Folly Beach, South Carolina

Appendix A
Coastal Engineering

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Sub-Appendix

1 Introduction

The U.S. Army Corps of Engineers (USACE) Wilmington District is evaluating continued Federal interest of the Folly Beach, SC coastal storm risk management (CSRM) project. The project extends 28,890 feet along beachfront of the City of Folly Beach, see **Error! Reference source not found.**-1. The ultimate goal of the study is to calculate the benefits for proposed project beachfill template for use in calculating the project benefit to cost ratio for a proposed 50 year extension to the authorization.

Figure 1-1. Folly Beach Project Area

The Beach-fx software was utilized to analyze the physical performance of the proposed template for the storm damage reduction project in the Folly Beach study area as well as the economic benefits and costs. Beach-fx is an event-based, Monte Carlo life cycle simulation tool capable of estimating storm damage along coastal zones caused by erosion, flooding, and wave impact. The software also calculates the economic benefits and costs associated with alternatives. The purpose of this appendix is to describe the Coastal Engineering input driving the Beach-fx software for the Folly Beach study area. This includes developing the representative reaches for the study area, a historical storm suite, historic shoreline change conditions, and profile response to the array of storm events using SBEACH.

2 Project Background

2.1 Current Authorized Project

The Folly Beach Shore Protection Project was authorized by Section 501 of the Water Resources Development Act of 1986, Public Law 99-662, as amended, and modified by the Energy and Water Development Appropriations Act of 1992, PL 102-104. The purpose of the project is to reduce damage to structures and shorefront property related to erosion and storms. The 1991 General Design Memorandum included a protective berm 15 ft wide at elevation 8.0 ft NAVD88 with a foreshore slope of 1V:10H to the mean high water (MHW) line then offshore at 1V:30H out to the existing bottom. The initial project length was 28,220 ft and the project included nine rehabilitated steel sheet pile groins. The initial and following beach fills included advanced nourishment of varying volume. The project was modified in 2005 with 670 feet added to the northeast end of the project for a total length of 28,890 ft.

2.2 Previous Nourishment Projects

Initial construction for the currently authorized project was completed in 1993 and involved the placement of approximately 2.7 million cubic yards (mcy) of sand on the beach with 3.1 mcy dredged from the Folly River. The shoreline was nourished in 2005 with approximately 2.3 mcy of sand from offshore. A partial nourishment occurred in 2007 with approximately 0.49 mcy of sand being placed on the beach. Borrow area locations are discussed in greater detail in Section 6 including a location map. A summary of past nourishment projects is provided in Table 2-1 and in Figure 2-1 with information available from the link below. Volume is placed on the beach is not the same as excavated from the borrow site. The Folly River has been used in previous nourishment projects of Folly Beach including 1993, 2013 and 2018. From 1979 to 2000 material dredged during maintenance of the navigation channel in the Folly River and Stono Inlet were placed on the southwest end of the island at the Charleston County Park. The Folly River is regularly recharged with material eroded from Folly Beach and beach nourishments sourced from offshore borrow sites adds to the littoral sand budget.
https://gis.dhec.sc.gov/renourishment/

2.3 Charleston Harbor Jetties

The 1987 the USACE report "Evaluation of the Impacts of Charleston Harbor Jetties on Folly Island, South Carolina" addressed the Section 111 issue of shoreline damage attributable to a federal navigation project (USACE, 1987). A sediment budget analysis was used to determine the impact of the jetties on the sub-aerial beach at Folly Island. The report states that approximately 57% of the sub-aerial beach volume loss can be attributed to the jetties. The report states that littoral sediment transport from the north has been blocked by the jetties causing a decreased sediment supply to Folly Island and to offshore areas. Morris Island is to the north of Folly and is also impacted by loss of sediment. The reduced sediment to the ebb-tide shoal and the steeping offshore profile has increased the wave energy along Folly Island and resulted in the landward migration of the ebb-tide shoals at Lighthouse Inlet.

2.4 Datums

All elevations provided in this report and used in the modeling efforts are in feet, NAVD88 vertical datum. The conversion from NGVD29 to NAVD88 is (NGVD29 – 0.98 ft) = NAVD88, the rounded value of - 1.0 ft has traditionally been used for the Folly Beach project. For NOAA nautical chart conversions the mean lower low water is at elevation -3.14 ft NAVD88.

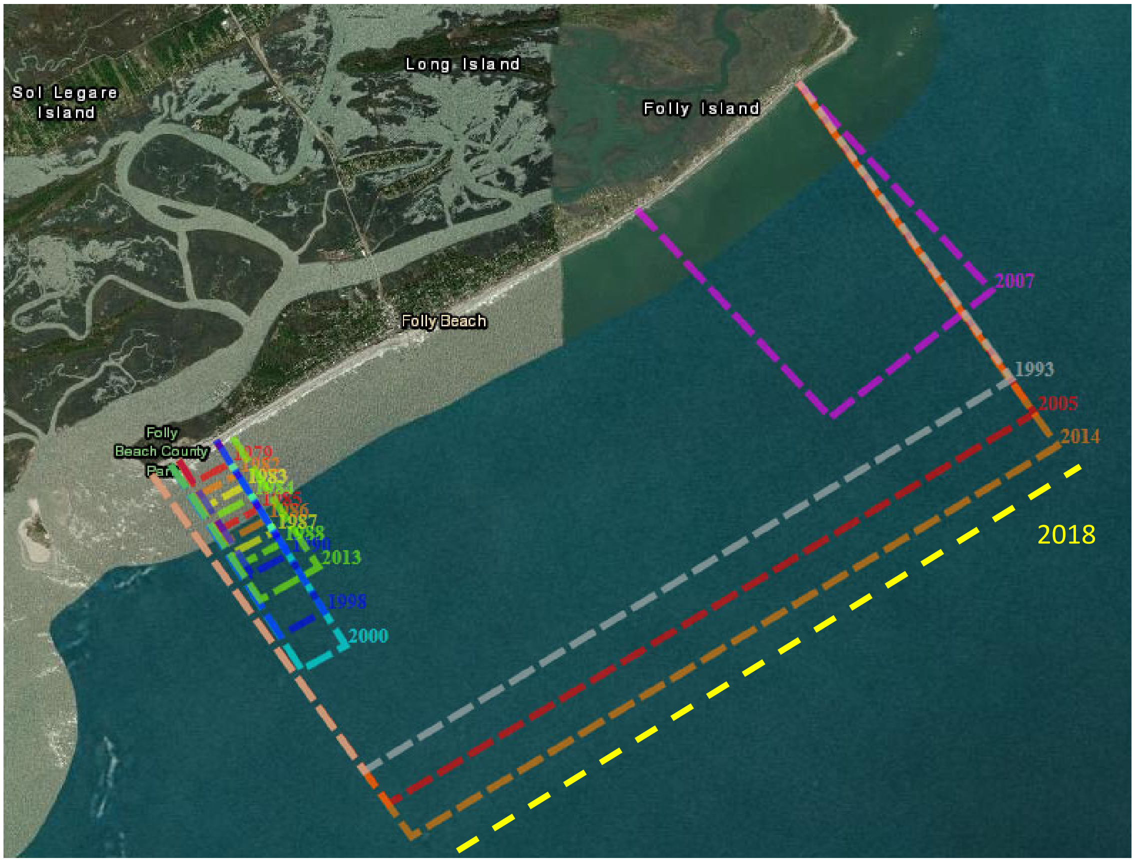

Figure 2-1. Previous Renourishment Events (Source: SCDHEC-OCRM)

Table 2-1. Previous Nourishment Projects

Year	Location or Station Volume Placed		Length (miles)	Total Placed (CY)	Source
1979	Southwest End		~0.5	20,000	Nav Channel
1982	Southwest End		~0.5	43,700	Nav Channel
1983	Southwest End		~0.5	43,700	Nav Channel
1984	Southwest End		~0.5	43,700	Nav Channel
1985	Southwest End		~0.5	43,700	Nav Channel
1986	Southwest End		~0.5	43,700	Nav Channel
1987	Southwest End		~0.5	43,700	Nav Channel
1988	Southwest End		~0.5	43,700	Nav Channel
1990	Southwest End		1.00	240,000	Nav Channel
1993	0+00	282+20	5.33	2,700,000	Folly River
1998	0+00	30+00	0.43	55,000	Folly River
2000	Southwest End		~0.5	101,500	Nav Channel
2005	0+00	288+90	5.34	2,395,000	Offshore
2007	188+00	288+90	1.91	490,000	Offshore (B)
2013	10+00	029+00	0.53	415,000	Folly River
2014	28+48	288+90	4.93	1,400,000	Offshore (A, B, C & D)
2018	28+48	288+90	4.93	1,200,000	Folly River

2.5 General Features

Folly Beach is located on Folly Island about eight miles south of Charleston, SC. The island is about six miles long and has a maximum width of 2,800 ft near the center of the island. The island narrows to 200 ft wide on the northeast end at a location known as the "Washout". The island is bounded by Lighthouse Inlet on the northeast and by Stono Inlet to the southwest. The tidally influenced Folly River is located behind the southeast end of the island and flows into Stono Inlet. Elevations on the island range from a low of 5 ft NAVD88 to over 14 ft NAVD88 along a remnant dune system that runs intermittently along the center of the island. The entire length of Folly Beach is experiencing shoreline recession with higher rates at the ends of the island and lower rates along the middle. The predominate longshore drift is toward the southwest. The mean grain diameter of the native beach is 0.17 mm (USACE, 2017).

2.6 Groin Structures

Groins are structures built perpendicular to a shoreline designed to trap and hold sand as it moves along the shore with the longshore drift. There are 50 groins along Folly Beach that were constructed by various local, state and federal agencies between the 1940's and 2013 (Folly Beach, 2015). An estimated 28 groins are non-functioning remnant timber and riprap structures and 22 are functioning. A GIS database was created to locate and catalog the structures and are shown in Figure 2-2.

There five existing timber sheet pile and riprap groins on the northeast end of the island originally constructed by the US Coast Guard in the 1970's. Three of the groins are in poor condition but are able to currently trap sand.

Nine groins were rehabilitated as part of the 1993 USACE beach nourishment project. The groins are located between Stations 109+00 and 158+00. The groins are steel sheet pile with a concrete cap and riprap placed along the base. The length of the nine groins varies between 100 and 200 ft with a crest elevation of approximately 6.5 ft NAVD88. The City of Folly Beach maintains the groins and they are currently functional.

In June 2013 a 745 ft long steel sheet pile groin with armor stone toe protection was constructed at the Charleston County Park on the southwest end of the island near Station 10+00. The groin was constructed in three sections to match the elevation of the berm, beach face and low-tide terrace (Kaczkowski, et al 2015). The project included 415,000 CY of material dredged from the Folly River to fill updrift reach of the groin. The groin was constructed to protect the Park's recreational beach and infrastructure.

Nine groins were rehabilitated in 2018 by the City of Folly Beach between Stations 164+30 to 210+60. Rehabilitation included removal of damaged timber sheet piles and rebuilding with armor stone and grout. Lengths of the groins varied between 242 ft and 336 ft to match the existing structure footprint. The general design included a crest elevation of 6.0 ft NAVD88 extending from the OCRM jurisdictional line to past the existing MHW contour then sloping downward to terminate with a crest elevation of approximately 2.0 ft NAVD88.

2.7 Revetments and Bulkheads

The Folly Beach shoreline is protected by numerous concrete and timber sheet pile bulkheads, stone revetments, concrete rubble revetments and bulkheads with armor stone at the base. The structures are of various length, elevation, design, age and construction quality. The location and elevations of exposed structures were surveyed in February 2019 by the Wilmington District. Information on buried armor structures was obtained from the 2015 Folly Beach Management Plan (Folly Beach, 2015). The location of structures included in the Beach-fx model can be reviewed in Figure 2-3.

The Central Business District (CBD) includes the Tides Hotel and condominiums that are protected by a engineered concrete sheet pile seawall 1,528 ft in length and is in good condition, Station 96+57 to 111+85. This section was entirely contained within Beach-fx model Reach 8 (described Section 4.1 in this report). In the early 1990's the South Carolina Department of Transportation (SCDOT) built a rock revetment to protect a 2,750 ft section of East Ashley Avenue at the "Washout" and is good condition. This revetment is between Station 210+00 to 237+50. The 2019 survey data was used to define the intermittent armoring at private beachfront lots within the Beach-fx model. New or replaced armor structures at single residential lots in Beach-fx were assumed to follow design guidelines in the Folly Beach Code of Ordinances. Locations with non-engineered small riprap or concrete rubble revetments were not included in the Beach-fx analysis.

The Beach-fx failure threshold for the armor structures utilized recommendations from the Egmont Key Feasibility Study and St Johns County SPP Beach-fx modeling efforts. The flooding armor failure threshold was assumed to occur when the structure was overtopped by 1.0 ft of flooding. Erosion failure for the timber bulkheads at residential properties was assumed to occur when ½ of the bulkhead height was exposed by erosion. Erosion failure of the concrete seawall in the CBD was assumed to fail when ¾ of the seawall was exposed. Erosion failure of stone revetments was assumed to occur when erosion reaches the base of the revetment. It was assumed that the seawalls and bulkheads are more likely to fail due to erosion before wave damage failure. A wave height of 10 ft was used as the wave damage armor failure threshold for seawalls and bulkheads to cover extreme storm events. For wave damage failure of revetments the USACE program ACES was used to determine the wave height until a damage level of 8 was reached in the rubble mound design revetment module.

