	Sand Source
2019	6,400	423,027	$20,900,000	Houston-Galv Nav Channel
2017	19,487	1,000,000	$16,746,500	Houston-Galv Nav Channel,South Jetty Borrow Area
2015	2,100	113,000	$5,000,000	
2015	4,980	629,188	$22,993,051	
2009	18,480	450,000	$6,000,000	East Beach, Steward Beach, Offshore
2008		42,000		Upland
2003	1,500	80,000		Big Reef borrow area
2001	1,310	13,300	$90,000	
2000	20,000	70,000		
1999	485	1,200		
1999	20,000	70,000		
1998	20,000	70,000		East Beach
1995	19,008	710,000	$5,900,000	Big Reef Shoal
1993	6,000	500,000		Galveston Ship Channel and Galveston Harbour
1985	1,456	14,989	$21,275	East Beach
Totals	**141,206**	**4,186,704**	**$77,650,826**	

3 Analysis of Alternative Solutions

Alternative solutions, described in Section 1.2, are evaluated in the sections that follow.

3.1 Topographic/Bathymetric Data

Available topographic/bathymetric shoreline surveys that were utilized for the purposes of this analysis are summarized in Table 5.

Table 5: Available topographic/bathymetric survey data utilized

Effective Date*	Source (see references)	Description
June, 2006	TAMUG, 2006	xyz transect data at 2-mile intervals, out to “DOC”
June, 2014	Atkins, 2014	wading depth survey – contours to “DOC”
May, 2015	Atkins, 2015	wading depth survey – beach contours
Sep., 2016	OCM Partners, 2021	CZMIL topobathy LiDAR to “DOC”
Sep., 2017	Atkins, 2017	wading depth survey – beach contours
Feb., 2018	Stratmap, 2018	LiDAR – beach only
Feb., 2019	NOAA, 2019	Leica Chiroptera II topobathy beach/nearshore

3.2 FWOP (Future Without Project) Alternative 1 – Projected Shoreline Change

Historic shoreline change rates track the annual evolution (feet per year) of the +4’ contour between 2014 and 2019, based on 15 cross-shore profiles, spaced at 1/3-mile intervals along the project area. Volumetric change rates (cubic yards per year) are similarly developed through transect comparisons, which are checked against GIS cut/fill operations using applicable DEM (digital elevation model) surfaces. Historically derived change rates are used to inform background erosion rates that are applied to FWOP and FWP (Future With Project) analyses for Alternatives 1-3.

Transects are labeled "PA1-15" (PA = project area) in chronological order from northeast to southwest. The domain of analysis is defined by the alongshore extent of the project area (totaling 4.84 miles measured in a straight line, or ~5.1 miles following shoreline curvature), and a cross-shore extent that spans from the CSRM (Coastal Storm Risk Management) line to the seaward extent of 2016 LiDAR, which is the limiting factor in 2014-2016 "depth of closure" survey overlap. Transects are intentionally aligned with available 2006 XYZ transects, which are used to extend the temporal domain of three transects (PA-2, -8 & -14) by extracting elevation data from 2014 to 2019 DEMs at each point. Initially the transects were divided into two reaches, as indicated by the red to blue color change of the CSRM line in Figure 12. However, the transects are eventually divided into three reaches (5 transects per reach) to conform with (1) morphological trends, and (2) the length of the recommended construction template (see Section 3.3.3).

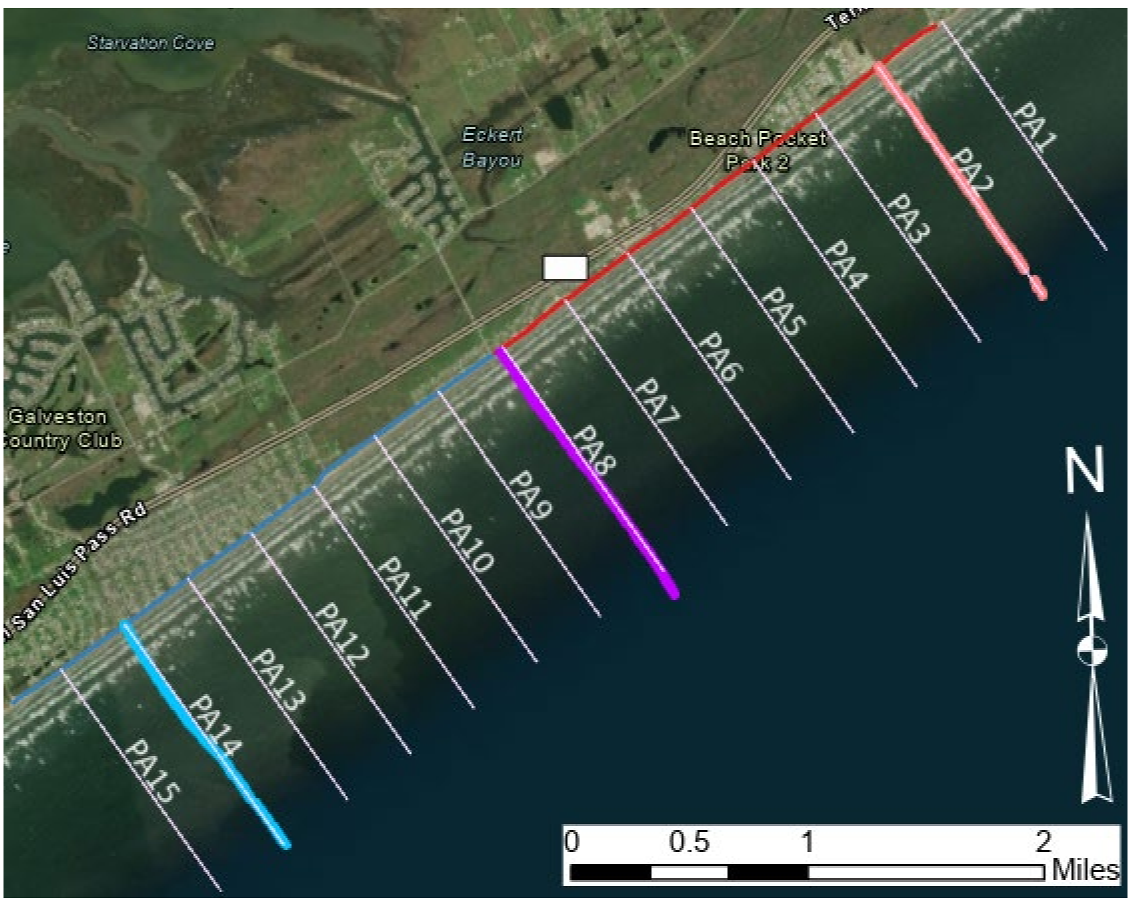

Figure 12: Plan view of transects in project domain

An example cross-section of transect (PA 7) is provided in Figure 13 and Figure 14, showing the approximate max offshore extent of available survey data, followed by a close-up of the beach profiles.