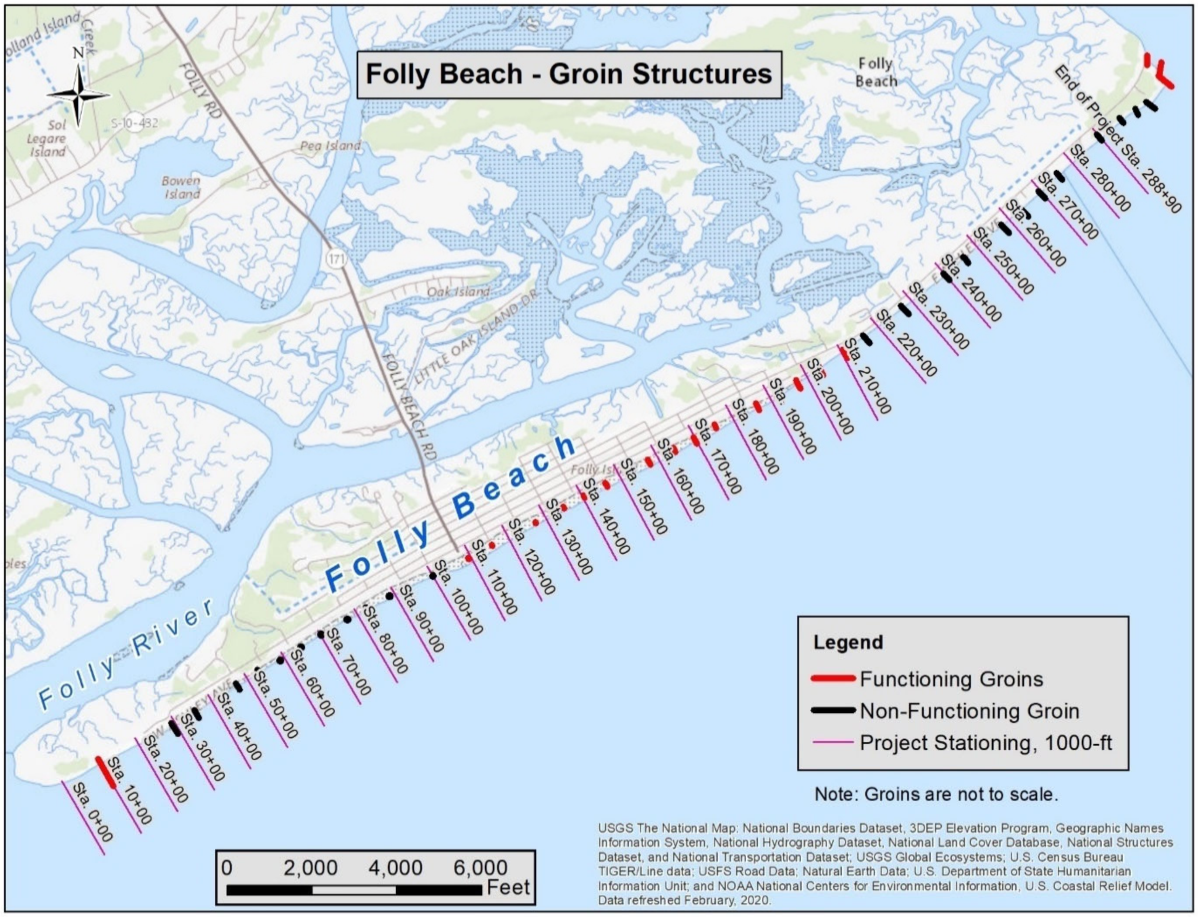

Figure 2-2. Existing Groin Structure Location

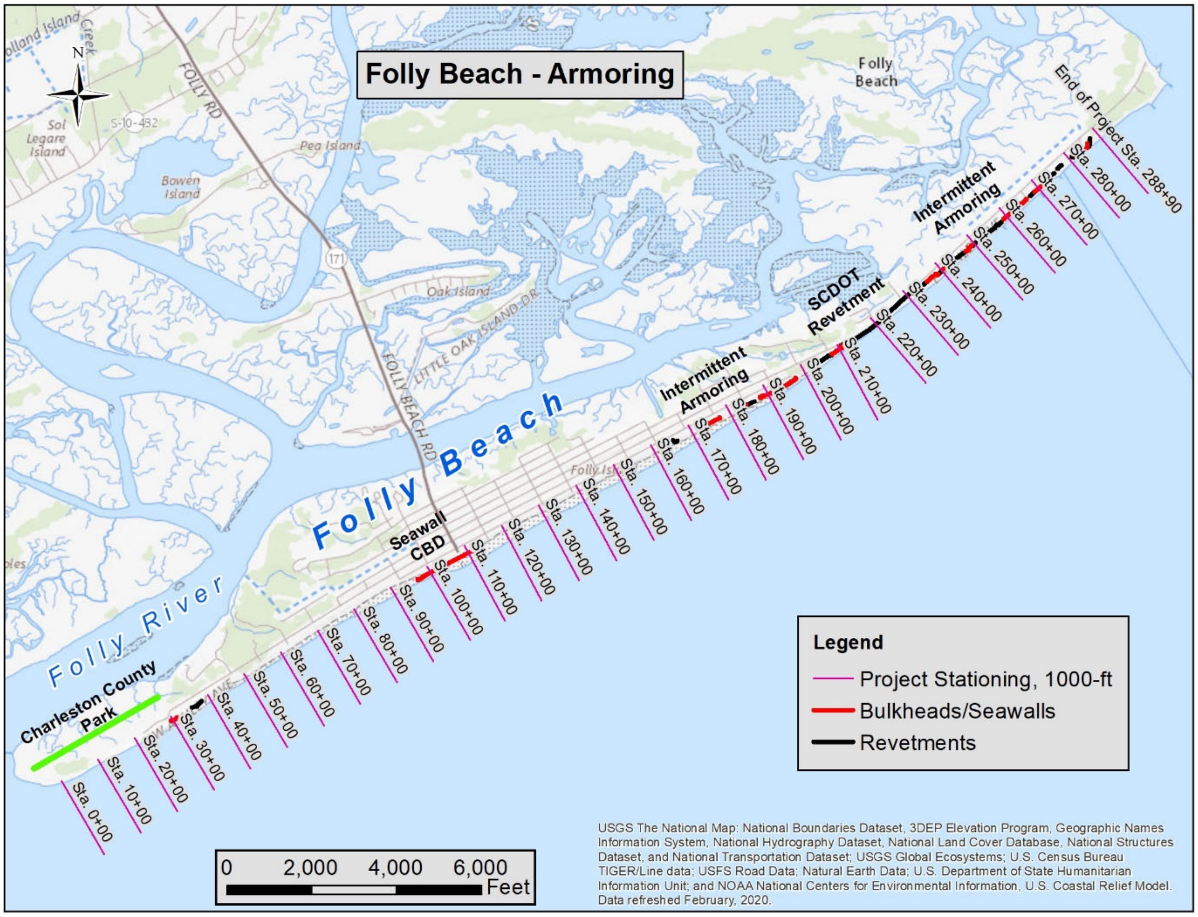

Figure 2-3. Existing Bulkhead, Seawalls and Revetment Sections

3 Natural Forces

3.1 Winds

Local winds are the primary means of generating the small-amplitude, short period waves that are an important mechanism of sand transport along the South Carolina shoreline. Winds in the project vicinity vary seasonally with prevailing winds ranging from the northeast though the southwest (in clockwise direction). The greatest velocities originate from the northeast quadrant in fall and winter months and from the southwest quadrant in the spring and summer.

Wind data offshore of the project area is available from the USACE Wave Information Study (WIS) Program. WIS hindcast data are generated using the numerical hindcast model WISWAVE (Hubertz, 1992). WISWAVE is driven by wind fields overlaying a bathymetric grid. Model output includes significant wave height, peak and mean wave period, peak and mean wave direction, wind speed, and wind direction. In the Atlantic, the available WIS hindcast database covers a 35-year period of record extending from 1980 to 2014.

WIS Station 63348 is representative of offshore deep water wind and wave conditions for the project area. Table 3-1 provides a summary of wind data from WIS Station 63348, located at latitude 32.58° N, longitude -79.67° W (about 17 miles east of Folly Beach; Figure 3-1). This table contains a summary of average wind speeds and frequency of occurrence broken down into eight 45 degree angle-bands. This table indicates that winds are predominantly from the southwest and northeast. The wind rose presented in Figure 3-2 provides a further breakdown of winds in the project area.

Table 3-1. Average Wind Conditions

Wind Direction (from)	WIS Station #63348 (1980 – 2014)	
	Percentage Occurrence (%)	Average Wind Speed (mph)
North	10.5	16.6
Northeast	17.8	16.6
East	9.8	12.2
Southeast	8.1	11.3
South	12.8	12.4
Southwest	21.1	14.1
West	10.8	15.7
Northwest	9.2	16.7

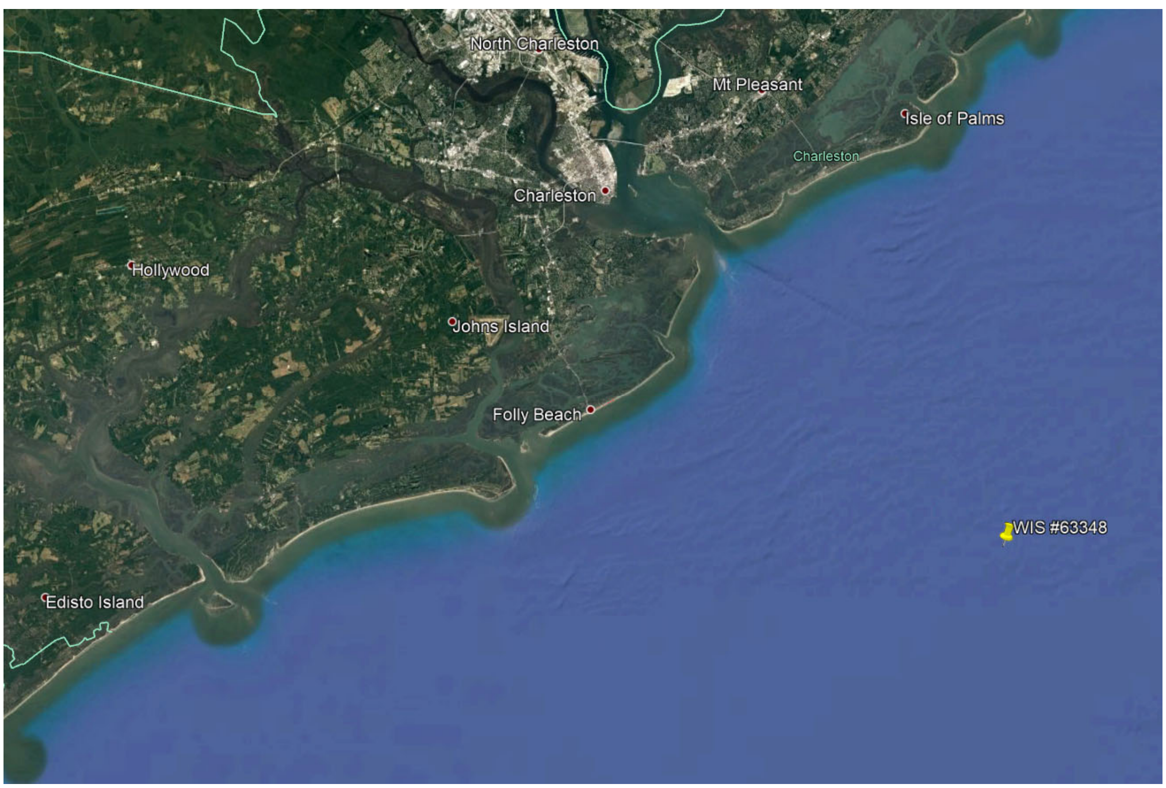

Figure 3-1. Location of WIS Station #63348 Relative to Project (Google Earth)

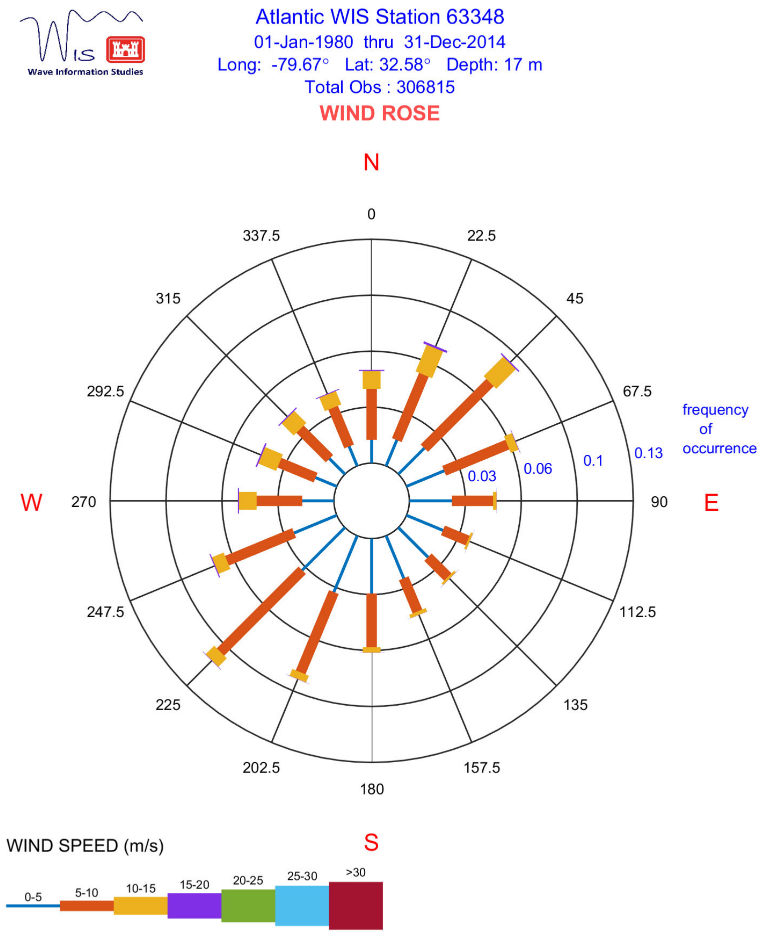

Figure 3-2. Wind Rose – WIS Station 63348 (USACE-ERDC)

Wind conditions in Coastal South Carolina are seasonal. A further breakdown of the wind data provides a summary of the seasonal conditions in Table 3-2. Between October and February, frontal weather patterns driven by cold Arctic air masses can extend into South Carolina. These fronts typically generate northeast winds before the frontal passage and northwest winds behind the front. Along much of the Atlantic coast "Northeaster" behavior is responsible for the increased intensity of wind speed in the northeast sector during the fall and winter months.

The summer months are characterized by southwest winds and tropical weather systems traveling west to northwest in the lower latitudes. Additionally, daily breezes onshore and offshore result from differential heating of land and water masses.

During the summer and fall months, tropical waves may develop into tropical storms and hurricanes, which can generate devastating winds, waves, and storm surge when they impact the project area. These storms contribute to the overall longshore and cross-shore sediment transport at Folly Beach. These intense seasonal events have an approximate recurrence interval of once every five years and will be discussed in greater detail under Section 3.4: Storm Effects.

Table 3-2. Seasonal Wind Conditions

Month	WIS Station #63348 (1980 – 2014)	
	Average Wind Speed (mph)	Predominant Direction (from)
January	17.4	NW
February	17.0	N
March	16.3	W
April	14.5	SW
May	12.8	SW
June	12.1	SW
July	12.1	SW
August	11.4	SW
September	13.2	NE
October	14.8	NE
November	16.3	NE
December	16.8	NE

3.2 Waves

The energy dissipation that occurs as waves enter the nearshore zone and break is an important component of sediment transport in the project area. Incident waves, in combination with tides and storm surge, are important factors influencing the behavior of the shoreline. The Folly Beach study area is exposed to both short period wind-waves and longer period open-ocean swells originating predominantly from the southeast.

Damage to the Folly Beach shoreline and upland development is attributable to large storm waves produced primarily by tropical disturbances, including hurricanes, during the summer and fall months, and by Northeasters during the late fall and winter months.

Wave data for this report were obtained from the long-term USACE WIS hindcast database for the U.S. Atlantic coast. This 35-year record extends from 1980 through 2014 and consists of a time-series of wave events at 3-hour intervals for stations located along the east coast. Similar to wind conditions, wave conditions in coastal South Carolina experience seasonal variability. The seasonal breakdown of wave heights is shown in Table 3-3.

Table 3-4 summarizes the percentage of occurrence and average wave height of the WIS waves by direction. It can be seen that the dominant wave direction is from the southeast, 83% of the waves are from between 90° and 180°. This can be seen in greater detail in the wave rose presented in Figure 3-3. The total wave climate reflects both the open-ocean swell and more locally generated wind-waves. Waves from the southwest quadrant are refracted by Stono Inlet ebb shoal and Kiawah Island.

Table 3-3. Seasonal Wave Conditions

Month	WIS Station #63348 (1980-2014)		
	Average Wave Height	Predominant Direction	Mean Period
	(ft)	(from)	(sec)
January	3.9	SE	8.6
February	3.9	SE	8.6
March	3.9	SE	8.1
April	3.6	SE	7.9
May	3.3	SE	8.1
June	3.0	SE	8.2
July	3.0	SE	8.3
August	3.0	SE	8.4
September	3.9	E	8.9
October	3.9	E	8.3
November	3.9	E	8.6
December	3.9	E	8.6

Table 3-4. Average Wave Heights (1980 to 2014)

Wave Direction (from)		WIS Station #63348 (1980-2014)	
		Percentage Occurrence	Average Significant Wave Height
	(degrees)	(%)	(ft)
N	0	0.5%	3.0
NNE	22.5	0.7%	3.3
NE	45	1.7%	3.6
ENE	67.5	6.4%	4.3
E	90	16.8%	3.9
ESE	112.5	29.8%	3.3
SE	135	22.6%	3.6
SSE	157.5	8.8%	3.6
S	180	5.3%	3.9
SSW	202.5	2.8%	3.9
SW	225	1.7%	3.9
WSW	247.5	0.9%	3.6
W	270	0.6%	3.6
WNW	292.5	0.5%	3.3
NW	315	0.5%	3.3
WNW	337.5	0.4%	3.0

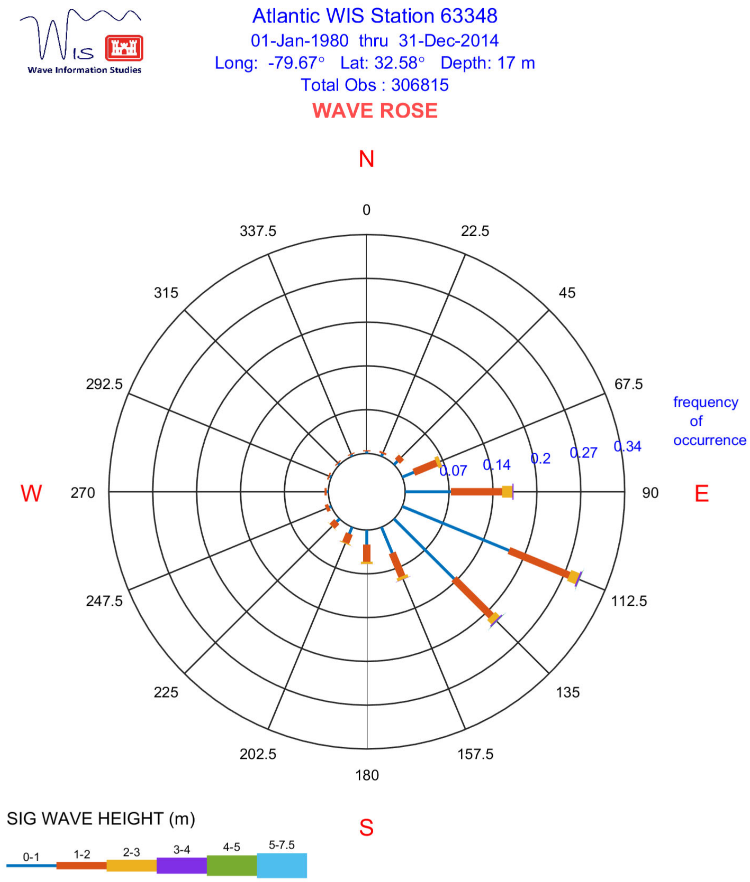

Figure 3-3. Wave Rose – WIS Station 63348 (USACE-ERDC)

3.3 Tides

Astronomical tides are created by the gravitational pull of the moon and sun and are predictable in magnitude and timing. The National Oceanic and Atmospheric Administration (NOAA) publishes tide tables for selected locations along the coastlines of the Unites States and locations around the world. These tables provide times of high and low tides, as well as predicted tidal amplitudes.

Tidal datums for the Folly Beach project site were obtained from NOAA tide station #8665530 Charleston, SC. Tidal ranges and datums are summarized in Figure 3-4 and Table 3-5. Mean high water (MHW) is at +2.26 ft NAVD88 and mean low water (MLW) is at -2.96 ft NAVD88 for a mean tide range of 5.22 ft in the project area. The record high water level was 9.38 ft NAVD88 during Hurricane Hugo on 22Sep1989. A temporary NOAA tide gage (Station #8666467) was available on the Folly River from 01Feb1977 to 31Jan1978. The mean tide range for the Folly River gage for that period was 5.38 ft.

Station Homepage: https://tidesandcurrents.noaa.gov/stationhome.html?id=8665530

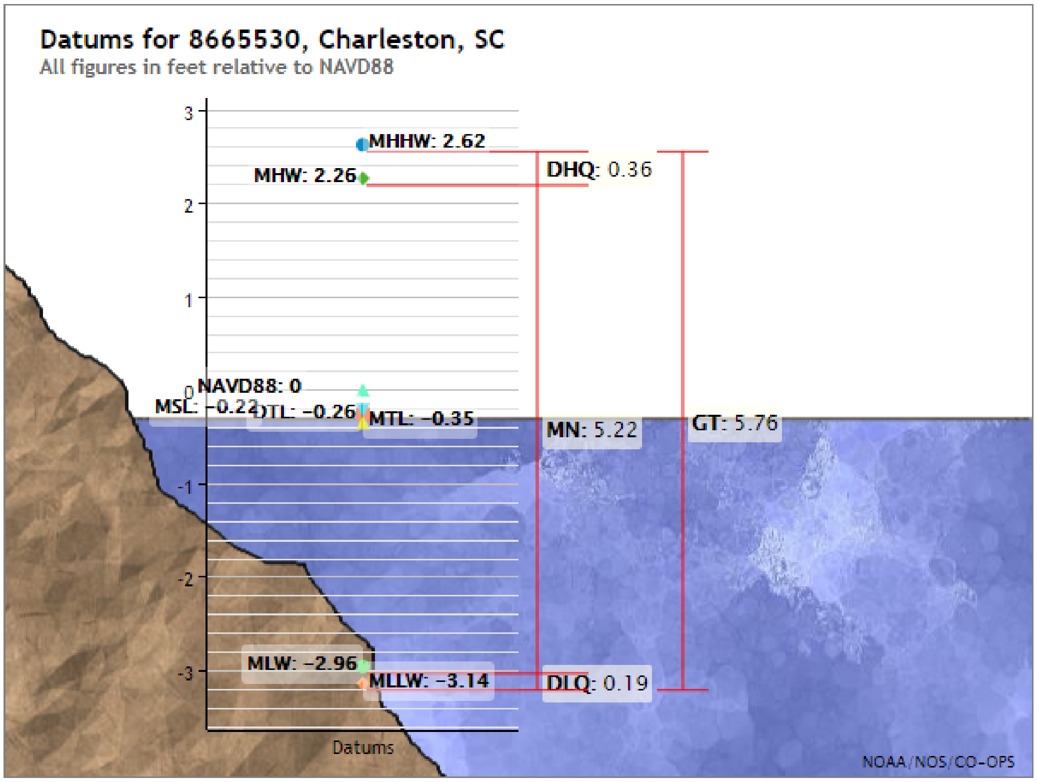

Figure 3-4. Tidal Range for NOAA Charleston Gage

Table 3-5. Tidal Datums

Tidal Datum	Elevation Relative to NAVD88 (feet)
Mean Higher High Water (MHHW)	2.62
Mean High Water (MHW)	2.26
North American Vertical Datum (NAVD88)	0.00
Mean Tide Level (MTL)	-0.35
Mean Low Water (MLW)	-2.96
Mean Lower Low Water (MLLW)	-3.14

3.4 Storm Effects

The shoreline of Folly Beach is influenced predominantly by tropical systems which occur during the summer and fall and Northeasters during the late fall and winter. Although hurricanes typically generate larger waves and storm surge, northeasters also impact the shoreline because of their longer duration and higher frequency of occurrence.

During intense storm activity, the shoreline is expected to naturally modify its beach profile. Storms erode and transport sediment from the beach into the active zone of storm waves. Once caught in the waves, this sediment is carried along the shore and re-deposited farther down the beach or is carried offshore and stored temporarily in submerged sand bars. Hurricanes and coastal storms, with high energy breaking waves and elevated water levels, can change the width and elevation of beaches and accelerate erosion. After storms pass, lower energy waves usually return sediment from the sand bars to the beach, which is restored gradually to its natural shape. While the beach profile typically recovers from storm energy as described, extreme storm events may cause sediment to leave the beach system entirely, sweeping it into inlets or far offshore into deep water where waves cannot return it to the beach. Therefore, a portion of shoreline recession due to intense storms may never fully recover.

Folly Beach is located in an area of significant hurricane activity. Figure 3-5 shows historic tracks of hurricanes and tropical storms from 1853 to 2019, as recorded by the National Hurricane Center (NHC) and is available from NOAA Office for Coastal Management. The dashed circle in the center of this figure indicates a 50-nautical mile radius from Folly Beach. Based on NHC records 67 hurricanes and tropical storms have passed within this 50-mile radius over the 166-year period of record. The 50-mile radius was chosen because any tropical disturbance passing within this distance would be likely to produce some damage along the shoreline. Stronger storms are capable of producing shoreline damage from greater distances.

Hurricane Hugo made landfall north of Charleston on September 22, 1989 as a Category 4 and was the costliest storm event in South Carolina history. Folly Beach experienced sustained winds of 85 mph and gust of 107 mph (FEMA, 2004). Another storm of interest is Hurricane Gracie which made landfall south of Folly Beach in September 1959 as a Category 4. In recent years, a number of named storms have significantly impacted the project area, including Florence (2018), Matthew (2016), Bonnie (2016), Ana and Joaquin (2015), and Beryl (2012). Damages from these storms, as well as from more distant storms causing indirect impacts, included substantial erosion and damage from winds, waves and elevated water levels. The storm suite did include storms greater than the historic event by the process of peaking the tide and phase of the historic event to produce the maximum storm surge possible. This peaking increased multiple storms above the 1% annual chance of exceedance.

There is concern that climate change is increasing the frequency and intensity of tropical storm events within the Atlantic Basin with the potential of increasing erosion along the eastern United States shorelines. The USACE Engineering Regulation (ER) No. 1100-2-8162 '*Incorporating Se Level Change in Civil Works Programs'* addresses the issue of future storm events and summarizes recent research. Four excerpts from the ER are provided below. The ER concludes that the science is inconclusive at this time as to if storms are increasing in frequency and intensity. The Folly Beach analyses did not include an increase future storm events. As with addressing relative sea level rise at Folly Beach, the potential for an increase in storm activity will be address in an adaptive management approach during the Planning, Engineering and Design phase of the study. Monitoring the impacts of climate change at Folly Beach will be coordinated with other regional CSRM projects including the Charleston Peninsula Study and the Edisto Island.

(1) Determining the effects of climate change on individual storms and on statistical descriptions of storm distributions is difficult because of the relatively small number of storms and the analytic problem of associating changes in measurements of storms with a few, very large-scale climate changes in basins around the world.

(2) At this time, no certain effects of climate change on tropical cyclone (TC) activity in terms of frequency, intensity, and rainfall across all global basins have been identified as changes to the variability of TC activity expected from natural causes (Knutson et al., 2010). As a result, the current science related to climate effects on TC activity relevant to the United States (U.S.) has

not reached the point of standard consensus necessary to inform a change in storm analysis baselines.

(3) In the Atlantic Basin including the Gulf of Mexico, the unadjusted record of raw hurricane counts in the best track Atlantic hurricane database (HURDAT) maintained by NOAA shows an increase since the early 1900s (Vecchi and Knutson, 2011). But when the record is adjusted for storms likely missed in the pre-satellite era before the mid-1970s, no significant increase can be seen since the late 1800s (Vecchi and Knutson, 2011). Also, the number of U.S. landfalling hurricanes since the late 1800s has not significantly changed (Vecchi and Knutson, 2011).

(4) Concerning the projected future effects of climate change on TC activity in all global basins (including the Eastern and Central North Pacific), the World Meteorological Organization (WMO) TC Expert Team (Knutson et al., 2010) concluded, based on atmospheric theory and high-resolution models, that by the late 21st century the number of tropical cyclones could remain at current levels or decrease by up to one-third; that average TC intensity could increase by up to 10%; and that near-storm (~50mi radius) rainfall rates could increase by ~20%.

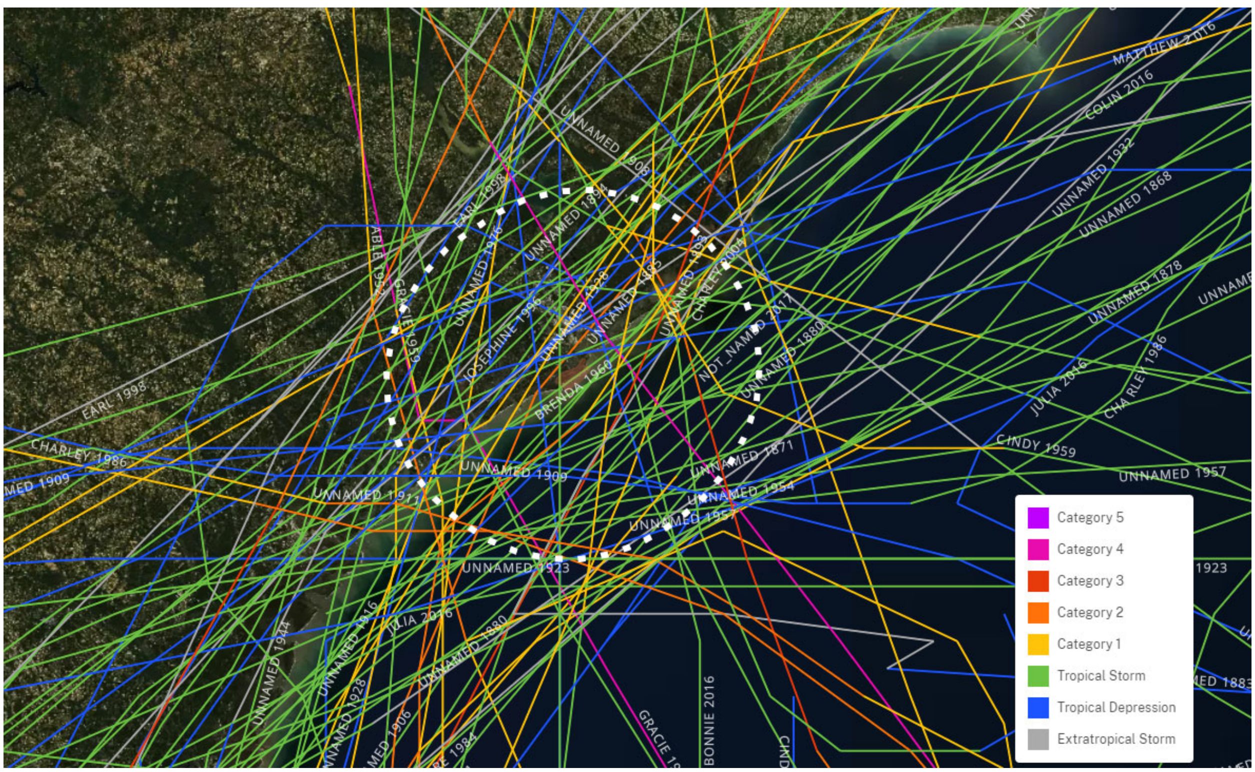

Figure 3-5. Hurricanes and Tropical Storm Tracks (1853 – 2019, 50 NM radius)

3.5 Storm Surge

Storm surge is defined as the rise of the ocean surface above its astronomical tide level due to storm forces. Surges occur primarily as a result of atmospheric pressure gradients and surface stresses created by wind blowing over a water surface. Strong onshore winds pile up water near the shoreline, resulting in super-elevated water levels along the coastal region and inland waterways. In addition, the lower atmospheric pressure which accompanies storms also contributes to a rise in water surface elevation. Extremely high wind velocities coupled with low barometric pressures (such as those experienced in tropical storms, hurricanes, and very strong Northeasters) can produce high, damaging water levels. In addition to wind speed, direction and duration, storm surge is also influenced by water depth, length of fetch (distance over water), and frictional characteristics of the nearshore sea bottom. An estimate of storm surge is required for the design of dune crest elevations. An increase in water depth may increase the potential for coastal flooding and allow larger storm waves to attack the shore.

Due to sand management over the life of the project within the dune (sand fencing and planting) the existing condition dune system along the Folly Beach study area varies from no dune to dunes between elevations 9 and 18 feet NAVD88 and is susceptible to overtopping from extreme storm surges. This can be seen from 3-6 which provides total storm surge levels vs storm frequency along Folly Beach and was obtained from the Charleston County Federal Emergency Management Agency (FEMA) Preliminary Flood Insurance Study (FIS) (FEMA, 2016). The total storm tide includes storm surge, wave setup and astronomical high tide. The record combined surge and peak wave height of 13 to 14 ft NAVD88 occurred at Folly Beach during Hurricane Hugo in 1989 (FEMA, 2004).

Table 3-6. Storm Tide and Frequency along Folly Beach (FEMA, 2016)

Annual Chance (%)	Return Period (Years)	Storm Surge Elevation (Feet, NAVD88)
10	10	5.5
2	50	7.5
1	100	10.0
0.2	500	13.5

3.6 Depth of Closure

The seaward limit of changes in depth over long-time periods due to movement of sediment is referred to as the “closure depth” and this depth is used for several calculations in the coastal analysis. The depth of closure along the Folly Beach shoreline varies from -9.0 ft NAVD88 at the ends of the island and -11.5 ft NAVD88 along the center of the island (Ebersole et al, 1996). The 2001 monitoring report of the 1993 nourishment project used a closure depth of -10.2 feet NAVD88 for the entire project length in calculating volume changes (CSE, 2001) and was used for this study.

3.7 Sea Level Change

Sea level change (SLC) at Folly Beach was evaluated following the guidelines presented in USACE Engineer Pamphlet EP 1100-2-1 “Procedures to Evaluate Sea Level Change: Impacts, Responses and Adaptation” (30Jun2019). The purpose of the EP was to provide instructional and procedural guidance to analyze and adapt to the direct and indirect physical and ecological effect of projected sea level change on USACE projects and systems of projects needed to implement Engineer Regulation (ER) 1100-2-8162.

ER 1100-2-8162 “Incorporating Sea Level Change in Civil Works Programs” (31Dec2013) provides both a methodology and a procedure for determining a range of SLC estimates based on global sea level change rates, the local historic sea level change rate, the construction (base) year of the project, and the design life of the project. Three estimates are required by the guidance, a Low (Baseline) estimate representing the minimum expected SLC, an Intermediate estimate, and a High estimate representing the maximum expected SLC. The guidance will be used to evaluate the future sea levels, the impacts to the Folly Beach project during the 50-Year project life and to assess the risk associated with the SLC estimates.

The first step in evaluating sea level change at Folly Beach was to identify a near-by NOAA water level gage with a sufficiently long data record. The analysis was based on the NOAA tide gauge located in Charleston, South Carolina (Station #8665530), approximately 8 miles north of Folly Beach. The gage is compliant and active with a historic record of 1901 to present, there was a data gap from 1905 to 1924. From Figure 3-6 the linear relative sea level trend for this gauge is 3.26 mm/year (0.01070 ft/year) with a 95% confidence interval of +/- 0.19 mm/year (0.00062 feet/year) based on monthly mean sea level data. For the 50-year project life of 2024 to 2074 this is equivalent to an increase of 0.54 ft in sea level. For stations with sufficient historical data the linear relative sea level trends were calculated by NOAA in overlapping 50-year increments. The variation on each 50-year trend is provided in Figure 3-7. The variation of each 50-year trend, with 95% confidence interval, is plotted against the mid-year of each 50-year period. The solid horizontal line represents the linear relative sea level trend using the entire period of record. Cyclical trends in the sea level data can be noted in both figures.

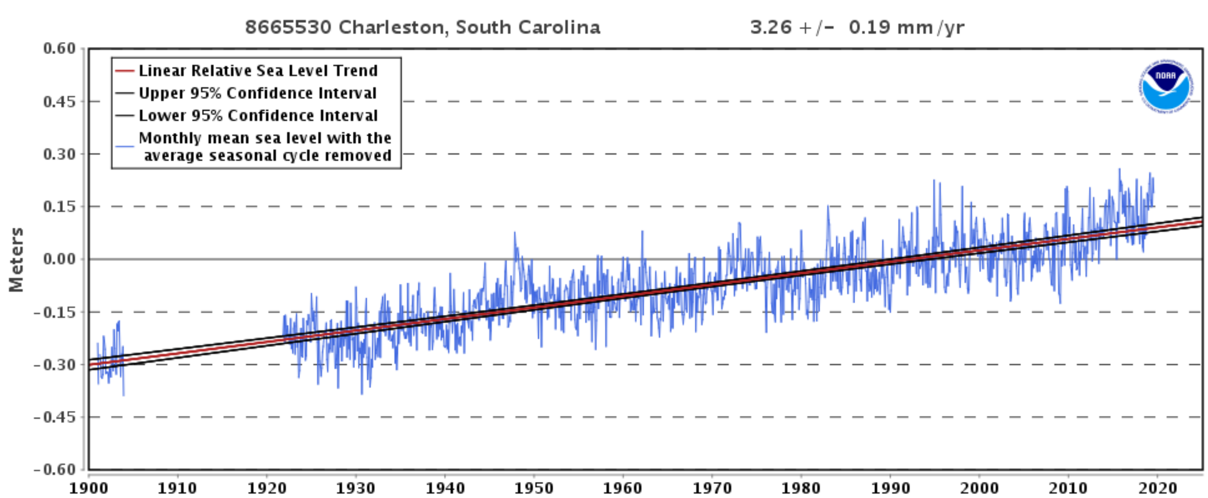

Figure 3-6. Relative Sea Level Trend, NOAA Gauge 8665530

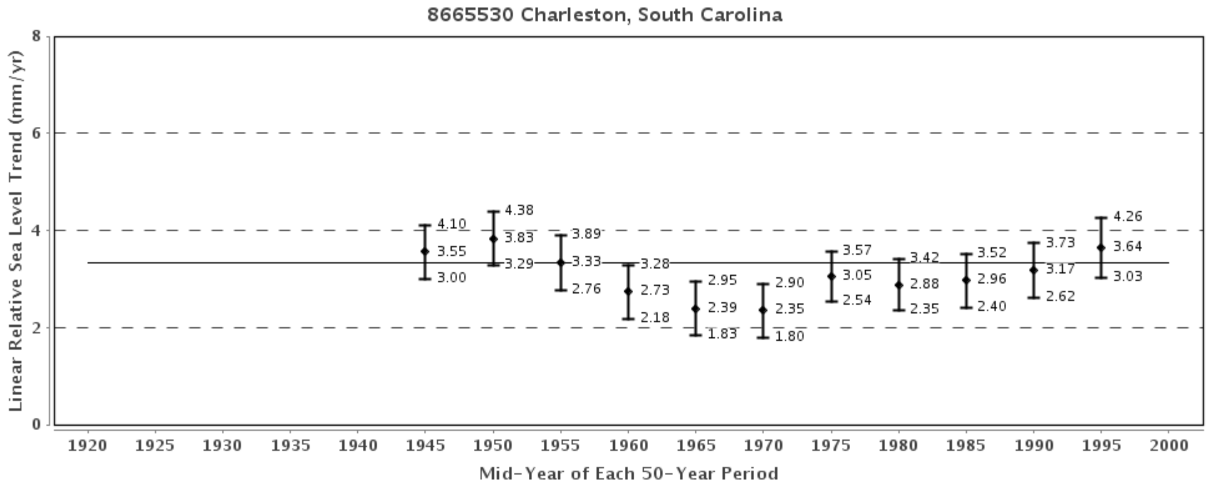

Figure 3-7. Variation of 50-Year Relative Sea Level Trend, NOAA Gauge 8665530

The second step in evaluating SLC at Folly Beach was to assess future trends, mainly will the rate of sea level rise accelerate in the future. Any future increase or decrease in this long-term trend along with land subsidence and glacial rebound needs to be addressed throughout the 50-year project life.