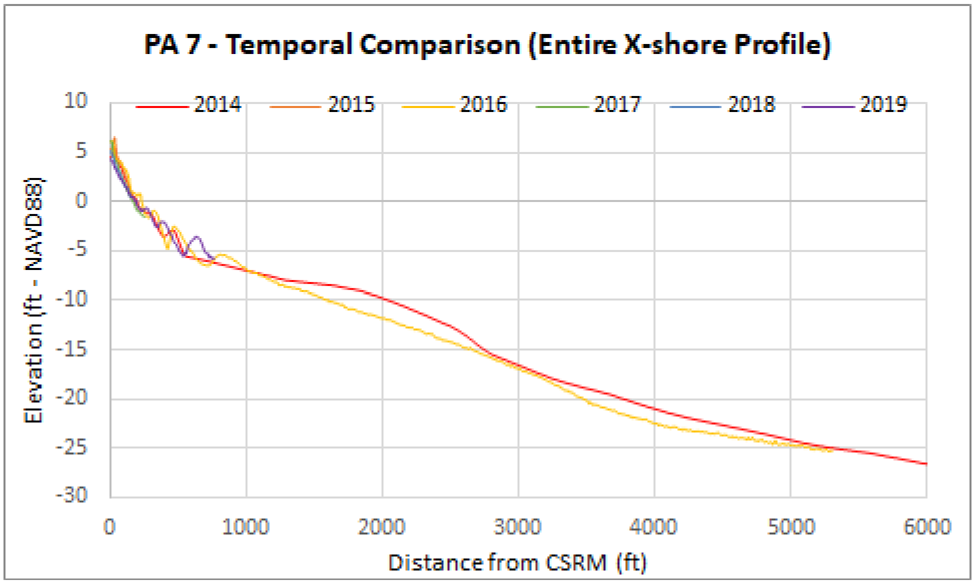

Figure 13: PA 7 evolution of active profile over survey years

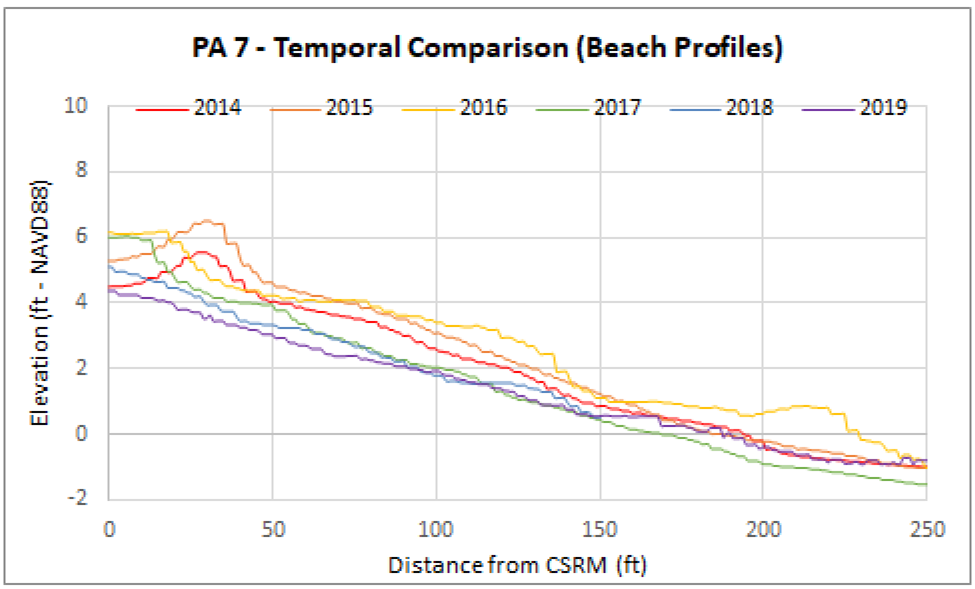

Figure 14: PA 7 evolution of beach profile over survey years

Temporal comparisons at each transect yield annual shoreline change rates (Table 6) in terms of (1) volume of sand accreted (+) or eroded (-) per linear foot alongshore, and (2) seaward advance (+) or landward retreat (-) of the +4' elevation contour, relative to the NAVD 88 datum; units are in cubic-yards per linear-foot per year (cyd/ft/yr), and feet per year (ft/yr), respectively.

Table 6: Summary of Historic Shoreline Change Analysis

	Shoreline Change (+ Advance / - Retreat)					Volumetric Change Rate (+ Accretion / - Erosion)						
	MHW Change Rate			4' Contour Change Rate		Transect Analysis					GIS Cut-Fill Analysis	
Transect Name	Net Change, 2014 to 2019	Max Advance	Max Retreat	Net Change, 2014 to 2019	Effective Rate	Beach (140' length)	Beach Max Accretion	Beach Max Erosion	Construction Template AOI (2014-2019)	DOC (2014-2016)	CT AOI (2014-2019)	DOC (2014-2016)
(NE to SW)	(lft/yr)	(lft/yr)	(lft/yr)	(lft/yr)	lft/yr	(cyd/lft/yr)	(cyd/lft/yr)	(cyd/lft/yr)	(cyd/lft/yr)	(cyd/lft/yr)	(cyd/lft/yr)	(cyd/lft/yr)
PA1	-0.27	13.94	-27.86	-1.39	-0.83	-0.33	2.82	-4.32	0.85	-139.93		
PA2	-3.67	43.07	-32.66	-1.36	-2.52	-0.13	1.32	-3.89	0.36	-86.28		
PA3	-0.92	29.38	-26.84	2.03	0.55	-0.07	3.81	-5.79	0.66	-52.13		
PA4	-2.15	28.30	-26.05	4.98	1.41	-0.17	2.71	-5.73	0.43	-103.72		
PA5	-3.81	9.58	-26.39	-5.35	-4.58	-1.23	0.89	-5.44	-1.01	-80.51		
Reach 1 Avg:	-2.16	24.85	-27.96	-0.22	-2.69	-0.39	2.31	-5.03	0.26	-92.51	-0.13	(85.42)
PA6	-3.79	13.89	-22.46	-0.19	-1.99	-0.83	2.24	-5.27	-0.39	-46.35		
PA7	-3.79	23.15	-26.81	-6.96	-5.37	-1.05	3.23	-5.28	-0.66	-65.03		
PA8	-3.45	40.47	-24.36	-6.30	-4.87	-1.05	0.93	-5.71	-1.19	-96.31		
PA9	-4.61	11.80	-37.90	-7.70	-6.16	-0.62	3.54	-4.98	-0.25	-85.11		
PA10	-2.72	27.64	-24.05	-7.61	-5.16	-0.45	1.69	-10.64	-0.97	-35.01		
Reach 2 Avg:	-3.67			-5.75	-5.75	-0.80	2.33	-6.38	-0.69	-65.56	-0.91	(60.53)
PA11	-4.31	12.93	-25.30	-4.58	-4.44	-1.04	2.59	-5.58	-0.66	-73.31		
PA12	-3.43	34.24	-25.62	-5.81	-4.62	-1.17	1.63	-5.99	-1.39	-92.56		
PA13	-3.74	19.75	-23.46	-5.64	-4.69	-1.10	0.93	-5.00	-1.36	-72.44		
PA14	-5.43	19.27	-26.07	-6.26	-5.85	-1.47	1.16	-6.42	-1.98	-72.11		
PA15	-4.81	14.54	-28.01	-5.39	-5.10	-0.70	4.14	-5.13	-0.78	-98.68		
Reach 3 Avg:	-4.34			-5.54	-5.54	-1.10	2.09	-5.62	-1.23	-81.82	-1.34	(75.54)
					TOTAL (CYD):	(20,506.6)	60,362.0	(152,905.6)	(14,944.7)	(2,039,319.6)	(21,291.7)	(1,882,870.6)
NOTE:	Reach 1 average change rate (ft/yr) show poor comparison to historic long-term rates, to remain conservative the effective rate is the arithmetic mean value of MHW & 4' contour historic retreat rates (negative) minus half a standard deviation; Reach 2 & 3 utilize mean retreat rates of the 4' elevation contour only											

The effective shoreline retreat rates, highlighted in green, inform FWOP results (Figure 15) and are the effective background erosion rates for FWP analyses (Section 3.3). Results yield shoreline retreat rates at -2.69 ft/yr, -5.75 ft/yr, and -5.54 ft/yr for Reaches 1, 2, and 3, respectively. Total retreat therefore ranges from approximately -40 to -86 feet over the 15-year period of analysis.

Reach 2 & 3 net rates are calculated as the distance between the position of the +4' (NAVD88) elevation contour at the end and beginning of the surveyed period, divided by elapsed time, which is then averaged amongst the five transects for each respective reach. The net rate for Reach 1 was calculated at -0.22 ft/yr using this method, which compares poorly with long-term rates in the region, reported at -7 to -8 ft/yr between 1930s and 2019 according to BEG studies (Paine, 2019). However, BEG also reports a significant reduction to the rate of retreat in this region in recent years according to 2019 updates, which report local rates closer to -4 to -5 ft/yr between 2000 and 2019 (Paine, 2019). The rates dropped notably upon the most recent update that accounted for the period between 2012 and 2019, which can be attributed largely to recent nourishments that have effectively reduced the rate of local erosion (see sections 2.6.2 & 2.6.3). It is anticipated that local nourishments will continue on a biannual basis into the near future, however, to build some conservatism into projections, the effective rate for Reach 1 is calculated using a different method than Reach 2 & 3. The Mean High Water Level net change rate is calculated at -2.16 ft/yr for Reach 1 (this accounts for intermediate sea level rise), which is averaged with the change rate of the +4' contour, then half of a standard deviation of the Reach 1 net change rates (for MHW and +4' contour) is added to reach the final value.

This method is intended to strike a balance between long-term and recent trends, under the assumption that regular nourishments will continue over the anticipated project life. Further, it is assumed that the relative magnitude and frequency of storms over the project life will be similar to conditions experienced over the duration of the monitoring period.

Annual volumetric losses calculated in the project area between 2014 and 2016 total approximately 2-million cubic-yards over the active profile, which equates to about 78 cyd/ft/yr. The volumetric rate of change is secondary to the advance/retreat rate, as it is not directly used in the economic analysis, however it does provide some valuable insights. For example, there is no apparent correlation between volumetric loss estimates calculated on the beach when compared to estimates over the entire (available) active profile, i.e. – beach change rates are not a good predictor for changes over the entire active profile in the same period of analysis. Similarly, when beach losses and "DOC" losses are normalized in terms of cubic-yards per square-foot per year, DOC losses are 5.5X higher than beach losses on average. This is indicative of a much larger active profile that is more dynamic offshore than is often suggested, however it is likely composed of much finer sediment than what is found on the beach according to sediment samples reviewed in section 2.6.1 and beach equilibrium profile theory concepts reviewed in section 3.3.3. Pilkey et al. (1993) provides supporting evidence, citing studies in the Gulf of Mexico that measured offshore bedstream currents of up to 200 cm/sec and large volumes of sediment transport to the edge of the continental shelf. Further, Pilkey notes that large volumes of sediment frequently move seaward of the DOC during both fairweather and storm conditions, though he does attribute large scale seaward flux to storm events.

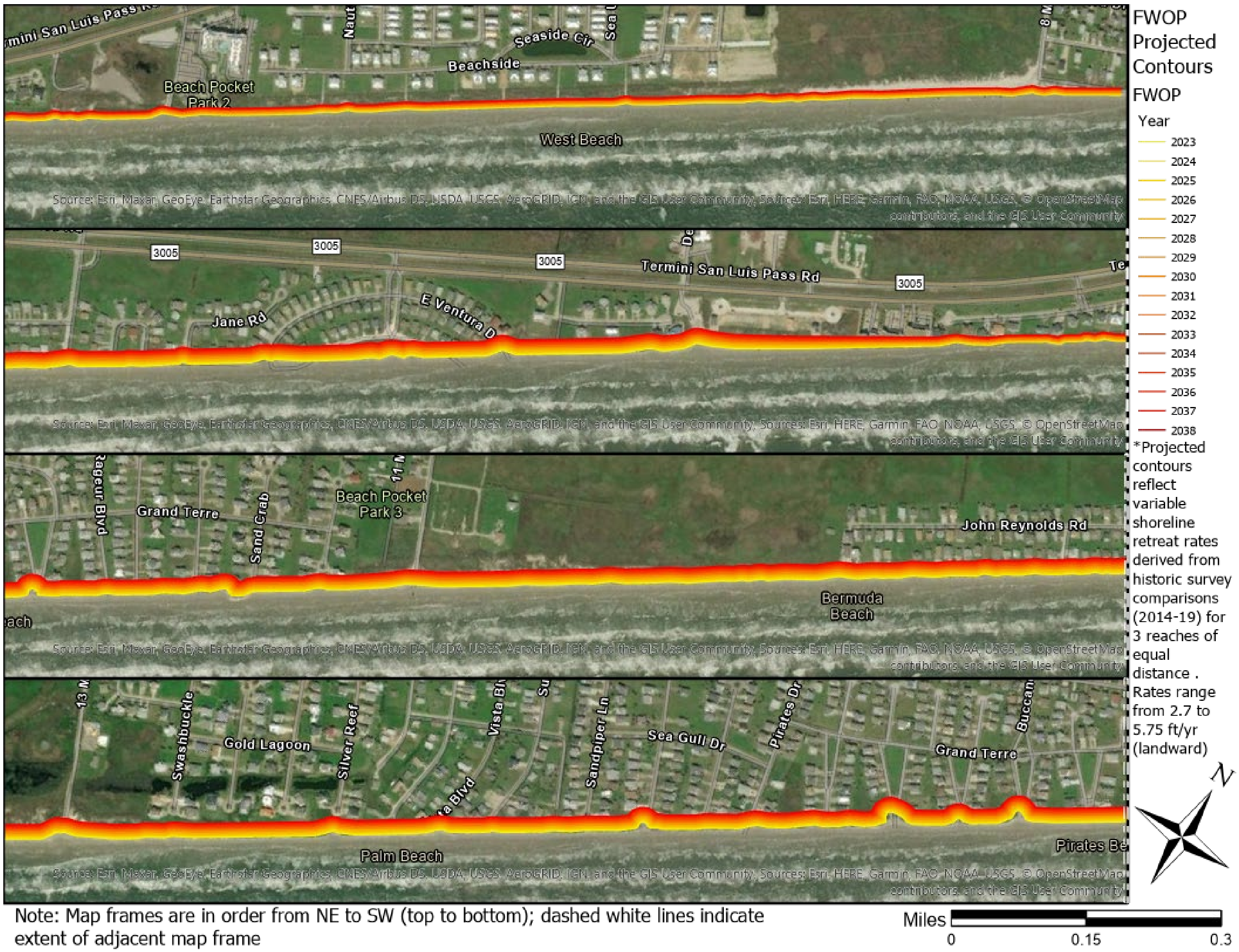

Figure 15: FWOP projected shoreline change in the project area from 2023 to 2038

3.3 FWP (Future with Project) Alternatives 2 & 3 – Beach Fill Design and Evolution

Alternatives 2 and 3 are beach nourishment alternatives that are differentiated only by their respective alongshore placement. The Alternative 2 location was developed by the PDT (project design team) based on NFS (non-federal sponsor) input. Results from the Alt. 2 analysis informed further collaboration amongst the PDT to inform Alternative 3 placement, which ultimately resulted in a 3000 ft shift southwest of the Alt. 2 template to extend benefits further into the Pirates Beach community. Details of the analysis, and results, are provided in sections that follow.

3.3.1 Design Berm Considerations

All shoreline change (retreat/advance) projections are based on the +4' NAVD88 contour unless otherwise stated. This elevation is selected for consistency with the design berm elevation. The significance of the +4' (NAVD88) elevation contour is multifaceted, and is selected according to the following list of considerations:

1. The contour coincides with the approximate (landward) limit of wave runup during typical conditions according to observation of aerial imagery.
    a. The wet/dry interface selected by BEG for 2019 updates is +3.84' NAVD88. If intermediate SLC is accounted for, the equivalent WSE in 2023 (assumed construction year) is +3.96' NAVD88 (Paine, 2019).
2. The 1-year AEP total WSE (still water elevation + intermediate sea level rise + 2% wave runup) is calculated at +4.6' NAVD88, according to Stockdon & MASE (with Melby modification) runup calculations (Melby, 2012).
    a. Structures located proximal to this elevation contour have historically been subjected to "buy-backs". This is likely because such structures are at immediate risk of exposure to surge and waves during high frequency storms (1 to 5-year AEP storms).
    b. Exposure to such events is unlikely to yield instantaneous failure of a properly constructed coastal structure, however it will rapidly evolve into an impractical liability to the local environment and surrounding structures. Without intervention, the structure will exacerbate local erosion (due to scour) and will eventually fail in the event of a more severe storm, elevating risk to nearby structures due to debris. Further, there is no obvious path towards intervention at this point since the structure is presumably in the immediate path of the natural dune/vegetation alignment, likely inhibiting construction of a uniform and contiguous system.
3. It is located seaward of the CSRM (Coastal Storm Risk Management) line for most of the project length, which was established as the landward construction limit for the purposes of the Coastal Texas Feasibility Study.
    a. It is important to note that the tentatively selected plan (TSP) from the Coastal Texas Feasibility Study includes the construction of dunes, which must not extend landward of the CSRM line. Assuming the plan is ultimately pursued,

the construction date will not likely occur until 10+ years from today. The establishment of dunes is key to mitigating the flood hazard posed by coastal storm surge, as well as to the long term the health of the beach. Well established dunes are fortified with vegetation that promotes aeolian (wind-blown) sand capture and ultimately provide a less-ephemeral, natural defense system against severe storm surge and waves.

b. The resilience of the dune system relies on a large enough beach/berm buffer to minimize the frequency of exposure to waves. This is particularly true of unvegetated dunes; however, vegetation tends to take several years to establish, leaving dunes vulnerable in the interim (USACE, 2008, V-4-3-2c).

c. Given these considerations, and assuming no change to the CSRM line, it seems imperative to the success of projects like Coastal Texas for regular nourishments to continue into the foreseeable future. Otherwise, continued shoreline recession and sea level rise will place the CSRM line at lower elevation and in closer proximity to the Gulf. This would introduce significant construction challenges, cost, and risk, particularly to dune construction projects such as the Coastal Texas TSP.

4. It is immediately adjacent and seaward of the vegetation line, allowing for beach fill construction to avoid disturbance of established vegetation.