The USACE online tool Sea Level Tracker was used to determine the current rate of SLC observed and the projected future trends in the rate of SLC, a link to the tool is provided below. Extreme water levels (EWL) incorporated into the tool are based on statistical probabilities using recorded historic monthly extreme water level values. The Sea Level Tracker is used to compare actual mean sea level (MSL) values and trends for specific NOAA tide gauges with the USACE SLC scenarios as described in ER 1100-2-8162 and Engineer Technical Letter (ETL) 1100-2-1. The Sea Level Tracker tool calculates the USACE Low, Intermediate and High sea level change scenarios based on global and local change effects. Historical MSL is represented by either 19-year or 5-year midpoint moving averages. Guidance in using the Sea Level Tracker and technical background is provided in USACE "Sea Level Tracker User Guide", Version 1.0, December, 2018.

https://climate.sec.usace.army.mil/slr_app/

The Sea Level Tracker tool was used to evaluate the NOAA Charleston tide gauge data. The regionally corrected rate of 0.00965 ft/yr was used as the rate of SLC and was sourced from Technical Report NOS CO-OPS 065 (NOAA, 2013) and accounts for vertical land motion. This regional rate is also the Low USACE estimated SLC rate. Based on the regional rate only, the sea level increase was 0.48 ft during the 50-year project life of 2024 to 2074. Figure 3-8 presents the results of the Tracker tool focused on trends between 1990 to 2020. The light blue line represents the 5-year moving average and the heavy dark blue line represents the 19-year moving average. The 19-year average is useful in that this represents the moon's metonic cycle and the tidal datum epoch. These estimates are referenced to the midpoint of the latest National Tidal Datum epoch, 1992. The reader is referred to ER 1100-2-8162 for a detailed explanation of the procedure, equations employed and variables included to account for the eustatic change as well as site specific uplift or subsidence to develop corrected rates. The red line is the High SLC prediction, the green is the Intermediate and the blue is the Low rate prediction. From Figure 3-8 it can be noted that the 19-year moving average tracks well with the intermediate rate. The 5-year rate is tracking upwards but is cyclical and does not match the tidal epoch period of 19-years.

The future USACE sea level predictions for the Folly Beach project based on the Charleston gauge are provided in Figure 3-9. For the 2024 to 2074 project life the predicted Low rate sea level rise (regional rate) is 0.48 ft, the Intermediate SLC increase was 0.99 ft and the High SLC increase was 2.58 ft. Table 3-7 includes a summary of the USACE SLC estimates and for comparison the regionalized NOAA estimates (NOAA et al, 2012) are also provided.

Table 3-7. USACE and NOAA 50-Year Sea Level Change Estimates

Project Year	Year	USACE			NOAA			
		Low	Int	High	Low	Int-Low	Int-High	High
Base	2019	0.04	0.10	0.30	0.04	0.11	0.25	0.41
Start	2024	0.08	0.17	0.45	0.09	0.18	0.38	0.61
	2034	0.18	0.33	0.82	0.19	0.34	0.69	1.09
	2044	0.28	0.51	1.26	0.28	0.52	1.05	1.66
	2054	0.37	0.71	1.78	0.38	0.72	1.48	2.34
	2064	0.47	0.93	2.37	0.47	0.94	1.96	3.12
End	2074	0.57	1.16	3.03	0.57	1.17	2.49	4.01
50-Year Increase =		0.48	0.99	2.58	0.48	0.99	2.11	3.4

To compare the predicted Charleston USACE SLC trends with near-by NOAA gauges, the tide gauges at Springmaid Pier (#8661070) in Myrtle Beach, SC and the Ft. Pulaski (#8670870) near Tybee Island, GA were reviewed. The 1990 to 2020 SLC trends with the 19-year and 5-year moving averages are provided in Figures 3-10 and 3-11. Both gages are active and compliant with over 40-years of data. The Ft. Pulaski gauge shows the same trends as the Charleston gauge with the 19-year moving average tracking well with the Intermediate rate and the 5-year average rising. For the Springmaid gauge the 19-year and 5-year moving averages are below the Low SCL curve but both are sloping upwards.

The USACE Intermediate SLC scenario was selected for the Folly Beach project because it tracked well with the 19-year moving average in Figure 3-8. The USACE predicted Intermediate rate was also selected for the Charleston Peninsula Coastal Storm Risk Management Feasibility Study. Similar SLC trends were noted at regional tide gauges. The Intermediate rate was also selected in coordination with the USACE Climate Preparedness and Resilience Community of Practice.

The third step in evaluating SLC was to assess the risk associated with selecting the Intermediate rate of SLC for the design and economic analysis. The Folly Beach CSRM project has the benefit of consisting of 'soft' construction methods. The proposed plan for Folly Beach includes a berm and dune template constructed of dredged sand material. The project does not include any new hard armor stone or concrete structures built to a set design elevation. The groin fields will lose effectiveness with sea level rise but this proposed project does not include any new or modified groins. The 2015 USACE Climate Change Adaptation Plan references ETL 1100-2-1 for guidance on how to plan and implement adaptation to changing sea level. For Folly Beach the initial berm elevation and width can be adjusted prior to the future renourishment cycle to address the impacts of SLC. There can also be additional nourishments, within consideration of project budget limits. Partial nourishments along the northeast half of Folly Beach is also an option where erosion rates are highest and sand travels southwest with the longshore current. Improved understanding, methods of analysis and data related to SLC will also become available during the life of the Folly Beach Project requiring updates to the predicted SLC presented in this study. Triggers for when planning should begin in adapting the project design or nourishment intervals will be developed and presented in the Operations and Maintenance Manual. Triggers will be based on changing rates of mean sea level at the Charleston NOAA gauge and by evaluating the performance of the Folly Beach CSRM.

The FEMA Base Flood Elevation (BFE), defined as the 1% Annual Exceedance Probability (AEP) Flood, is the regulatory requirement for the elevation or floodproofing of structures and are referenced to FEMA panels and transects, see Figure 3-12. BFE at Folly Beach varies along the shoreline and averages about elevation 10 ft NAVD88 (Section 3.5: Storm Surge). The BFE plotted relative to relative sea level change, see Figure 3-13. As a reference the tidal datums and extreme water levels (including the BFE) for the Charleston Gauge #8665530 are shown in Figure 3-14.

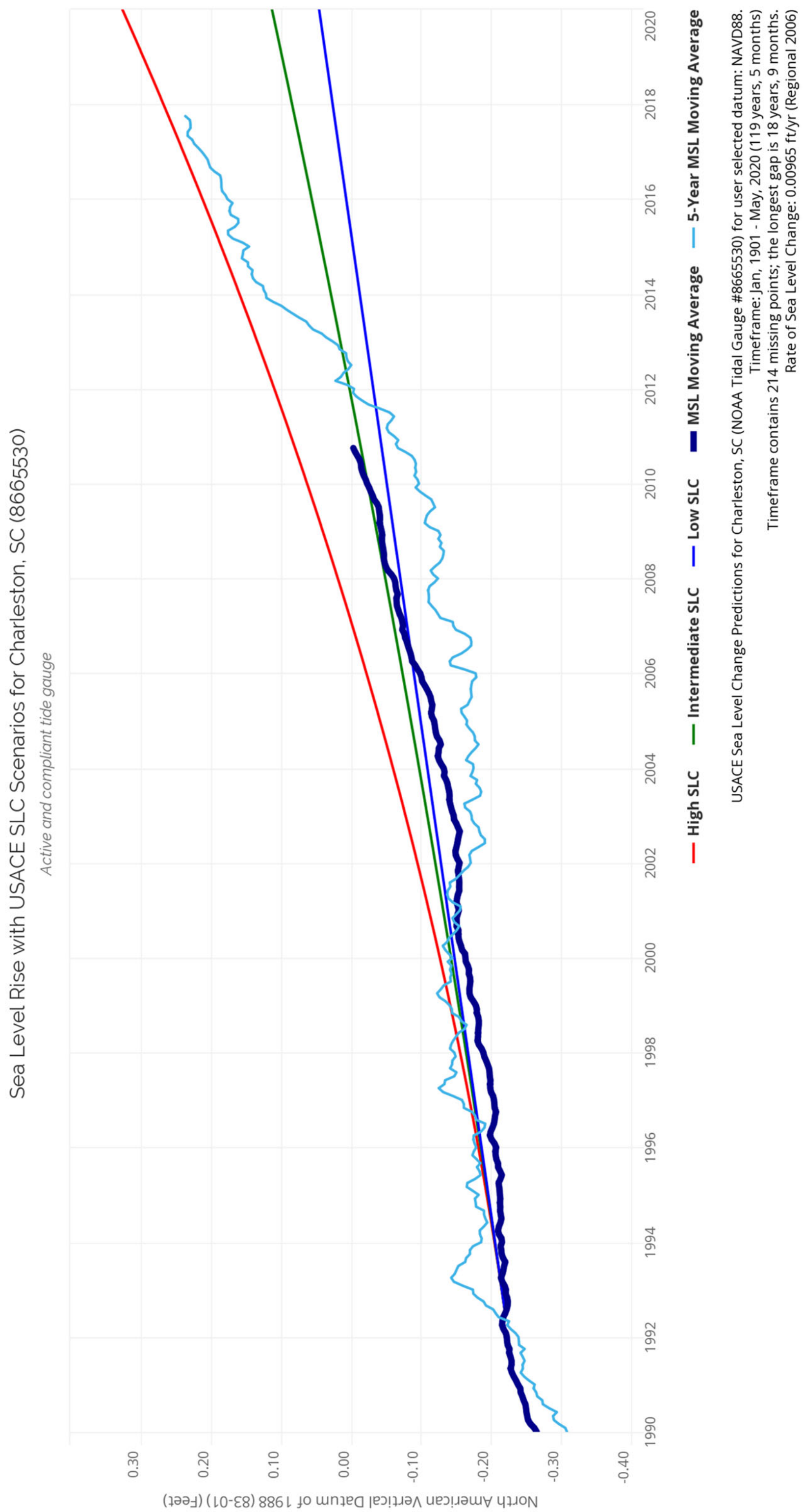

Figure 3-8. Charleston NOAA Gauge #8665530 SLC with 19-Year and 5-Year Moving Average

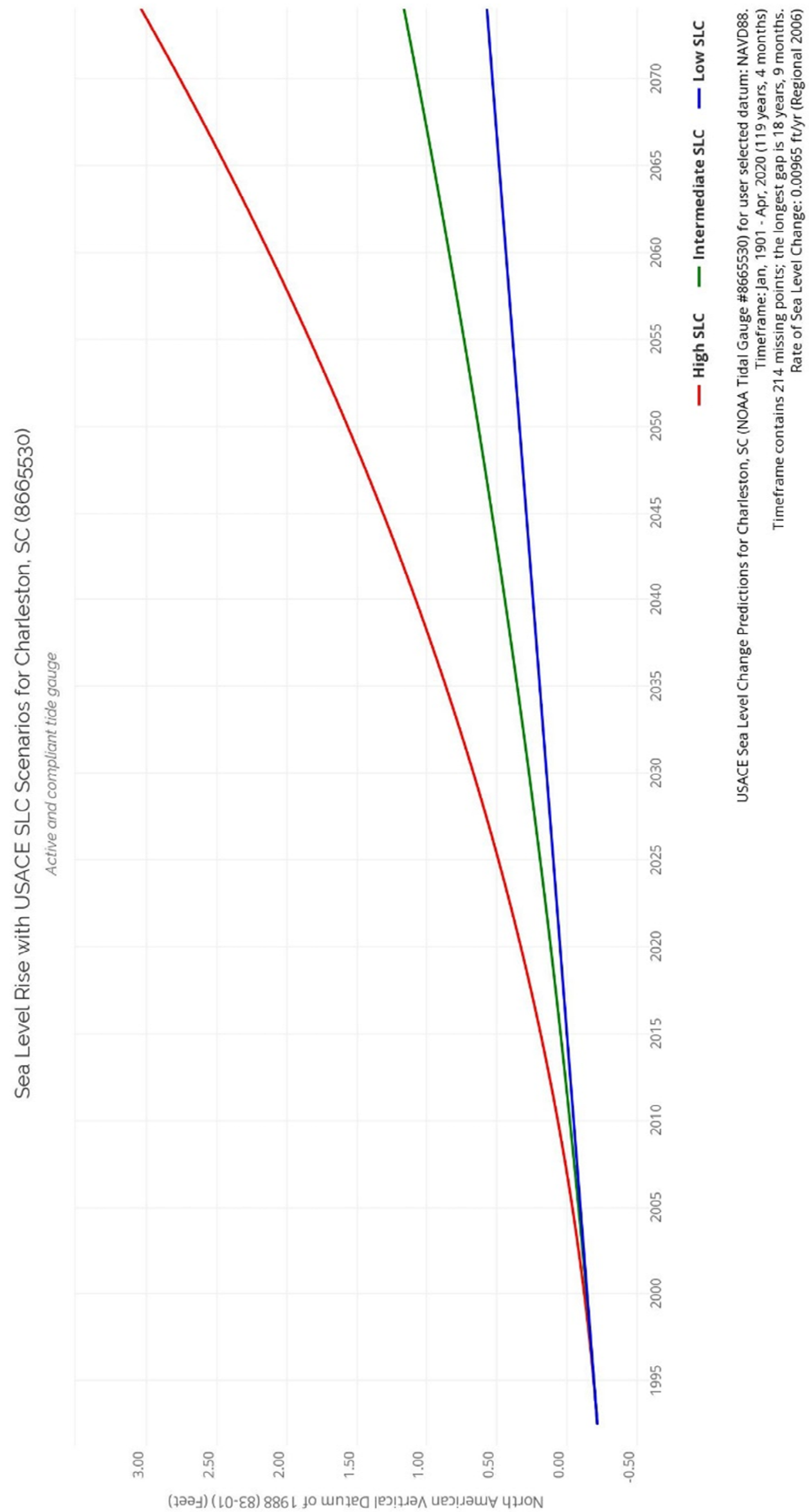

Figure 3-9. USACE Sea Level Change Predictions, Project Life 2024 to 2074

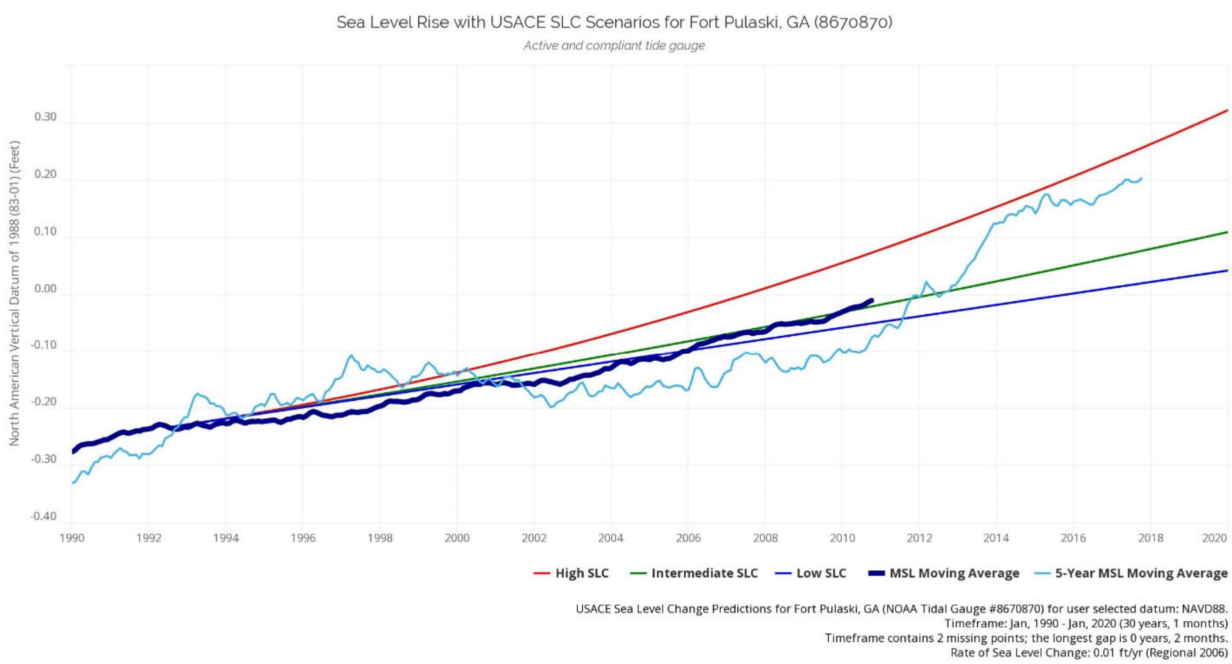

Figure 3-10. Ft. Pulaski, GA NOAA Gauge #8670870 SLC with 19-Year and 5-Year Moving Average