5. The elevation roughly matches the design berm elevation of past nourishment projects.

3.3.2 Depth of Closure

The depth of closure (DOC) is intended to define the seaward limit of the active profile, which is the theoretical cross-shore extent of sediment movement, beyond which elevation changes are thought to be negligible. Guidance and wave data from the Coastal Inlets Research Program (CIRP) are utilized to calculate the depth of closure. Wave data, hindcast from 1980 to 2012, originates from local WIS stations 73070 & 73071 (see Figure 5). The data are shoaled by CIRP to a uniform depth of 30 feet for all GOM (Gulf of Mexico) WIS stations, unless already located in shallower water (Brutsche, 2015). Station data are used to calculate the DOC with equations developed by Hallermeier (1981) and Birkemeier (1985). Results are converted from metric units and averaged across stations for three total values.

(Hallermeier, 1981) $$h_{*inner} = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right)$$ *Eq. 1*

(Hallermeier, 1981) $$h_{*outer} = (\overline{H}_s - 0.3\sigma_s)\overline{T}_s\left(\frac{g}{5000D}\right)^{0.5}$$ *Eq. 2*

(Birkemeier, 1985) $$h_* = 1.57H_e$$ *Eq. 3*

where, $$H_e = \overline{H}_s + 5.6\sigma_s$$

The three methods yielded average values of 16 ft, 41 ft, and 11 ft (rounded), respectively. Values calculated with Hallermeier's equations (16 ft & 41 ft) represent an inner DOC and outer DOC, respectively. The respective depths define the seaward limits of the littoral zone, and the less dynamic shoal zone. Hallermeier's values show good comparison with historical surveys and are adopted for the purposes of this study. The inner DOC is utilized for longshore diffusivity calculations in Section 3.3.4. The outer DOC is applied to beach equilibrium concepts; however, it is limited by the extent of available, overlapping survey, which extends to an approximate elevation of -25.5 feet (NAVD88). The limiting elevation ultimately has negligible impact on the analysis as a result of intersecting profiles that occur due to assumed differences in native and borrow fill characteristics, discussed further in Section 3.3.3.

3.3.3 Beach Equilibrium – Cross-shore Spreading Component

The cross-shore elevation profile shape of a given shoreline is largely controlled by its sediment composition and associated grain size. Empirically derived formulas predict beach equilibrium shape from a profile shape parameter (A-parameter), that is directly correlated to the D_{50} grain size. The shape of a submerged profile can be calculated based on the characteristic D_{50} grain size with Equation 4 (EM 1110-2-1100, Equation IV-3-7).

$$h = Ay^{2/3} \qquad \textit{Eq. 4}$$

where

$$\mathrm{h} = \text{water depth at a distance } (\mathrm{y}) \text{ from the shoreline}$$
$$\mathrm{A} = \text{a scale parameter based on sediment particle size}$$

The median grain size associated with an active profile can be used to develop a theoretical equilibrium profile with the equation above. Similarly, the concept can be used to fit an equivalent grain size to an existing beach profile, or to modify a design profile based on differences between native and borrow fill D_{50} parameters according to guidance from EM 1110-2-1100 Part V. The added distance of translation W_{add} (V-4-5) is used to modify the design profile as a function of depth (y) based on the sediment characteristics of the native and borrow fill with Equation 5 (EM 1110-2-1100, Equation V-4-5).

$$W_{add}(y) = y^{3/2}\left[\left(\frac{1}{A_F}\right)^{3/2} - \left(\frac{1}{A_N}\right)^{3/2}\right] \qquad \textit{Eq. 5}$$

Where A_N is the A-parameter associated with native sand and A_F is the A-parameter for fill/borrow sand. The added distance is positive (seaward) if borrow material is finer than native sand, resulting in increased cross-shore spreading and a more gradual design profile slope. Borrow material that is coarser than native sediment results in a negative (landward) "added distance" yielding a steeper design slope that intersects the native shoreface. The latter theoretically requires less fill to achieve the same added beach width.

Native beach samples collected by TAMUG in 2005 yield a D_{50} of 0.094 mm (see section 2.6.1). The theoretical D_{50} is estimated from the representative (averaged) existing profile in BMAP (Beach Morphology Analysis Package) with the least square method yielding a theoretical D_{50}=0.09 mm, as seen in Figure 16.

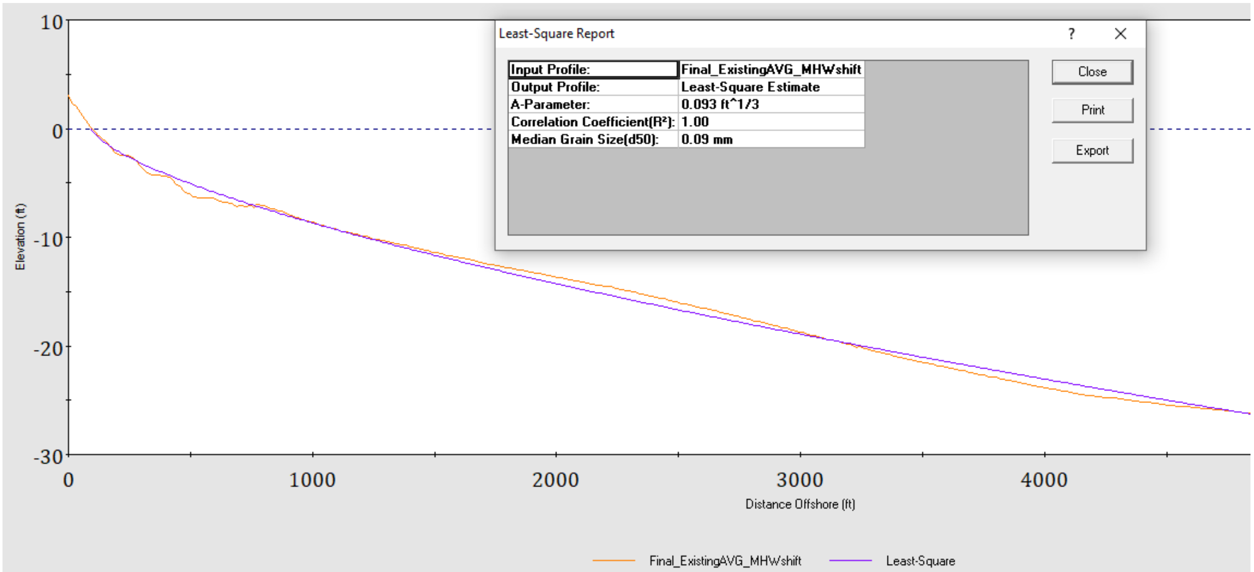

Figure 16: Screenshot of BMAP least square estimate results, which yield an equivalent D50 of 0.09mm; profile is translated vertically such that MHW=0 to capture entire submerged profile

The borrow fill D_{50} is estimated based on 2016 Galveston entrance (ship) channel samples, which indicate significant variation in the overall gradation/distribution throughout the channel. There is no obvious way to generate an appropriately weighted average from available borrow fill samples, however given the nature of "added width" concepts, a conservative approach is taken by eliminating the coarsest outlier, then attempting to weight the remaining samples spatially based on the indicated channel station. The assumed borrow and native material sediment sizes are summarized in Table 7.

Table 7: Effective D50 and A-parameter for native material and borrow fill

Sediment Parameters	D_{50} (mm)	A (ft^1/3)
Borrow Fill	0.11	0.1
Native Beach	0.09	0.087

The existing representative profile is developed in BMAP by averaging 2019 profiles (minus two outliers), which are then combined with the averaged 2016 profiles to extend seaward coverage to the effective DOC. The averaged 2016 profile is translated landward to tie into the end elevation of the 2019 profile to create the representative existing profile.

Next the design profiles are developed based on the design berm height established in section 3.3.1 (+4' NAVD88), beach equilibrium profile concepts, past construction template dimensions, and an assumed volumetric range of available borrow fill. The anticipated volume of suitable borrow material for beneficial use is between 490K cubic yards and 630K cubic yards, based on 2019 and 2015 placement records, respectively. Design profiles consist of (1) the translated profile, (2) the anticipated design profile, and (3) the construction template. The translated profile is developed by clipping the portion of the existing profile that extends seaward of the design berm elevation, then translating it by the design berm width. Differences in borrow fill and native beach characteristics then inform the added width correction to yield the anticipated design profile. The construction template defines the general shape, dimensions, and elevations of a proposed beach fill design for construction purposes. It must have a berm elevation and volume equivalent to the anticipated design profile, which requires an iterative design process between the two. The existing and design profiles are provided in Figure 17.