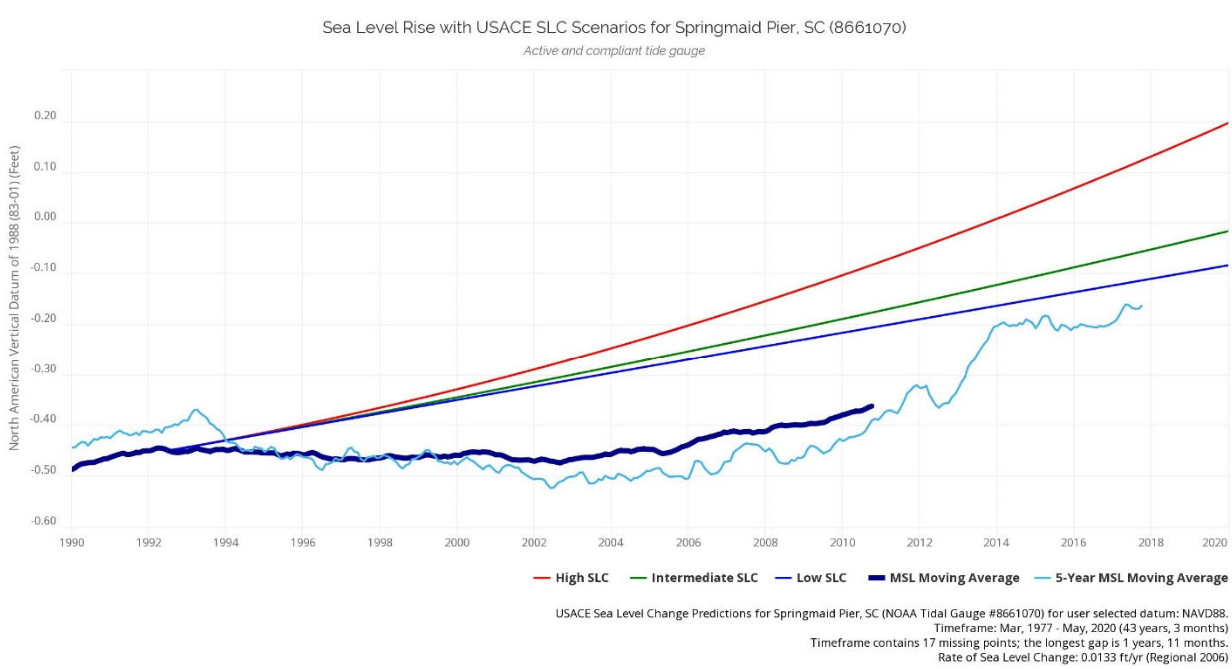

Figure 3-11. Springmaid Pier, SC NOAA Gauge #8661070 SLC with 19-Year and 5-Year Moving Average

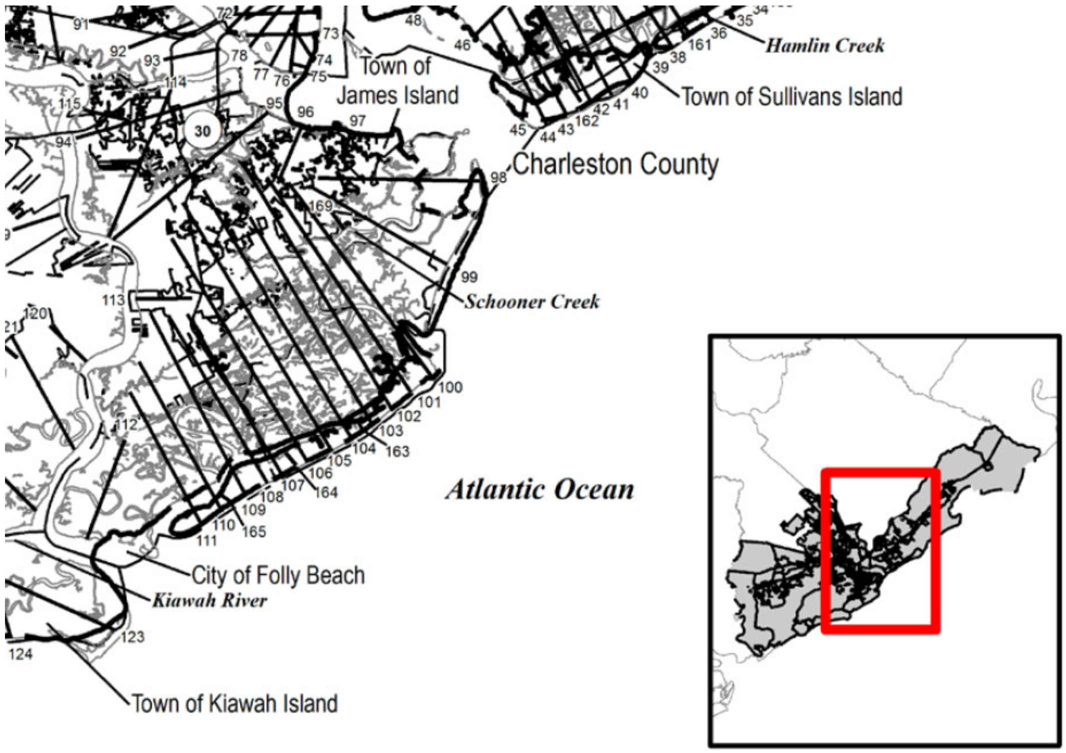

Figure 3-12. FEMA Flood Insurance Study Transect Location for Folly Beach

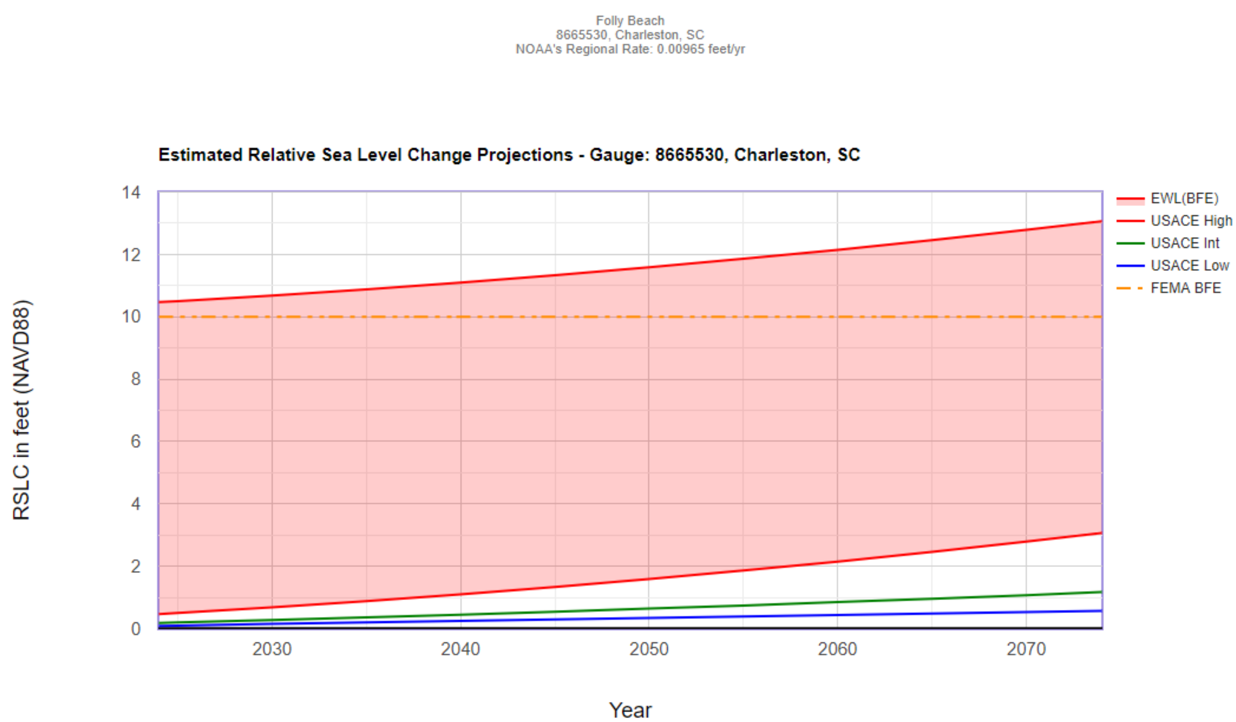

Figure 3-13. Estimated Relative Sea Level Change with BFE

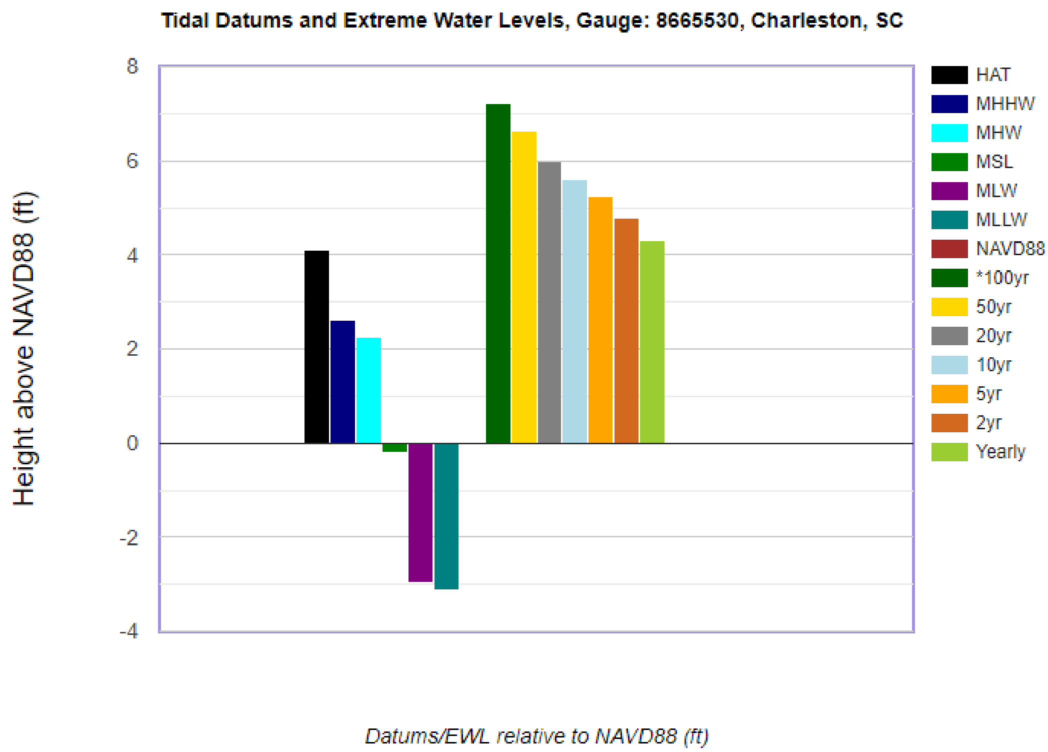

Figure 3-14. Tidal Datums and Extreme Water Levels

3.8 Storm Tide and Back Bay Flooding

Potential impacts of rising sea level on total water levels experienced at the site include overtopping of waterside structures, increased shoreline erosion, and flooding of low lying areas. Three cross-sections were drawn along the Folly Beach project site to determine elevations across the island, see Figure 3-15. Elevations at each transect are plotted with the BFE as well as the 2%, and 0.2% AEP water elevations for the High SLC scenario (+2.58 ft) at the end of the project life, see Figures 3-16, 3-17 and 3-18. The figures indicate that for existing conditions most of Folly Beach is currently susceptible to flooding during the 1% AEP and 0.2% AEP. The northeast end of the island is below elevation 10.0 ft NAVD88 and is susceptible for flooding during all flood events.

Relative vulnerability to flooding during extreme events is consistent between both with and without project conditions. Beach projects are resilient and adaptable to sea level changes by adjustments of the berm and dune elevation as sea level increases. While such an adjustment is not authorized within this study, it is something that will need to be considered for future project authorizations as well as maintenance by the local sponsor. The Beach-fx model incorporated back bay flooding by using the peak surge levels present on the oceanside along the rear of the economic reaches to ensure there was no double counting of structure or damage element cost or benefits.