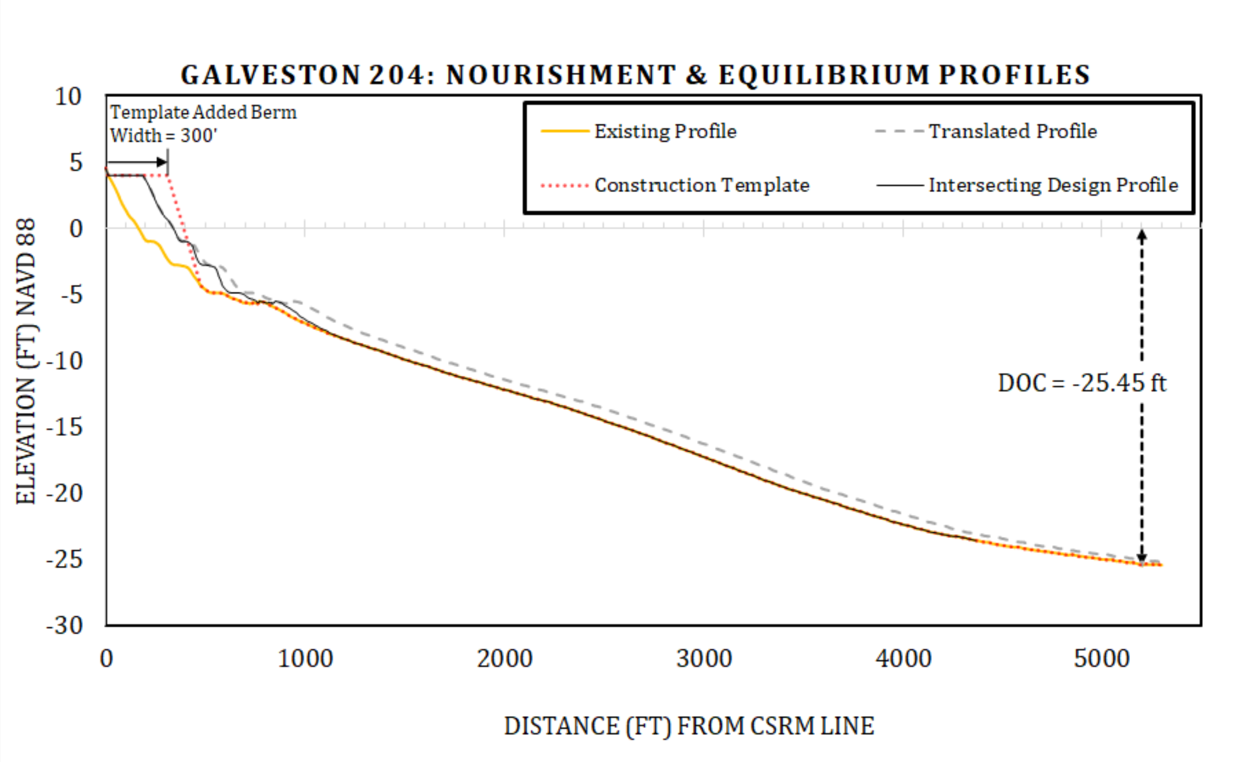

Figure 17: Existing and design profiles based on beach equilibrium concepts

The construction template dimensions include a 300' added berm width, followed by a 1:20 slope to tie into the existing profile. A three-dimensional version (DEM) of this template is created in GIS, extending the entire length of the project area, which is used to determine total fill requirements by comparing the construction template DEM with the 2019 DEM, using GIS cut/fill operations. The calculations revealed that approximately 1/3 of the total project length could be covered by 530K cubic-yards of fill material, which is on the lower end of the range of anticipated borrow fill. The project length is then split into three reaches of equal length and the cut/fill analysis is run again to confirm uniformity of fill requirements. By comparing volume requirements with the construction template (530K cyd or 59 cyd/ft), the equivalent design profile added berm width, after cross-shore equilibration, is determined to be 175 feet.

3.3.4 Longshore Diffusion – Alongshore Spreading Component

The Pelnard-Considere equation, or P-C equation, is solved analytically to determine the planform evolution of a beachfill.

$$(\text{Pelnard} - \text{Considere}, 1956) \qquad \frac{dy}{dt} \cong G\frac{d^2y}{dx^2} \qquad \textit{Eq. 6}$$

Where y is the cross-shore direction, x is the alongshore direction, and t is time. Longshore diffusivity, represented by parameter G, is calculated as follows:

$$G = \frac{2C'H_b^{5/2}\cos 2\theta_b}{(h_* + B)} \qquad \textit{Eq. 7}$$

$$C' = \frac{K\sqrt{g/\delta_b}}{8(S-1)(1-p)} \qquad \textit{Eq. 8}$$

Where H_b is the breaking wave height, θ_b is the breaking wave angle relative to shore normal, h_* is the depth of closure, B is the berm height, K is the sediment transportation coefficient, g is acceleration of gravity, δ_b is the breaking wave index, S is specific gravity of sand, and p is porosity of sand. The inner DOC ($h_* = 16ft$; see Section 3.4.2) is utilized, as it defines the littoral zone (Hallermeier, 1981; Brutsche, 2015).

There are multiple solutions to the Pelnard-Considere (P-C) equation, depending on the shape of fill, and the presence of groins or inlets. The rectangular beach fill solution was selected instead of the trapezoidal fill solution (despite the trapezoidal planform shape of the construction template) for simplicity and to remain conservative. The trapezoidal fill solution results in a reduction to end losses, hence the conservatism, and it complicates the process used to (1) add background erosion, and (2) correlate the P-C solution with background erosion to XY coordinates for GIS representation (see Section 3.4.5). Other solutions were considered, but ultimately eliminated under the assumption that the project area is located sufficiently far from groins and inlets, such that their impact is negligible on the beachfill evolution.

The solution for a rectangular beachfill project on a long straight beach is seen in Equation 9.

$$y(x,t) = \frac{Y}{2}\left\{ \begin{array}{l} erf\left[\frac{l}{4\sqrt{Gt}}\left(\frac{2x}{l}+1\right)\right] \\ -erf\left[\frac{l}{4\sqrt{Gt}}\left(\frac{2x}{l}-1\right)\right] \end{array} \right\} \qquad \textit{Eq. 9}$$

Where l is the alongshore length of beach fill, Y is the cross-shore width, and t is time in years. The cross-shore added berm width, Y, of the design profile (Y = 175 ft) is used, rather than the construction template berm width, under the assumption that all cross-shore flux occurs immediately and prior to longshore diffusion (Work, 1997).

3.3.5 Results – Beach Fill Longevity / Berm Evolution – (explanation of results)

Results in Figure 18 and Figure 19 show the planform evolution of the beachfill Alternatives 2 & 3, respectively. The planform construction template is indicated by the tan polygon. Shoreline change projections, represented by the group of lines with violet to yellow color progression, show the estimated movement of the +4' (NAVD88) contour, projected annually from 2023 to 2048. The FWP analysis period is extended 10-years beyond the original FWOP period of analysis to accommodate the framework of the economic analysis and calculate FWP benefits that extend beyond the FWOP period of analysis. The shoreline change curves account for cross-shore equilibration of the construction template profile, statistically derived background erosion, and longshore diffusion of each beachfill alternative.

The one-line shoreline retreat results compare well with volumetric loss projections, indicating losses inside the original placement area (construction template) at over half of the original beach fill in year one, approximately 80% by year 5, and 100% loss between years 8 and 10. This is fairly consistent between each alternative, with minor differences due to varying background erosion rates. The results will inform the economic analysis, which will also account for benefits that result from longshore diffusion along the project area. Based on these results, a 5-year (maximum) renourishment period is recommended, which coincides with 20% retained fill. This recommended nourishment interval does not address episodic erosion due to storms in between nourishment intervals.

Further, and arguably more importantly, continued monitoring (survey) is strongly recommended. Analytical methods utilized for the purposes of estimating longshore diffusivity and cross-shore equilibration are limited in real-world applications. While statistically derived background erosion rates mitigate some uncertainty inherent in the analytical solutions, analytical projections which form the basis of design here should not be considered representative of actual shoreline evolution. Additional discussion on assumptions and recommendations is provided in Section 4.2.

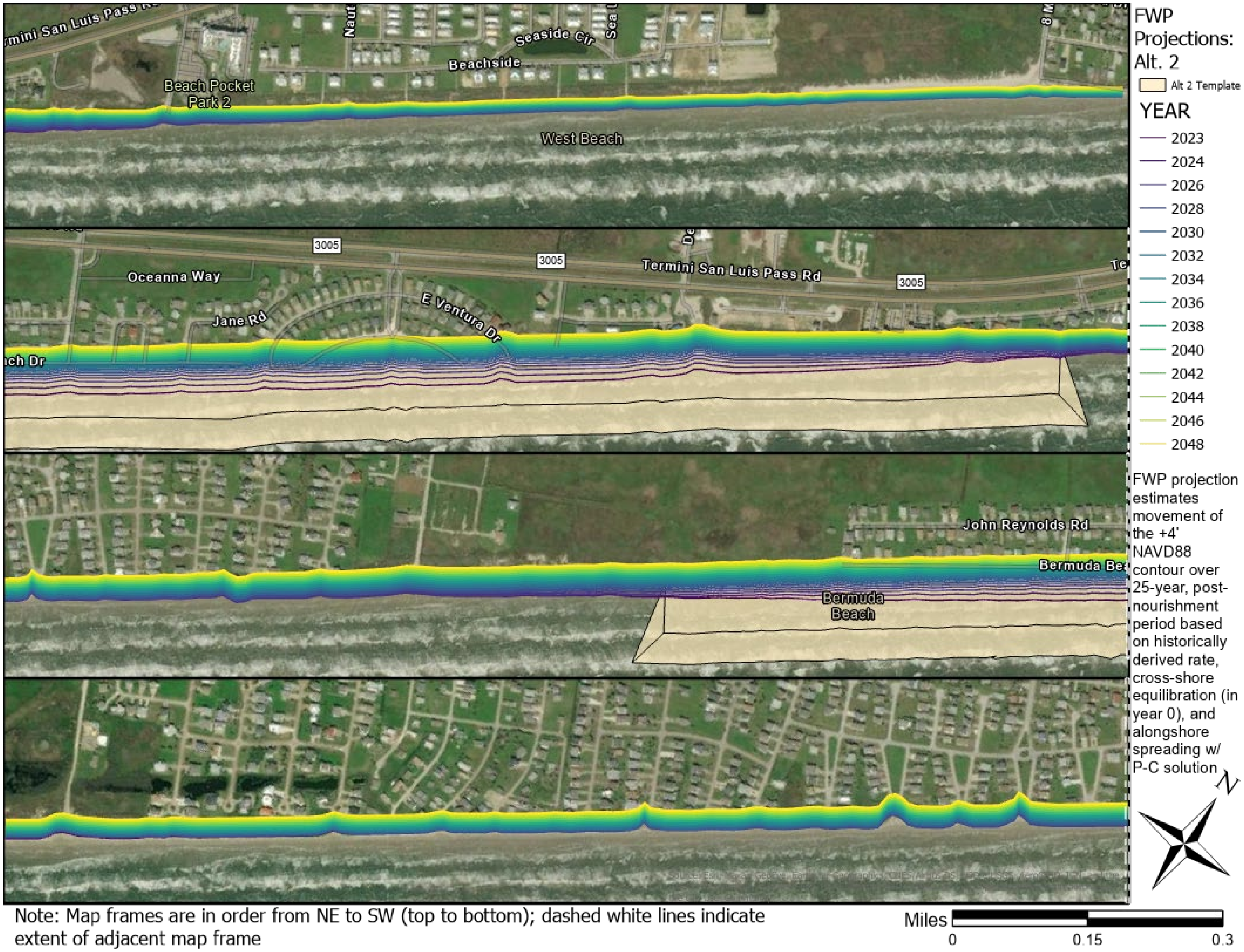

Figure 18: FWP Alternative 2 results; construction template polygon & projected shoreline change shown with violet to yellow line group

Note: Map frames are in order from NE to SW (top to bottom); dashed white lines indicate extent of adjacent map frame

Miles 0 0.15 0.3

Figure 19:FWP Alternative 3 results construction template polygon & projected shoreline change shown with violet to yellow line group

3.4 FWP Alternatives 4 & 5 – Seawall Extension

Alternatives 4 & 5 call for extension of the seawall from the existing southwestern termination point. The alternatives are differentiated only by the total extended length. Alternative 5 extends the seawall approximately 5.8 miles to the southwestern extent of the project area, while Alternative 4 extends 3.3 miles to the approximate midway point. A plan view of Alternative 4 & 5 (with overlapping footprints) is provided in Figure 20.

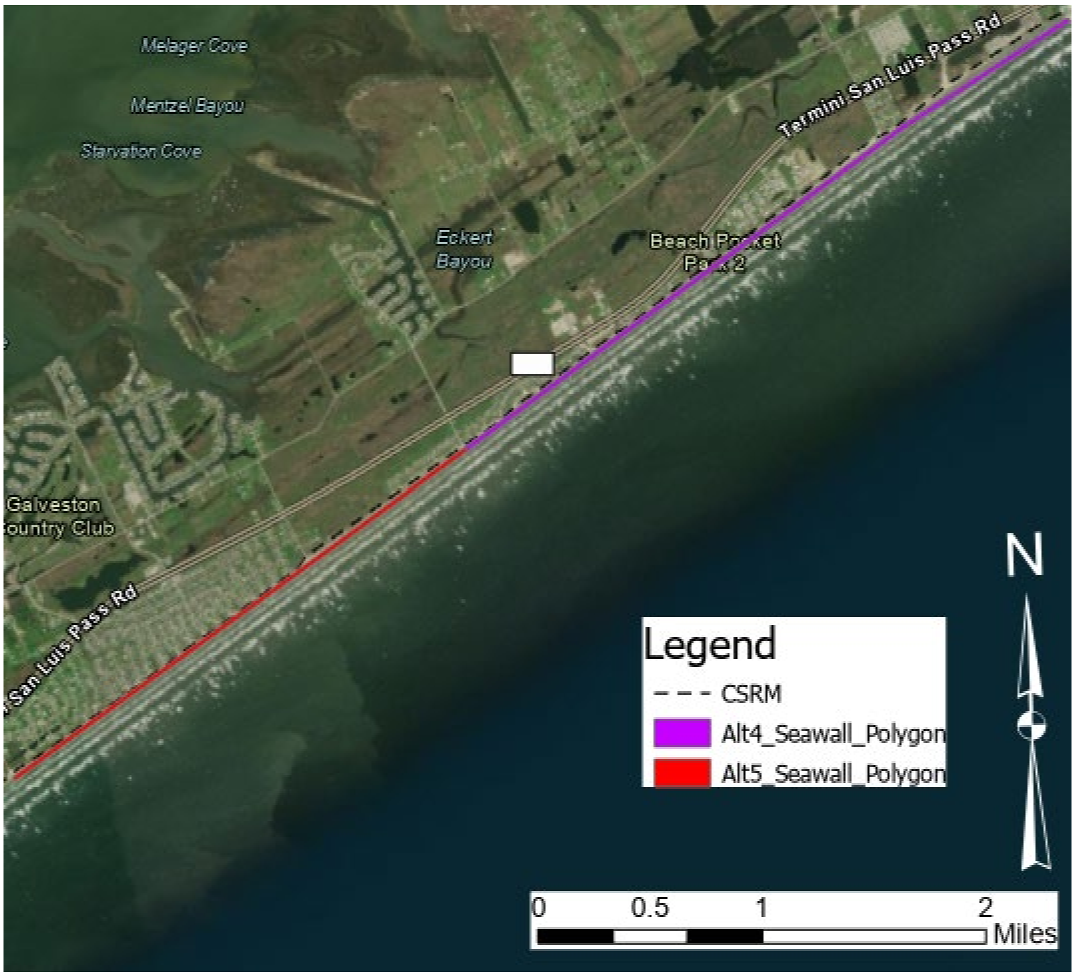

Figure 20: Plan view of Alternative 4 & 5 concepts

To evaluate feasibility of these alternatives in detail would require a large-scale, multidisciplinary, and multifaceted analyses, which is unwarranted based on the project scope. Instead, a brief qualitative overview of the design requirements and considerations is provided to screen the alternatives.

As-built drawings developed by the USACE Galveston District in 2009 show new construction and repairs made to the seawall following damages that were incurred by Hurricane Ike in 2008. On the west end, new construction included the replacement of the western ~270 ft span and a ~200 ft landward return with cutoff walls (steel sheet piling) to mitigate scour damage from flanking.

A plan view and cross-sectional view of the new seawall construction are provided in Figure 21 and Figure 22.