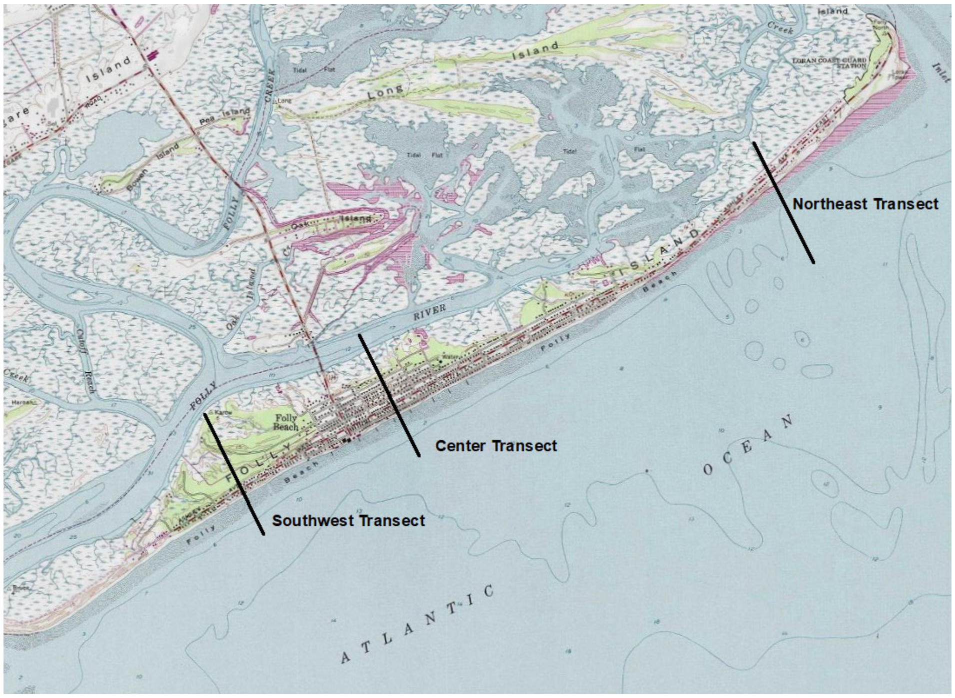

Figure 3-15. Folly Beach Elevation Transects

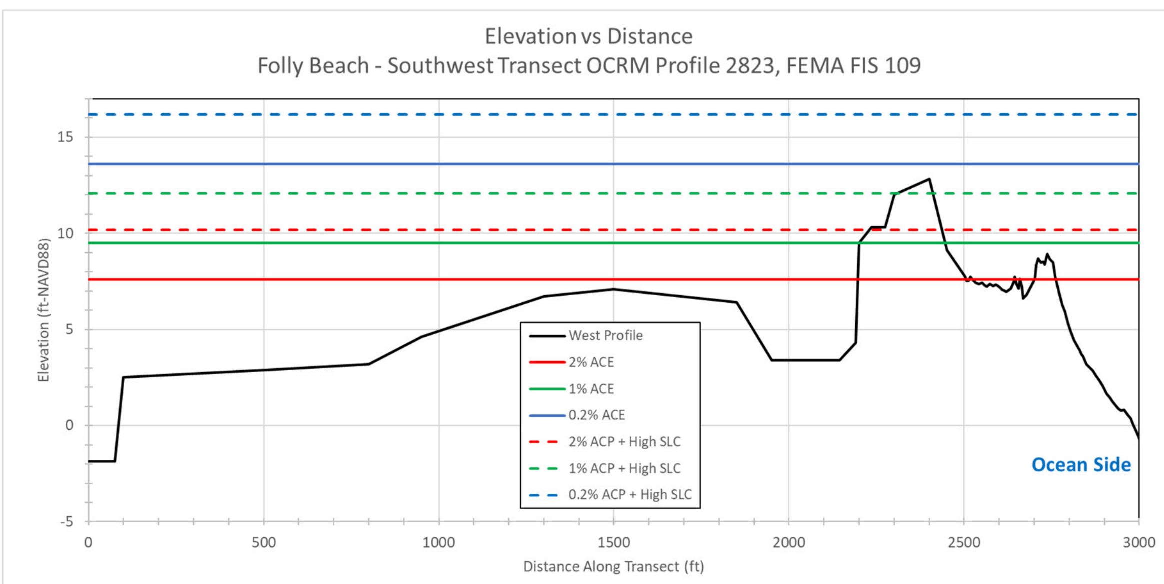

Figure 3-16. Land and AEP Elevations – Southwest Transect

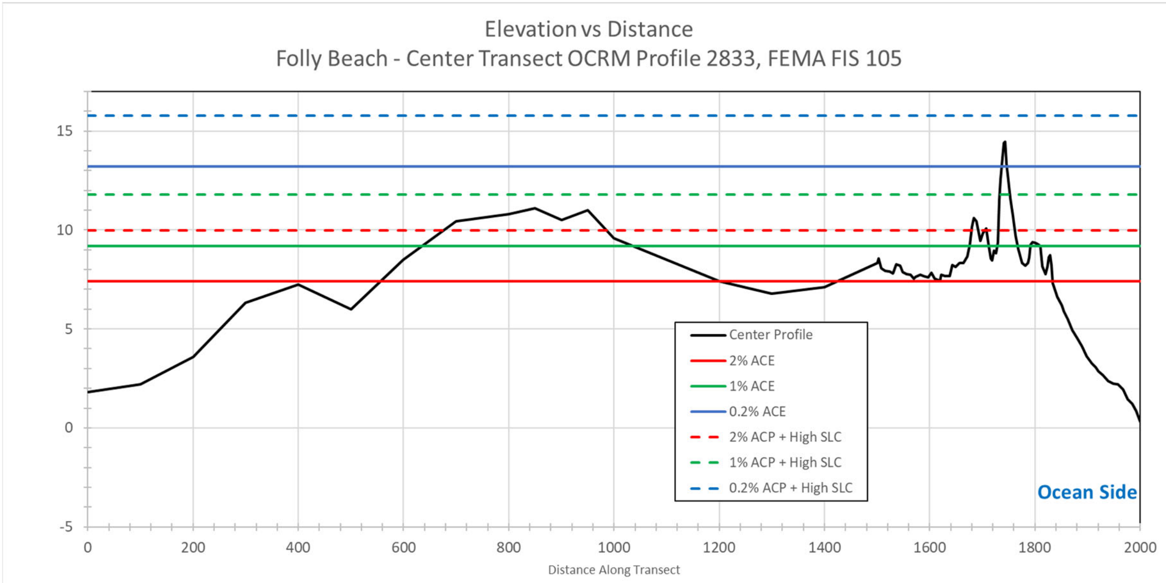

Figure 3-17. Land and AEP Elevations – Center Transect

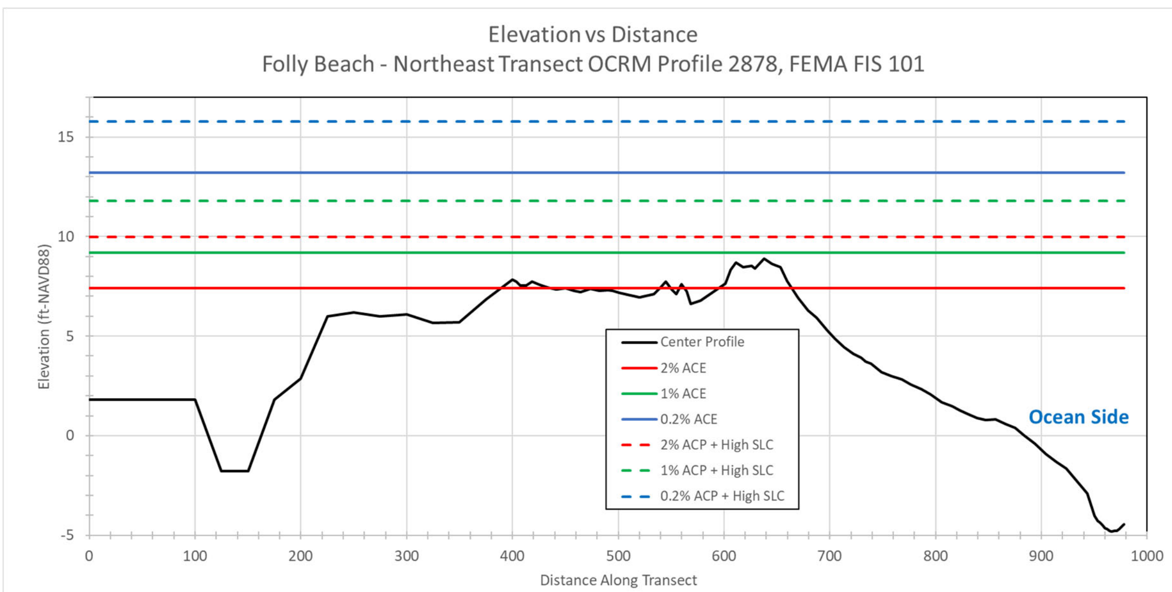

Figure 3-18. Land and AEP Elevations – Northeast Transect

4 Beach-fx Life-Cycle Shore Protection Project Evolution Model

Federal participation in projects is based on a favorable economic justification in which the benefits of the project outweigh the costs. Determining the Benefit to Cost Ratio (BCR) requires both engineering analysis (project cost, performance, and evolution) and economic analyses (plan formulation, plan selection, and quantification of project benefits). The interdependence of these functions has led to the development of the life-cycle simulation model Beach-fx. Beach-fx combines the evaluation of physical performance and economic benefits and costs of shore protection projects (Gravens et. al., 2007), particularly beach nourishment, for justification of Federal participation.

4.1 Background & Theory

Beach-fx is an event-driven life-cycle model. USACE guidance (USACE, 2006) requires that flood damage reduction studies include risk and uncertainty. The Beach-fx model satisfies this requirement by incorporating risk and uncertainty throughout the modeling process. Over the project life-cycle, typically 50 years for new studies, the model estimates shoreline response to a series of historically based storm events applied for each of three USACE sea level change scenarios as required by USACE Engineering Regulation, ER 110-2-8162 (USACE, 2013) and Engineer Pamphlet EP 1100-2-1 as described in Section 3.7. These plausible storms, the driving events, are randomly generated using a Monte Carlo simulation. The corresponding shoreline evolution includes not only erosion due to the storms, but also allows for storm recovery, post-storm emergency dune and/or shore construction, and planned nourishment events throughout the life of the project. Risk based damages to structures are estimated based on the shoreline response in combination with pre-determined damage functions for all structure types. Uncertainty is incorporated within the input data (storm occurrence and intensity, structural parameters, structure and contents valuations, and damage functions) and in the applied methodologies (probabilistic seasonal storm generation and multiple iteration, life cycle analysis). Results from the multiple iterations of the life cycle are averaged over a range of possible values.

The project site itself is represented by divisions of the shoreline referred to as “Reaches”. Because this term may also be used to describe segments of the shoreline to which project alternatives are applied (SBEACH reaches), Beach-fx reaches will be referred to in this appendix as “economic reaches”. Economic reaches are contiguous, morphologically homogenous areas that contain groupings of structures (residences, businesses, walkovers, roads, etc…), all of which are represented by Damage Elements (DEs). DEs are grouped within divisions referred to as Lots. Figure 4-1 shows a conceptual representation of the model setup. A single SBEACH Reach may be composed of several economic reaches. Economic reaches capture the diversity of shoreline dimension and erosion potential that can occur over a single economic reach.

Within the model, each economic reach is associated with a representative beach profile that approximates the cross-shore profile and beach composition of the reach. Multiple economic reaches may share the same representative beach profile while groupings of economic reaches may represent a single design reach. For Folly Beach, the project area was separated into 9 SBEACH reaches and 26 economic model reaches. Table 4-1 provides Folly Beach SBEACH and economic reaches with a map shown in Figure 4-2.

Implementation of the Beach-fx model relies on a combination of meteorology, coastal engineering, and economic analyses and is comprised of four basic elements:

- Meteorological driving forces
- Coastal morphology
- Economic evaluation
- Management measures

The subsequent discussion in this section addresses the basic aspects of implementing the Beach-*fx* model. For a more detailed description of theory, assumptions, data input/output, and model implementation, refer to Gravens et al. 2007; Males et al., 2007, and USACE 2009.

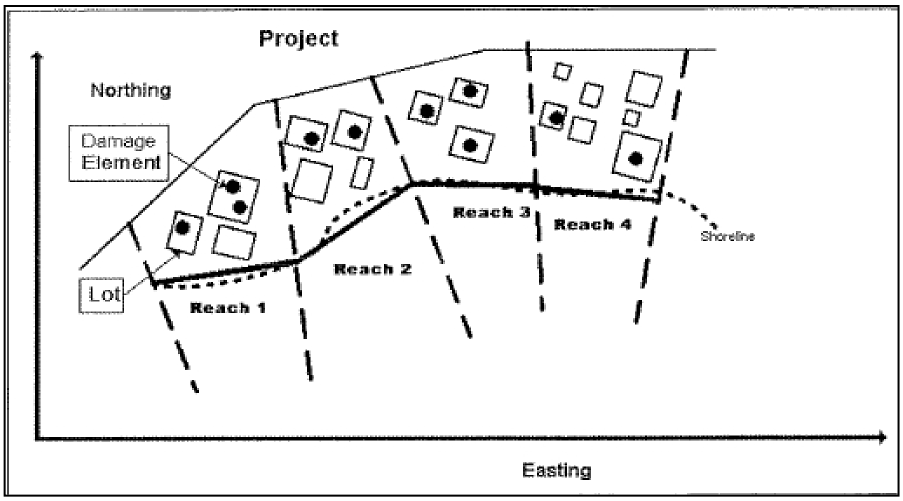

Figure 4-1. Beach-fx Model Setup Representation

Table 4-1. Folly Beach Economic and SBEACH Reaches

SBEACH Reach	Economic Reach
FB 01	R01
FB 02	R02
FB 03	R04 – R07
FB 04	R08
FB 05	R09 – R13
FB 06	R14 – R17
FB 07	R18 – R20
FB 08	R21 – R24
FB 09	R25- R26

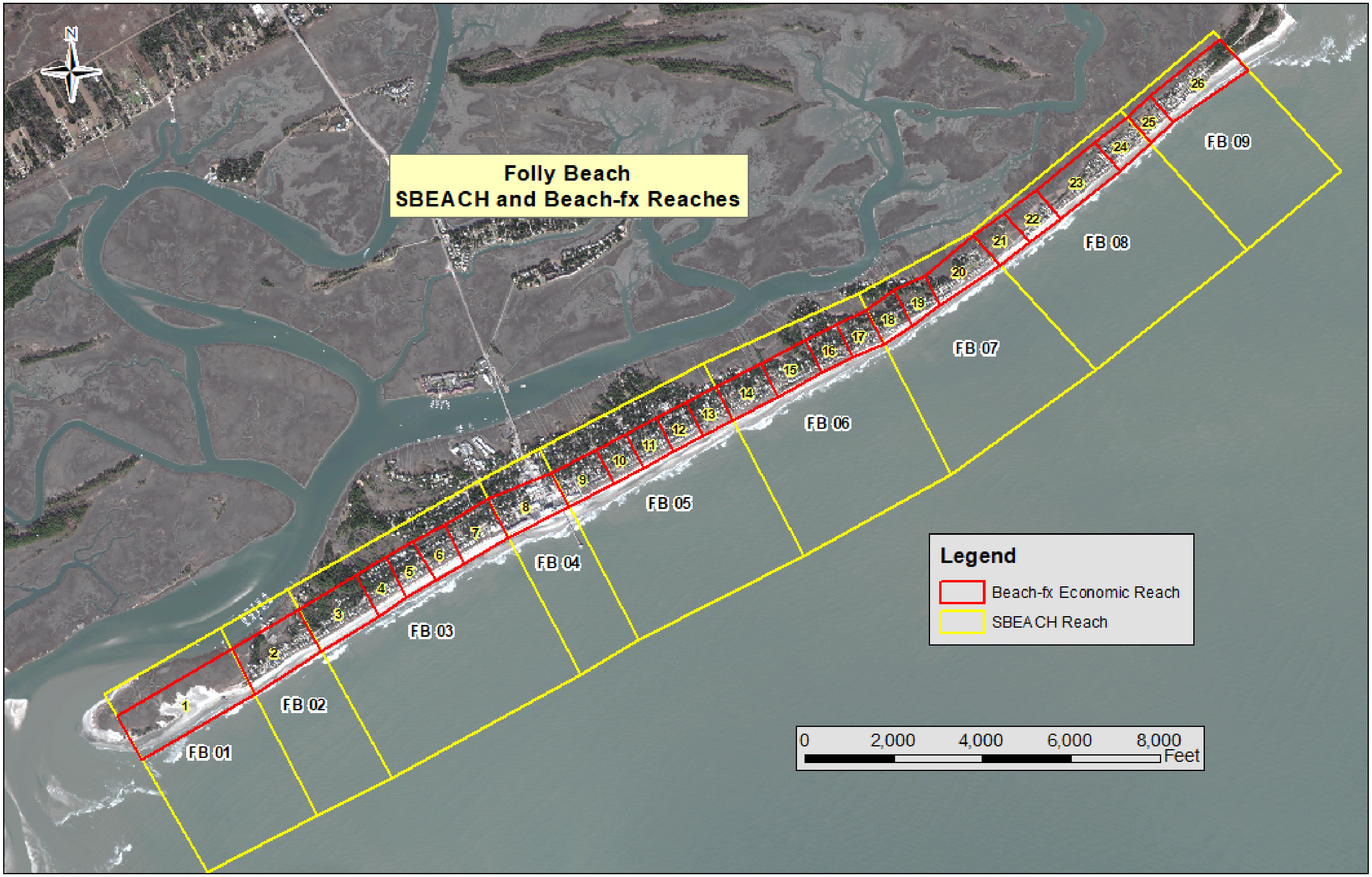

Figure 4-2. Folly Beach SBEACH and Beach-fx Economic Reaches

4.2 Engineering Parameters

4.2.1 Meteorological Driving Forces

The predominant driving force for coastal morphology and associated damages within the Beach-fx model is the historically based set of storms that is applied to the life-cycle simulation. Because the coast of South Carolina is subject to seasonal storms, tropical storms (hurricanes) in the summer months and extra-tropical storms (Northeasters) in the winter and fall months, the "plausible storms" dataset for Folly Beach is made up of both types. These storms were derived from hindcast data obtained from Oceanweather Incorporated (see Sub-Appendix A: Storm Suite Development – Folly Beach). The Folly Beach plausible storm set contains 21 tropical storms and 16 extra-tropical storms, see Table 4-2.

Because storm events may to be of limited duration, passing over a given site within a single portion of the tide cycle, it is assumed that any of the historical storms could have occurred during any combination of tidal phase and tidal range. Therefore, each of the plausible storm surge hydrograph was combined with possible variations in the astronomical tide. This was achieved by combining the peak of each storm surge hydrograph with the astronomical tide at high tide, mean tide falling, low tide, and mean tide rising for each of three tidal ranges corresponding to the lower quartile, mean, and upper quartile tidal ranges. This resulted in 12 combinations for each historically based storm and a total of 252 tropical storm conditions and 192 extra-tropical storms in the plausible storm dataset.

In addition to the plausible storm dataset, the seasonality of the storms must be specified. Storm seasons are based on the season in which the original historical storm occurred. Storm probability is defined through the Probability Parameter which is determined for each season and storm type by dividing the number of storms by the total number of years in the storm record (extra-tropical or tropical). Two storm seasons and two dormant periods were specified for Folly Beach, see Table 4-3.

The combination of the plausible storm dataset and the specified storm season allows the Beach-fx model to randomly select from storms of the type that fall within the season currently being processed. For each storm selected, a random time within the season is chosen and assigned as the storm date. The timing of the entire sequence of storms is governed by a pre-specified minimum storm arrival time. To allow for the possible frequency of Northeaster events in this area, a minimum arrival time of 10 days was specified for Folly Beach. Based on this interval, the model attempts to place subsequent storm events outside of a 20 day window surrounding the date of the previous storm (i.e. a minimum of 10 days prior to the storm event and a minimum of 10 days following the storm event). However, due to the probabilistic nature of the model the minimum arrival time may be overridden as warranted during the course of the life cycle analysis.

Table 4-2. Storm Selection

Tropical Storms	Extratropical Storms
30-Nov-1925	2-Feb-1961
25-Jul-1926	3-Mar-1962
15-Sep-1928	1-Feb-1973
9-Aug-1940	9-Feb-1973
18-Oct-1944	10-Feb-1981
14-Sep-1945	10-Feb-1985
16-Oct-1950	2-Jan-1992
28-Aug-1952	10-Feb-1993
13-Oct-1954	12-Mar-1993
23-Sep-1959	26-Jan-1998
7-Sep-1964	3-Feb-1998
1-Sep-1979	1-Jan-1999
20-Sep-1989	20-Mar-2001
14-Nov-1994	15-Feb-2003
7-Oct-1996	6-Feb-2013
13-Sep-1999	30-Apr-2013
23-Oct-2005	
3-Sep-2008	
1-Oct-2015	
5-Oct-2016	
9-Sep-2017	

Table 4-3. Folly Beach Beach-*fx* Storm Seasons

Storm Season	Start Date	End Date	Probability Parameter Extra-Tropical Storm	Probability Parameter Tropical Storm
Extra-tropical	Jan 1	Apr 30	0.48	0.00
Dormant	May 1	Jun 30	---	---
Tropical	Jul 1	Nov 30	0.00	0.33
Dormant	Dec 1	Dec 31	---	---

4.2.2 Coastal Morphology

The Beach-*fx* model estimates changes in coastal morphology through four primary mechanisms:

- Shoreline storm response
- Applied shoreline change
- Project-induced shoreline change
- Post-storm berm recovery

Combined, these mechanisms allow for the prediction of shoreline morphology for both with and without project conditions.

4.2.3 Shoreline Storm Response

Shoreline storm response is determined by applying the plausible storm set to simplified beach profiles that represent the shoreline features of the project site. For this study, application of the storm set to the idealized profiles was accomplished with the SBEACH coastal processes response model (Larson and Kraus 1989). SBEACH is a numerical model which simulates storm-induced beach change based on storm conditions, initial profiles, and shoreline characteristics such as beach slope and grain size. Output consists of post-storm beach profiles, maximum wave height and wave period information, and total water elevation including wave setup. Pre- and post-storm profiles, wave data, and water levels can be extracted from SBEACH and imported into the Beach-fx Shore Response Database (SRD). The SRD is a relational database used by the Beach-fx model to pre-store results of SBEACH simulations of all plausible storms impacting a pre-defined range of anticipated beach profile configurations.