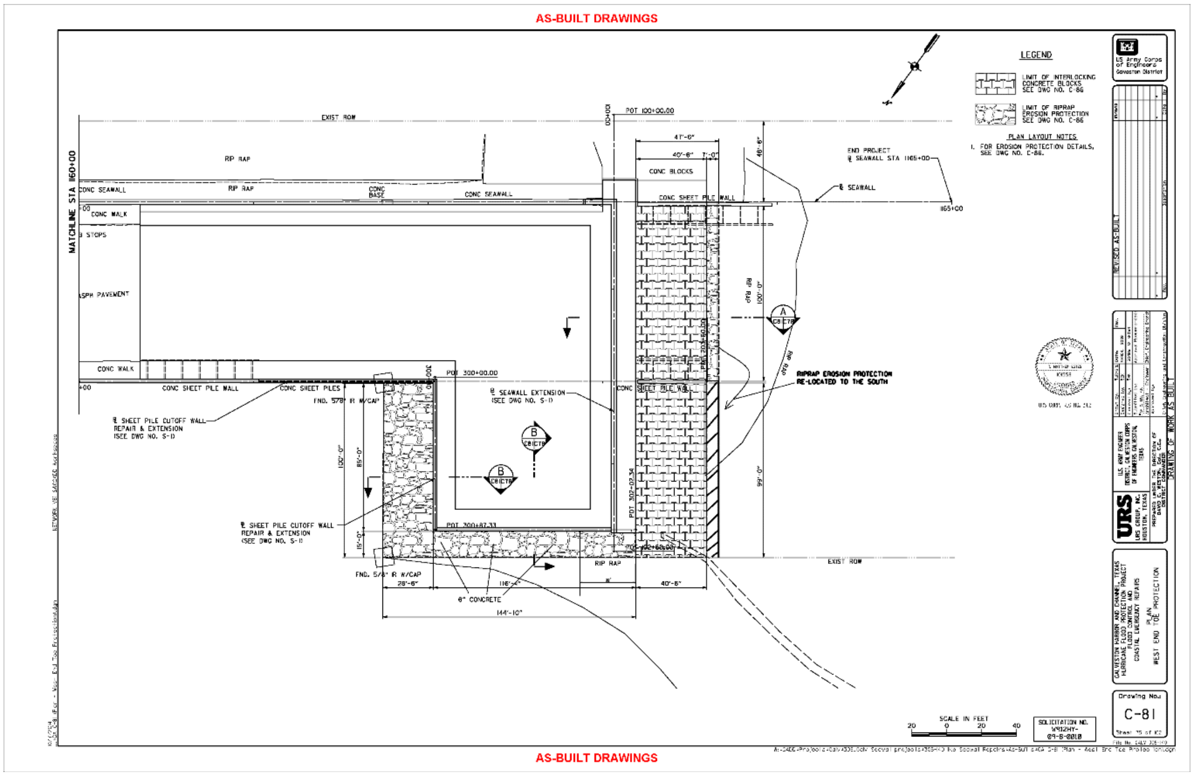

Figure 21: West end seawall construction, plan view of toe protection (USACE-SWG, 2009)

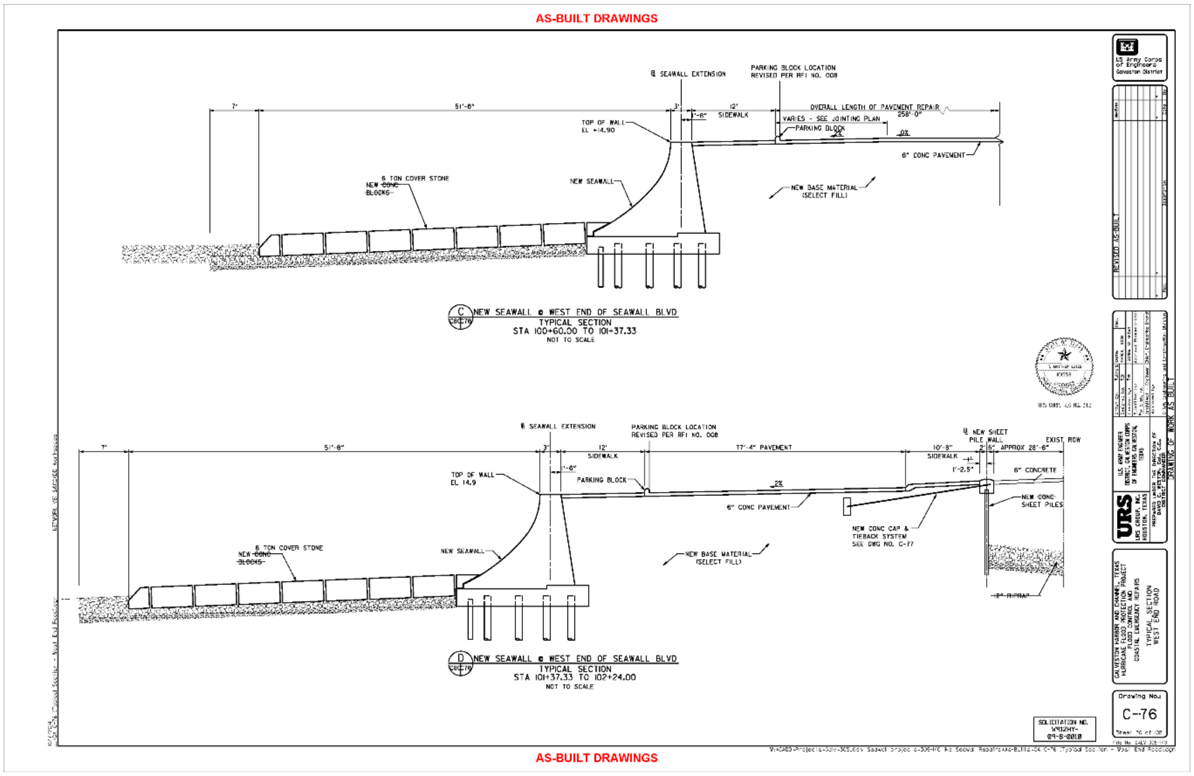

Figure 22: XS of new seawall construction on West End per March 2009 As-Built Drawings; Drawing No. C-76 (USACE-SWG 2009)

The drawings indicate a top of seawall elevation at +14.9 ft (NAVD88), with a total pavement top width at ~100 ft (as depicted by Figure 20 polygons). In ArcGIS the Surface Volume tool is used to estimate the fill volume required by each alternative, as defined by their respective polygon boundaries, the +14.9 ft elevation plane and the 2019 DEM. According to GIS calculations, Alternative 4 and 5 require 1.46M and 0.86M cubic yards of fill, respectively. This does not account for the fill that would be required both landward and seaward of the prospective alternatives, nor does it account for the actual seawall concrete volume or other materials.

The required fill exceeds the anticipated volume of borrow fill, which may alone be enough to consider the prospective alternatives infeasible. However, even if the significant environmental and economic challenges were to be addressed, the seawall extension alternatives are still faced with a host of challenges that would be impractical to overcome, as summarized in the bulleted list below:

- **Scour** – If waves can reach the seawall, its presence will induce scour, exacerbating local erosion. Ultimately large armor stone (and associated maintenance) will be required to prevent the wall from being undermined.

- **Fill** – In addition to the previously mentioned considerations, a seawall alternative does not alleviate the need for beach nourishments. On the contrary, it increases reliance/dependence on continued nourishments and cuts off a cross-shore sediment source. The longevity of a seawall alternative is dependent upon a seaward beach, which acts as a buffer limiting the frequency and duration of exposure to waves. In other words, alternative 4/5 can not be considered without considerably more beach fill than what is anticipated for alternative 2/3.

- **Public perception** – Residential areas behind the seawall would benefit from additional protection against storm surge and coastal erosion, relative to other alternatives. However, these areas may also face beach access challenges, a diminished view of the Gulf, and a reduction to the overall beach width if regular nourishments are not conducted. Further, adjacent shorelines to the southwest would likely see accelerated erosion as a result.

The project area is at higher risk of damages from storm surge than most of the island. As such, it is not unreasonable to consider more robust solutions to potentially mitigate that risk. However, this would need to be part of a larger study effort that lends consideration to comparable alternatives for that level of risk mitigation. For example, an offshore breakwater (or series of breakwaters) is a more economically comparable hardened structure that alleviates some of the drawbacks of a seawall. Alternatively, a large-scale dune restoration & beach nourishment project, such as the Coastal Texas Feasibility Study TSP (tentatively selected plan), offers a soft-structure alternative that may suit the needs of this region more appropriately when compared to Alternatives 4 & 5.