4.2.4 Idealized Representative Profiles

In order to develop the idealized SBEACH profiles from which the SRD was derived, it was necessary to first develop representative profiles for the project shoreline. The number of representative profiles developed for any give project depends on the natural variability of the shoreline itself. Typically, profiles taken along the project shoreline are compared, aligned and averaged into composite profiles representative of dimensionally consistent segments of the shoreline. A representative profile may define one or more economic model reach. For Folly Beach nine representative profiles define the 26 economic reaches. This is necessary as each of the 26 economic reaches have either a unique background erosion rate or upland width. Folly Beach also included reaches where the majority of the shoreline reach length is armored. Representative profiles are developed according to the similarity between the following seven dimensions:

- Upland elevation
- Dune slope
- Dune height
- Dune width
- Berm height
- Berm width
- Foreshore slope

The start year of the current Beach-fx analysis is 2019 and the base year is 2024. The last nourishment prior to the start year was completed in early 2018. The 2024 shoreline would represent 4 years of erosion applied to the template. In order to estimate a 2024 shoreline, representative profile dimensions for the initial shoreline condition were derived from the late December 2018 and early January 2019 OCRM survey. Because the 2018/2019 OCRM survey did not capture the full upland extent of the dune system, additional upland information was obtained from a LiDAR elevation survey conducted by the USACE Charleston District in 2016.

Idealized profiles were calculated from the 2018/2019 shoreline survey, supplemented by the 2016 inland LiDAR survey, using the Composite Dune Methodology. Table 4-4 provides the dimensions of the idealized future without project representative profiles and the economic reaches they define.

Table 4-4. Dimensions of Idealized Without Project Representative Profiles

SBEACH Reach	Economic Reach	Upland Elevation	Dune Elevation	Dune Width	Dune Slope	Berm Elevation	Berm Width	Foreshore Slope
		(ft- NAVD88)	(ft- NAVD88)	(ft)	(H:1V)	(ft- NAVD88)	(ft)	(H:1V)
FB 01	R01	10	10	0	0.333	8	125	0.033
FB 02	R02	11	11	0	0.333	8	50	0.033
FB 03	R04 – R07	11	14	25	0.333	8	25	0.033
FB 04	R08	12	12	35	0.333	8	125	0.033
FB 05	R09 – R13	10	12	45	0.333	8	50	0.033
FB 06	R14 – R17	10	10	0	0.333	8	25	0.033
FB 07	R18 – R20	10	10	0	0.333	8	0	0.033
FB 08	R21 – R24	9	9	0	0.333	8	0	0.033
FB 09	R25- R26	9	9	0	0.333	8	0	0.033

4.2.5 SBEACH

SBEACH simulates beach profile changes that result from varying storm waves and water levels. These beach profile changes include the formation and movement of major morphological features such as longshore bars, troughs, and berms. SBEACH is a one-dimensional model that considers only cross-shore sediment transport. Longshore wave, current, and sediment transport processes are not included in SBEACH and are computed externally when required.

SBEACH is an empirically based numerical model, which was formulated using both field data and the results of large-scale physical model tests. Input data required by SBEACH describes the storm being simulated and the beach of interest. Basic requirements include time histories of wave height, wave period, water elevation, beach profile surveys and median sediment grain size. Beach-fx is designed to import and process output files exported directly from the SBEACH model.

SBEACH simulations are based on six basic assumptions:

- Waves and water levels are the major causes of sand transport and profile change
- Cross-shore sand transport takes place primarily in the surf zone
- The amount of material eroded must equal the amount deposited (conservation of mass)
- Relatively uniform sediment grain size throughout the profile
- The shoreline is straight and longshore effects are negligible
- Linear wave theory is applicable everywhere along the profile without shallow-water wave approximations

Once applied, SBEACH allows for variable cross shore grid spacing, wave refraction, randomization of input waves conditions, and water level setup due to wind. Output data consists of a final calculated profile at the end of the simulation, maximum wave heights, maximum total water elevations plus setup, maximum water depth, volume change, and a record of various coastal processes that may occur at any time-step during the simulation (accretion, erosion, over-wash, boundary-limited run-up, and/or inundation).

4.2.5.1 SBEACH Calibration

Traditionally, calibration and verification of the SBEACH model is performed as part of the study being undertaken. However, survey profile data at OCRM monuments beyond MLW were not available for calibration of the Folly Beach model immediately before and after significant storms. SBEACH parameters were determined from modelers experience with similar project shorelines and from studies on SBEACH model calibration for a given beach slope and sand size (Leadon, 2015; Leadon & Nguyen, 2011). The native mean grain size at Folly Beach is 0.17 mm and the inverse beach slope varies between 20 and 30 along the shoreline. Based on those conditions, the sediment transport rate coefficient (K) was estimated at 2.0 x 10^{-6} m^4/N and coefficient for slope-dependent term (ε) at 0.005 and the avalanching maximum slope at 40°. Time step was step to 1 minute to ensure stability of the model results. Sensitivity analysis indicated that model results were sensitive grid cell size and time step but not to the sand grain size.

4.2.5.2 SBEACH Simulations

Folly Beach SBEACH simulations were completed for each of the without project profiles and an array of incremental profiles covering a range of potential with-project conditions in combination with each of the tropical and extra-tropical storms in the plausible storm database. From these profiles, changes in the key profile dimensions were extracted and stored in the Folly Beach-fx SRD.

4.2.6 Applied Shoreline Change

The applied shoreline change rate (in feet per year) is a Beach-*fx* morphology parameter specified at each of the model reaches. It is a calibrated parameter that returns the historic background shoreline change rate for that location. Calibration is essential to insure that the morphology behavior is appropriate and representative of the study area.

The applied erosion rate used in Beach-fx is the expected rate of shoreline change in the absence of storm events (USACE, 2009). Beach-fx uses a suite of historic storm events over the 50-year project life along with the background erosion rate. It should be noted that this shoreline change rate is averaged over the period of record and does not represent the initial high rates of change that occur immediately after a nourishment project or that might be cyclical or a recent change in the shoreline trends. The planform rates are used later in Beach-fx simulations to capture the higher rates after nourishments and are based on more recent profile data.

The South Carolina Department of Health and Environmental Control's (SCDHEC) Office of Ocean and Coastal Resource Management (OCRM) has established 31 permanent beach profile monuments along Folly Beach, see Figure 4-3. The surveyed profiles extend seaward from the perpetual easement line out to a distance of approximately 3,300 ft offshore and to of depth of -13.5 ft to -16.5 ft NAVD88. The profiles are typically surveyed once a year since 1988 and are provided from OCRM in the NAVD88 datum. The OCRM profile database was the primary source of data used in the coastal morphology analysis because of its consistency in capturing the dune, shore and submerged profile along the same azimuth each year. All available OCRM data was imported into the USACE Regional Morphology Analysis Package (RMAP) software program within CEDAS for processing and analysis of the beach profile data. RMAP Analysis tools were used to calculate the distance from the OCRM monument seaward to the MHW elevation 2.26 ft NAVD88 contour for each year in the dataset to develop the shoreline change rates. RMAP was also used to develop the representative profiles used in SBEACH and Beach-fx by averaging the OCRM profiles within the reach to create the one representative profile.

The results of the historic shoreline analysis at Folly Beach revealed recession and accretion rates that varied both in time and in location along the shoreline. There are numerous natural and man-made features that influence the shoreline change rates at Folly Beach when compared to other shoreline in the Southeast. A 1987 Section 111 report determined that the Federal Charleston Harbor navigation jetties were responsible for 57% of the shoreline retreat at Folly Beach (USACE, 1987). The Section 111 report calculated an averaged Folly Beach long-term shoreline erosion rate of -4.2 ft/yr for the years of 1857 to 1983. Folly Beach is bounded by two inlets with tidal shoals that are continually evolving over time. Terminal groins at ends of the island complicates the dynamics in those areas. Morris Island is located northeast of Folly Beach and has a history of high erosion also related to the navigation jetties. The retreat of Morris Island has likely influenced increasing rates of shoreline retreat on the on the northeast end of Folly Beach. Another issue noted in calculating shoreline change rates on the northeast end of the island was the influence of bulkhead and revetment armoring. After a nourishment event the mean high tide line quickly retreats landward but slows as armoring in encountered.

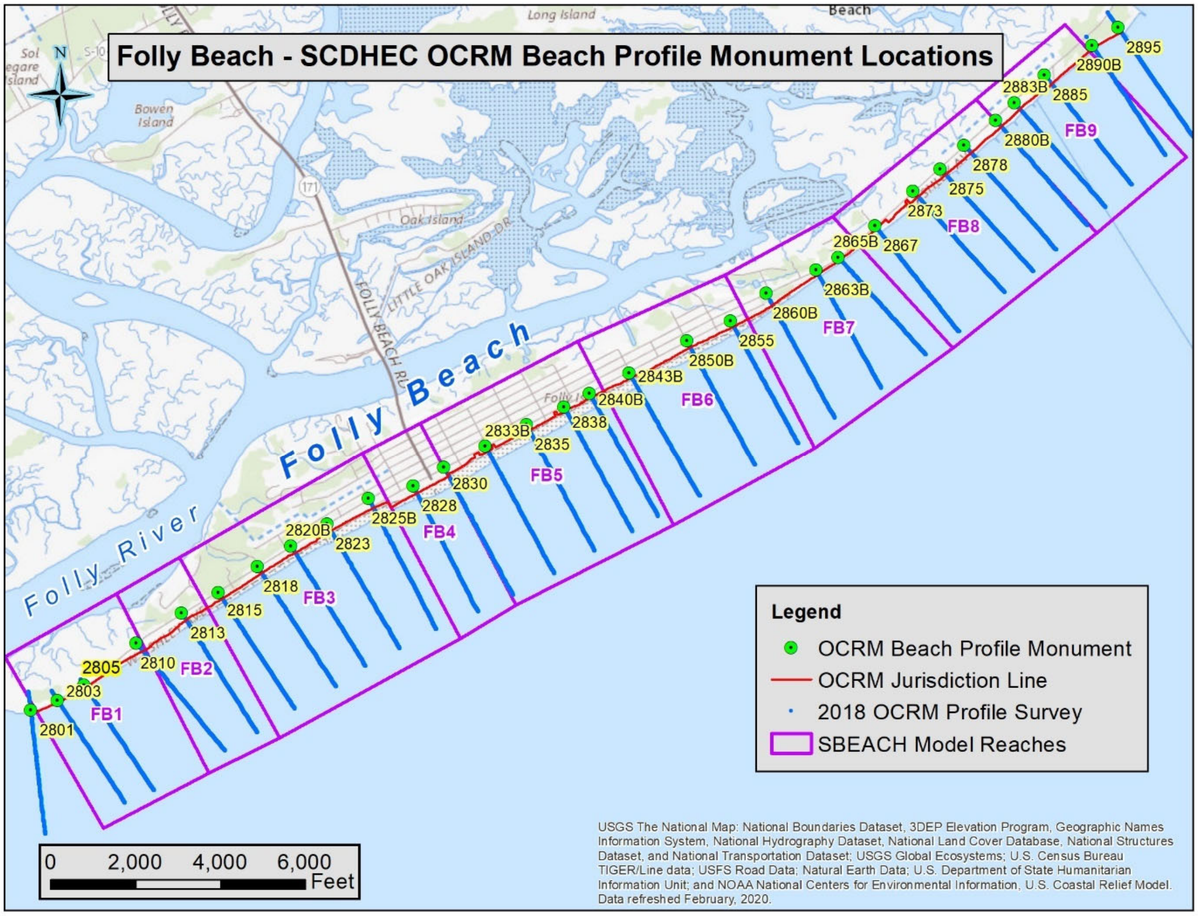

Figure 4-3. OCRM Beach Profile Survey Monuments

The OCRM profile data were used in calculating the historic shoreline change rates. The calculations looked at two periods between beach nourishment projects. Period 1 was between the July 1993 and May 2005 nourishment projects and Period 2 was between the June 2007 and June 2013 projects. The immediate post-nourishment survey was not used in the calculation to allow adjustment of the construction berm. Published long-term OCRM shoreline change rates were also reviewed but profiles on the southeast end were not used given the new terminal groin (SCDHEC, 2010).

The historic shoreline change rate calculations for Reaches FB1 and FB2 were impacted by the 2013 construction of the terminal groin and beach nourishment on the southwest end of the island. Historic rates at OCRM profiles 2805, 2810 and 2813 in FB1 and FB2 exceeded -20 ft/yr prior to 2014. Following adjustments to the new groin, the rates have varied with accretion and erosion in SBEACH Reaches FB1 and FB2. A rate of -2.0 ft/yr was used for those reaches. Shoreline rates for FB4 using OCRM monument 2828 was highly variable (accretion and erosion) and was likely influenced by the Folly Beach Fishing Pier, the interactions with the concrete seawall and by beach scraping. FB4 used an average of the rates from FB3 and FB5. The rates calculated for FB5 to FB7 are relatively high but were consistent through time. The shoreline change rates for FB8 and FB9 on the northeast end of the island have significantly increased since 2008. The loss of Morris Island is likely impacting sediment transport along with the changing dynamics of Lighthouse Inlet shoal on the northeast end. Planform erosion rates used with the nourishment project in-place were significantly higher than the historic applied erosion rates for FB8 and FB9. The groin fields along also play a role in the varying erosion rates along Folly Beach. As the beach profile lowers and retreats the groins become more effective in holding the sand in place with the MHW line becoming more stable within the groins fields.

The Beach-fx calibration followed the steps outlined in Section 7.2 of the Beach-fx Application Guide. The first step in calibrating the Beach-fx model was to determine the role of storm climatology and the post-storm recovery factor. The applied erosion rates were set to zero for each reach to determine the storm induced erosion. The berm width recovery factor was set at 90%. During Beach-fx calibration, applied erosion rates were adjusted for each model reach and the Beach-fx model was run for 100 iterations for the 50-year project life. Calibration is achieved when the rate of shoreline change, averaged over hundreds of life cycle simulations, is equal to the background (target) shoreline change rate expected. Table 4-5 provides the historical background erosion rates and the calibrated Beach-fx applied erosion rates.

Table 4-5. Historic Background and Calibrated Beach-fx Applied Erosion Rates

Model Reach	Historic Background Rate	Calibrated Applied Erosion Rate
	(ft/yr)	(ft/yr)
FB1	-2.00	-1.31
FB2	-2.00	-1.49
FB3	-5.40	-5.30
FB4	-4.33	-3.80
FB5	-3.27	-2.82
FB6	-4.90	-4.46
FB7	-7.66	-7.38
FB8	-7.00	-6.30
FB9	-8.88	-8.21

4.2.7 Project Induced Shoreline Change

The project induced shoreline change rate accounts for the alongshore dispersion of placed beach nourishment material. Beach-fx requires the use of shoreline change rates in order to represent the planform diffusion of the beach fill alternatives after placement. The GenCade model was selected for the Folly Beach analysis and a combination of the Genesis and Cascade models developed by the USACE and is on the approved software list for this application. The Genesis model accounts for the interaction of the existing groin fields and terminal groins with beach nourishment. The Cascade model has the ability to simulate the impact of inlets and regional geomorphology.

4.2.7.1 GenCade Model

The development of the GenCade on-line shoreline evolution model of Folly Beach was performed under contract with the engineering firm Moffatt & Nichol. The contract required the compilation and analysis of historical beach profile data to develop and calibrate a planform evolution model and to conduct analytical calculations relative to post-nourishment shoreline change rates of Future with Project (FWP) scenarios in the study reaches along Folly Beach. Details of the Moffat & Nichol analysis and results are provided in Sub-Appendix B.

4.2.7.2 Shoreline Change Rates

Using the calibrated GenCade model, the project induced shoreline change rates for the selected plan were calculated. Table 4-6 provides the calculated project induced shoreline change rates for the first 12-years after the initial beach nourishment in 2024. The rates reflect the high erosion rates of the beachfill during the first three years as the system adjust. Longshore current transported much of the sand eroded from northeast reaches (R18-R26) to the middle and southwest reaches which reflected accretion during the first years of the project. In the later years of the 12-year project, the change rates moderate and become more uniform as the beach profile is lowered and the groin fields become more effective in trapping sand and as beachfront armor is encountered. Higher rates were noted at transitions in the project alignment; the concrete seawall extends seaward in R8 and at R12 the profile transitions existing dune and berm lines. Table 4-7 includes the planform shoreline change rates for the four beach nourishments averaged over the 12-year period. The trends in Table 4-7 are similar but there are differences reflecting the different grain size from the borrow areas and different starting beach profiles at the time of the renourishment. Within the Beach-fx simulation, the applied erosion rates were subtracted from the planform erosion rates to ensure erosion was not double counted. Storm wave induced erosion continued within the Beach-fx simulation.

The GenCade model was also used to optimize the beachfill taper at the ends of the project by evaluating distances of 750 ft, 1,000 ft and 1,500 ft. Model results indicated the three distance were all viable alternatives and the 750 ft distance was selected on the ends and a 500 ft transition between the 35 ft and 50 ft berm widths between reach 21 and 22.

The initial results of the Beach-fx model using the GenCade developed planform rates were used to refine the Tentatively Selected Plan (TSP) dune and berm beach fill design. The original TSP design included a 35 ft wide berm along the southwest segment of the project between Beach-fx reaches R2 and R21 and a 50 ft wide berm along the northeast segment between reaches 22 and 26. Because of the higher erosion rates along economic reaches R18 to R21, the 50 ft wide berm was extended south for a total length of 9,720 ft between reaches R18 to R26. The planform rates were updated to reflect the change in the berm widths and transition location in the final Beach-fx model simulations.