4 Recommendations

The following is a summarization of the alternatives reviewed for consideration with recommendations for each alternative. This is followed by a discussion highlighting areas of uncertainty within this study, and a review of future work recommendations that could be implemented to improve/expand upon the existing analysis.

4.1 Alternatives Summary and Recommendations:

Alternative 1 (FWOP): Alternative 1 should be avoided, as it offers no beneficial use of materials dredged from the ship channel. Instead, the materials would be placed in a designated offshore placement area, where they would be more difficult to access for later use. Given the limited availability of naturally sourced sand, it is important to utilize any locally sourced (dredged) beach-quality borrow fill for nourishment purposes. Beneficial use of the material does result in an incremental cost increase relative to offshore placement. However, benefits are provided at a lower cost than pumping sand from offshore sources which has been proposed for large-scale nourishment projects such as the Coastal Texas Protection and Restoration Feasibility Study (USACE, 2020).

TSP - Alternatives 2 & 3 (FWP – Beach Nourishment): Alternatives 2 & 3 offer the best solution for beneficial use of the dredged material. The economic analysis details the benefits associated with each alternative, which will ultimately decide the tentatively selected plan (TSP) for the purposes of this study effort.

Alternatives 4 & 5 (FWP – Seawall Extension): The seawall extension alternative is not considered feasible within the project constraints.

4.2 Assumptions & Future Work Recommendations

The following will review assumptions to highlight areas of uncertainty and offer future work recommendations to improve upon the existing analysis.

Available Data:

- **Sediment Samples**: Sediment grain size samples, of native beach and borrow fill, are spatially and temporally limited, resulting in a medium-high level of uncertainty related to borrow fill sediment parameters and a medium level related to native beach sediment parameters.
  - **Assumptions**: Native beach estimates are based on comparison between theoretically derived & sampled D_{50} estimates. Borrow fill estimates are based on 2016 Galveston entrance (ship) channel samples, which indicates significant variation in the overall gradation/distribution. A conservative approach is utilized, eliminating the coarsest outlier, then attempting to weight the remaining samples spatially based on the indicated channel station.
  - **Significance**: Sediment texture/size is key to the accuracy of beach equilibrium profile concepts and the development of sediment transportation estimates via analytical and/or numerical solutions. Overestimating grain size of borrow fill can result in unrealistic and less conservative design estimates related to fill longevity.
  - **Future work recommendations include**: (1) improved spatial and temporal resolution of borrow & native fill sampling, (2) improved documentation to map & compare D_{50} estimates over time, and (3) development of specific design guidance to develop weighted D_{50} estimates for borrow fill that account for spatial variation and volumetric composition of sampled texture.

- **Survey Data:** Survey is limited in the cross-shore direction, and "depth of closure" surveys from 2014 and 2016 to not extend to the calculated outer limit of the active profile.
  - **Assumptions**: The Hallermeier inner and outer DOC is calculated & averaged according to WIS data from two nearby stations (73070 & 73071), at 16 feet and 41 feet, respectively, however the calculated outer limit is outside the extent of available survey. The inner limit (16' depth) is used to calculate alongshore/lateral diffusion with the P-C solution. The outer DOC is limited by the overlap between available survey, which is ultimately defined by an approximate elevation of -25.5 feet (NAVD 88).
  - **Significance**: Since it is assumed that the D_{50} of borrow fill is greater than that of native beach material, beach equilibrium concepts yield intersecting profiles, which limits the significance of missing survey data, given that D_{50} assumptions

are accurate. Further, the historical shoreline retreat rate estimates (ft/yr) are used to develop FWP projections that inform the economic analysis, which also mitigates the significance of the missing data. However, the total volume change (loss) over the entire active profile remains unknown, which ultimately yields a high level of uncertainty in regard to the (1) verification of the calculated outer DOC, and (2) calculated total volumetric loss rate over active profile.

- **Future work recommendations**: (1) Improve/maximize the cross-shore extent of future survey work to capture the theoretical outer limit of the DOC. (2) Track the upcoming (2021) beach nourishment evolution with frequent topographic and bathymetric surveys.

FWOP Analysis:

- **Shoreline Change Rates**: The FWOP analysis utilizes historically derived shoreline change rates from 2014 – 2019 surveys to project future shoreline change.
  - **Assumptions**: Shoreline change between 2019 and 2038 will continue at a similar rate.
  - **Significance**: The influence of storm events, nourishments, offshore morphology, sea level change, subsidence, and the resistance to erosion offered by the exposed material substrate are among a few of the considerations that may result in a net change to the rate of erosion.
  - **Future work recommendations**: Shoreline change is not constant, as evidenced by year-to-year historic survey comparisons. It's not possible to predict year-to-year fluctuations or to account for all factors that contribute to historically observed changes. However, probabilistic models that are informed by, and calibrated to, measured data offer a significant reduction to the uncertainty associated with mid- to long-term projections. The collection and documentation of measured data has improved significantly in recent years, however there are still many missing pieces. In addition to previously suggested items (survey/sediment sampling improvements), the primary "missing piece" can be summarized as an improved network of gauges, buoys, and other (temporary or permanent) ocean measurement devices. The overall value of such an investment is difficult to overstate as it is capable of significantly improving the models that inform coastal design, strategic planning, and related construction. Ultimately, this is fundamental to making informed engineering decisions that improve the resilience of the sediment-starved Texas coastline against rising sea levels. While outside the purview of this project, a robust, inter-agency effort to improve coastal data collection is strongly recommended for future work.

FWP Analysis:

- **Alongshore spreading:** Longshore diffusivity (spreading) is estimated analytically, according to the one-line (+4' contour) P-C (Pelnard-Considere) solution (see Section 3.3.4).

- **Assumptions:** An infinitely long shoreline with a cross-shore profile that always remains in equilibrium (no cross-shore flux) is assumed, therefore cross-shore spreading losses must be accounted for separately. Further assumptions include, no currents, constant wave direction, small angle of wave incidence, and a linear relation between incidence angle and littoral drift (Kim, 2020).
- **Significance:** The P-C solution is only used to account for alongshore spreading. Several of the above assumptions are addressed through use of historically derived erosion rates and beach equilibrium profile concepts to modify projected shoreline change. Still, alongshore spreading is applied uniformly throughout the project area, regardless of the net (long-term) littoral drift direction. This is not likely to be reflected in reality. However, it is somewhat dependent on seasonal timing of placement. If nourishment is placed in the spring/summer it will tend to spread northeast initially, according to seasonal trends.
- **Future work recommendations:** The one-line, numerical model GenCade could be employed to improve the distribution/shape of alongshore spreading results. This would be a low effort endeavor. However, the degree of value added to the project should be tempered by the fact that GenCade is similarly governed by a modified version of the P-C equation.

- **Cross-Shore Equilibrium:** Cross-shore equilibrium profile theory concepts are used to estimate cross-shore flux/spreading of the placed beach fill material (see Section 3.3.3).
  - **Assumptions:** Shoreface equilibrium profile theory is a useful design concept, however it is inherently problematic due to a number of assumptions and oversimplifications, including, but not limited to: (1) the depth of closure oversimplification, (2) sediment-rich shoreface assumption, and (3) assumption that all sediment movement is driven by wave orbital motion, acting on the shoreface. Additionally, the use of a single sediment parameter to describe the theoretical equilibrium profile is an oversimplification that is compounded by lacking sediment data. Further, it is assumed that conditions/storm events that occur over the project life will be similar to the surveyed period from which shoreline change rates were derived.
  - **Significance:** Compounding uncertainty associated with the above assumptions is somewhat mitigated by the application of statistically derived shoreline change projections. Reliance on theoretical concepts is lessened. However, there is statistical uncertainty inherent in the probabilistic nature of predicting future storm events, which increases with the total duration of projections.
  - **Future work recommendations:** Beachfill performance could be simulated in a cross-shore model like Beach-fx or CSHORE. These models may add some value,

however they are limited by some of the same assumptions and by the availability of statistically derived data for calibration purposes. The utility of such models is limited to relatively short simulation periods, and the modeled results are only as good as the calibration and user-specified inputs.

Conclusion/Summary:

During pre-construction, engineering and design (PED) phase of the project, modeling recommendations may provide some value. However, this is limited by the availability of statistical data for calibration and user-defined inputs. This gap can be addressed now by more frequent monitoring (survey) of upcoming beach fill projects, including the 2021 project that is slated to occur over the summer. This, and improved sediment sampling, would provide valuable data that could aid in the improvement of related estimates and models during PED.

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