Table 4-6. Project Induced Planform Shoreline Change Rates, Years 2024 to 2035

Beach-fx Reach	Shoreline Change Rates (ft/yr)											
	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
R#2	-3.0	-6.3	-7.5	-6.7	-4.1	-1.3	0.9	2.2	2.9	3.1	3.1	3.0
R#3	-1.2	1.2	2.0	1.8	1.2	0.9	1.0	1.2	1.5	1.7	1.9	1.9
R#4	8.4	8.6	7.7	6.0	4.4	3.5	2.7	2.1	1.8	1.6	1.5	1.5
R#5	12.5	13.7	9.6	6.9	5.2	3.7	2.8	2.1	1.7	1.4	1.2	1.1
R#6	30.5	12.9	7.2	4.8	3.6	2.7	2.1	1.6	1.3	1.0	0.8	0.7
R#7	2.8	-1.3	-1.1	-0.5	0.1	0.3	0.3	0.3	0.2	0.1	0.0	-0.1
R#8	-33.8	-14.3	-7.6	-4.7	-3.3	-2.5	-2.0	-1.7	-1.5	-1.4	-1.3	-1.3
R#9	18.5	2.7	-1.5	-2.8	-3.2	-3.2	-3.1	-2.9	-2.7	-2.6	-2.5	-2.4
R#10	18.3	6.2	0.3	-2.0	-3.0	-3.3	-3.3	-3.3	-3.1	-3.0	-2.9	-2.9
R#11	-4.4	-3.1	-2.8	-3.2	-3.4	-3.5	-3.5	-3.4	-3.4	-3.3	-3.2	-3.1
R#12	-29.6	-10.6	-6.2	-4.4	-3.6	-3.3	-3.2	-3.1	-3.1	-3.2	-3.2	-3.3
R#13	-11.0	-10.0	-6.2	-4.3	-3.4	-3.0	-2.9	-3.0	-3.1	-3.2	-3.3	-3.4
R#14	0.3	-1.9	-2.2	-2.2	-2.2	-2.4	-2.6	-2.8	-3.0	-3.2	-3.3	-3.4
R#15	8.5	4.8	1.6	-0.4	-1.7	-2.6	-3.2	-3.6	-3.9	-4.1	-4.3	-4.2
R#16	6.9	2.1	-0.6	-2.4	-3.5	-4.3	-4.8	-5.1	-5.3	-5.4	-5.5	-5.8
R#17	-3.6	-5.0	-5.6	-5.9	-6.2	-6.3	-6.4	-6.4	-6.4	-6.4	-6.4	-6.8
R#18	-18.6	-13.5	-11.8	-10.7	-9.9	-9.3	-8.9	-8.6	-8.5	-8.3	-8.2	-7.9
R#19	-19.1	-18.0	-15.5	-13.7	-12.6	-11.8	-11.3	-10.9	-10.5	-10.3	-10.1	-9.8
R#20	-21.2	-17.2	-15.9	-14.9	-14.2	-13.6	-13.1	-12.7	-12.4	-12.0	-11.7	-11.5
R#21	-3.5	-12.0	-13.2	-13.5	-13.6	-13.5	-13.4	-13.2	-13.0	-12.7	-12.4	-12.1
R#22	-12.6	-11.4	-12.1	-12.5	-12.7	-12.8	-12.8	-12.7	-12.5	-12.2	-12.0	-11.8
R#23	-13.4	-11.9	-11.6	-11.7	-11.8	-11.9	-11.8	-11.6	-11.4	-11.2	-11.0	-10.8
R#24	-9.3	-10.2	-11.5	-11.7	-11.5	-11.2	-11.0	-10.7	-10.6	-10.4	-10.2	-10.2
R#25	-4.8	-11.5	-12.4	-11.8	-11.1	-10.5	-10.1	-9.8	-9.7	-9.7	-9.8	-10.0
R#26	-21.7	-13.0	-9.3	-7.6	-6.9	-6.7	-6.6	-6.9	-7.2	-7.6	-8.1	-8.5

4.2.8 Post Storm Berm Recovery

Post storm recovery of eroded berm width after passage of a major storm is a recognized process. Within Beach-fx, post-storm recovery of the berm is represented in a procedure in which the user specifies the percentage of the estimated berm width loss during the storm that will be recovered over a given recovery interval. It is important to note that the percentage itself is not a "stand alone" parameter that is simply applied during the post storm morphology computations. The percentage of berm recovery is estimated prior to model calibration and becomes a tunable calibration parameter to ensure model convergence (when the model reproduces the target erosion rates as discussed in Section 4.2.6: Applied Shoreline Change). For Folly Beach calibration required a varying berm recovery factor of 90% over a recovery period of 21 days.

Table 4-7. Project Induced Planform Shoreline Change Rates, 12 Year Average

Beach-fx Reach	Average Shoreline Change Rates (ft/yr)			
	Jan2024 Fill	Jan2036 Fill	Jan2048 Fill	Jan2060 Fill
R#2	-1.1	0.1	0.2	-1.5
R#3	1.3	0.6	0.3	-0.4
R#4	4.1	0.7	0.3	-0.2
R#5	5.2	0.5	0.1	-0.2
R#6	5.8	0.4	0.2	-0.1
R#7	0.1	0.0	0.0	0.0
R#8	-6.3	-0.4	0.0	0.1
R#9	-0.5	0.2	0.9	0.9
R#10	-0.2	-1.2	-0.9	-0.9
R#11	-3.3	-3.0	-3.2	-3.3
R#12	-6.4	-6.9	-7.1	-7.0
R#13	-4.7	-5.3	-5.4	-5.2
R#14	-2.4	-2.7	-2.8	-2.4
R#15	-1.1	-1.2	-1.3	-0.9
R#16	-2.8	-2.8	-2.8	-2.3
R#17	-6.0	-5.9	-6.0	-5.5
R#18	-10.3	-10.4	-10.4	-10.3
R#19	-12.8	-12.9	-12.9	-13.0
R#20	-14.2	-14.3	-14.3	-14.5
R#21	-12.2	-12.2	-12.2	-12.5
R#22	-12.4	-12.4	-12.4	-12.6
R#23	-11.7	-11.7	-11.7	-11.8
R#24	-10.7	-10.8	-10.8	-10.9
R#25	-10.1	-10.2	-10.2	-10.5
R#26	-9.2	-9.2	-9.2	-9.2

4.2.9 Management Measures

Shoreline management measures that are provided for in the Beach-fx model are emergency nourishment and planned nourishment.

4.2.9.1 Emergency Nourishment

Emergency nourishments are generally limited beach fill projects conducted by local governments in response to storm damage. The Beach-fx model assumes emergency fill events have a single profile template, a consistent length of coverage, and occur when specific post-storm shoreline conditions are met. Folly Beach does not have a history of consistent emergency nourishment in response to storm related erosion. The lack of a history of consistent locally sponsored post-storm emergency events, makes assigning realistic emergency fill triggers and specifications within Beach-fx impossible. Therefore, this management measure was not included in the Folly Beach-fx analysis.

4.2.9.2 Planned Nourishment

Planned nourishments are handled by the Beach-fx model as periodic events based on nourishment templates, triggers, and nourishment cycles. Nourishment templates are specified at the model reach level and include all relevant information such as order of fill, dimensions, placement rates, unit costs, and borrow-to-placement ratios. Planned nourishments occur when user defined nourishment triggers are exceeded and a mobilization threshold volume is met. At a pre-set interval, all model reaches which have been identified for planned nourishment are examined. In reaches where one of the nourishment threshold triggers is exceeded, the required volume to restore the design template is computed. If the summation of individual model reach level volumes over the extent of the project exceeds the mobilization threshold volume established by the user, then nourishment is triggered and all model reaches identified for planned nourishment are restored to the design template.

4.2.9.3 Nourishment Templates

Beach-fx planned nourishment templates are defined by three dimensions, the template dune height, template dune width, and template berm width. Berm elevations and dune and foreshore slopes remain constant based on the existing profiles. The SBEACH Data Generator was used to develop multiple dune and berm combinations for simulation with SBEACH and the storm suite. Dune combinations included top widths between 5 ft and 45 ft and top elevations from 9.0 ft to 15.0 ft NAVD88. The dunes have a side slope of 3H:1V. Berm widths varied between 0.0 ft and 150 ft at 25 ft increments. A summary of profile template alternatives evaluated is provided in Table 4-8. A berm elevation of 8.0 ft NAVD88 was selected as this is the existing berm elevation noted in OCRM profiles with no scarps. Beach-fx is limited to a single berm at a constant elevation. The 35 ft berm was later added to refine the design between 25 ft and 50 ft berms.

Table 4-8. SBEACH Profile Alternative Templates Analyzed

SBEACH Reach	Dune Elevations (ft)	Dune Top Widths (ft)	Berm Widths (ft)	Total Profiles
1	10, 11, 12, 13, 14, 15	5, 15, 25, 35, 45	0, 25, 35, 50, 75, 100, 125	180
2	11, 12, 13, 14, 15	5, 15, 25, 35, 45	0, 25, 35, 50, 75, 100, 125	150
3	11, 12, 13, 14, 15	5, 15, 25, 35, 45	0, 25, 35, 50, 75, 100, 125	150
4	11, 12, 13, 14, 15	5, 15, 25, 35, 45	0, 25, 35, 50, 75, 100, 125	150
5	12, 13, 14, 15	5, 15, 25, 35, 45	0, 25, 35, 50, 75, 100	100
6	10, 11, 12, 13, 14, 15	5, 15, 25, 35	0, 25, 35, 50, 75, 100	120
7	10, 11, 12, 13, 14, 15	5, 15, 25, 35	0, 25, 35, 50, 75, 100, 125	144
8	9, 10, 11, 12, 13, 14, 15	5, 15, 25, 35	0, 25, 35, 50, 75, 100, 125, 150	196
9	9, 10, 11, 12, 13, 14, 15	5, 15, 25, 35	0, 25, 35, 50, 75, 100, 125, 150	196

4.2.9.4 Nourishment Distance Triggers and Mobilization Threshold

Beach-fx planned nourishment templates have three nourishment distance triggers (1) berm width, (2) dune width, and (3) dune height. Each distance trigger is a fractional amount of the corresponding nourishment template dimension. When the template dimensions fall below the fraction specified by the trigger, a need for re-nourishment is indicated. For Folly Beach the dune width trigger was set to 0.90, dune height trigger was 0.85 and the berm width trigger was set to 0.75.

The mobilization threshold (minimum nourishment volume required to trigger a nourishment cycle) can be set in coordination with the berm trigger to control the nourishment cycles. The berm trigger can be used to maintain an “allowable” minimum berm width if desired. For Folly Beach, rather than a specific minimum berm width, the trigger and threshold were used to ensure an “allowable” minimum volume of material. The berm trigger was set at 0.75, which allows Beach-fx to begin assessing volume deficiencies almost immediately. The mobilization threshold was then set to a volume reflecting expected volume losses between placement events. The mobilization threshold was 1,500,000 cubic yards, see Economics Appendix for additional details.

4.3 Recommended Plan

From the Beach-fx economic analysis of the dune and berm combinations a recommended plan was developed. The recommended plan included a dune and berm combination for economic reaches 2 through 26. Reach 1 includes the Charleston County Park and was not economically feasible. The plan includes a continuous 5.0 ft top width dune at elevation 15.0 ft NAVD88 with a 35 ft wide berm on the southwest end and a 50 ft berm along the northeast end, details are provided in Section 5.

Alternative engineering designs were considered and rejected. A series of detached breakwaters along the shoreline was rejected because of cost and as a hazard to swimmers and navigation. Rock revetments and seawalls were rejected based on negative environmental impacts on sea turtle nesting and limited available real estate for the structures along the shoreline.

5 Project Design

5.1 Project Length

The Folly Beach Recommended Plan includes two segments that will receive nourishment, see Figure 5-1. The southeast segment is 16,970 ft in length and extends from station 22+00 to 191+70 and includes a 750 ft transitions on the southeast end that extends into the Charleston County Park. The northeast segment is 9,720 ft in length and extends from station 191+70 to 288+90 and includes a 750 ft transition to an existing groin at the northeast end. The total project length is 26,690 ft or 5.1 miles. Typical profiles of the dune and berm template in the southwest and northeast segments are provided in Figures 5-2 and 5-3. A general description of the Recommended Plan is provided below.

Southwest Segment
Station: 22+00 to 191+70
Length: 16,970 ft
Berm Width: 35 ft
Berm Elevation: 8 ft NAVD88
Dune Top Width: 5 ft
Dune Elevation: 15 ft NAVD88

Northeast Segment
Station: 191+70 to 288+90
Length: 9,720 ft
Berm Width: 50 ft
Berm Elevation: 8 ft NAVD88
Dune Top Width: 5 ft
Dune Elevation: 15 ft NAVD88

5.2 Project Baseline

The project construction baseline will be seaward of the SCDHEC OCRM Jurisdictional Baseline and in the general vicinity of the landward toe of the existing dune. In regions where the existing dune is ill defined, extrapolation from adjacent areas with dunes, consideration of localized topography, and position infrastructure will be considered. Due to the complexity of the shoreline, involving residential and commercial structures as well as instances of shoreline armor, the exact baseline will not be fully determined until the Planning, Engineering, and Design (PED) phase of the study. During the PED and construction phases coordination with the local sponsor and with private property owners will be required to ensure there is no ponding of stormwater runoff landward of the project and there is adequate stormwater drainage.

5.3 Project Dune

The plan includes raising the dune to a uniform elevation of 15 ft NAVD88 with a minimum top width of 5 ft. The peak storm surge and wave heights during Hurricane Hugo in the storm suite defined the dune crest elevation. Existing dunes may be extended seaward depending on the baseline location and elevation and will be better defined during the PED phase. The existing beachfront dune line along Folly Beach is variable with multiple dune lines both seaward and landward of project construction baseline including reaches with no dune. The southwest segment of Folly Beach currently has an established dune line at elevations 10 ft to 13 ft NAVD88 generally landward of the project baseline. The middle section of Folly Beach currently has a dune system at elevation 11 to 15 ft landward and seaward of the project baseline. The exact layout of the dune and berm template will be determined during the PED phase. The northeast segment of the project generally has either no dune or no existing dune above elevation 10 ft NAVD88.

5.4 Project Berm

The berm elevation is at elevation 8.0 ft NAVD88, which is consistent with the previously authorized project and approximates the natural berm elevation. The berm width is 35 ft wide in the southwest segment and 50 ft in the higher erosion prone northeast segment between Beach-fx Reaches 18 to 26. Restricting the design berm elevation to the natural berm elevation minimizes scarping of the beach fill as it undergoes readjustment. Vertical scarps can hinder the beach access of nesting sea turtles, and may also pose safety problems related to recreational beach use. Other reasons for mimicking the natural berm elevation are related to storm damage protection. A berm constructed at a lower elevation would increase the probability of overtopping by relatively frequent storms, thereby offering less protection to upland development and/or existing dunes. A higher berm elevation could result in problems related to backshore flooding due to excessive rainfall or wave overtopping. A higher berm may also be more susceptible to wind-induced erosion.

5.5 Project Beach Slopes

After adjustment and sorting of the placed material by wave action, the material is expected to adjust to an equilibrium beach slope, similar to the native beach. Beach slopes tend to be variable dependent on location of nearby groin and beach armoring. Beach slopes in the project are vary between 1V:20H to 1V:30H. Sand from the various borrow sites may also differ in mean grain size with different slopes after the equilibrium profile and the wave climate is achieved.

It is unnecessary and impractical to artificially grade beach slopes below the low water elevation since they will be shaped by wave action. The front slope of the beach fill placed at the time of construction or future renourishment may differ from that of the natural profile. The angle of repose of the hydraulically placed material depends on the characteristics of the fill material and the wave climate in the project area. With steep initial slopes, the material will quickly adjust to the natural slopes. For design purposes it is assumed that that construction berm will have an approximate slope of 1V:15H.

5.6 Project Cross-Shore Dimensions

The project cross-shore dimensions, seaward of the construction baseline will vary on the existing beach profile at the time of construction. The plan includes a dune with a top width of 5 ft at elevation 15 ft NAVD88 and side slopes of 1V:3H. With a berm elevation of 8.0 ft NAVD88 at the project construction baseline, the base of the proposed dune will be 47 ft wide. With the 35 ft berm the total project cross-shore width would be 82 ft and for the 50 ft berm the width would be 97 ft. The total width of the construction template will be wider and will be determined during the PED phase.

5.7 Project Volumes and Renourishment Interval

Each complete Beach-fx model run consists of 100 iterations, each iteration was estimated that initial construction in the base year (2024) would require approximately 1.8 mcy, followed by an additional 2.1 mcy of re-nourishment on average at 12 year intervals. The selected project layout can be reviewed in Figure 5-1.

Table 5-1 provides the Beach-fx project initial volumes and re-nourishment interval volumes for each of the three sea level change scenarios. Each complete Beach-fx model run consists of 100 iterations, each iteration representing the life of the project (50 years). The volumes include overfill ratios for the different borrow area used within Beach-fx. Based on the recommended plan with 100 iterations an average volume was determined for each initial fill event and each subsequent renourishment event. Model runs were made for each of the three sea level rise cases, Base (low), Intermediate, and High. Based on the economic analysis the renourishment interval was set at 12 years. Initial fill will be from Lighthouse Inlet, second from Folly River, third from Stono Inlet and the final fill from Folly River. The final nourishment was increase to include two additional years of eroded volume to reach the end of the 50-Year project.

Table 5-1. Beach-fx Project Volumes and Renourishment Interval: 50 Year Project

Project Volumes (Project Life – 50 Years)				
Sea level change Case	Volume Description	Initial Fill Volume (cubic yards)	Renourishment Interval (years)	Average Volume per Interval (cubic yards)
Base	Min - Max	---	12	1,676,000 – 2,138,000
	Average	1,779,000		1,864,000
Intermediate	Min - Max	---	12	1,854,000 – 2,507,000
	Average	1,833,000		2,108,000
High	Min - Max	---	12	3,618,000 – 2,486,000
	Average	2,002,000		2,899,000

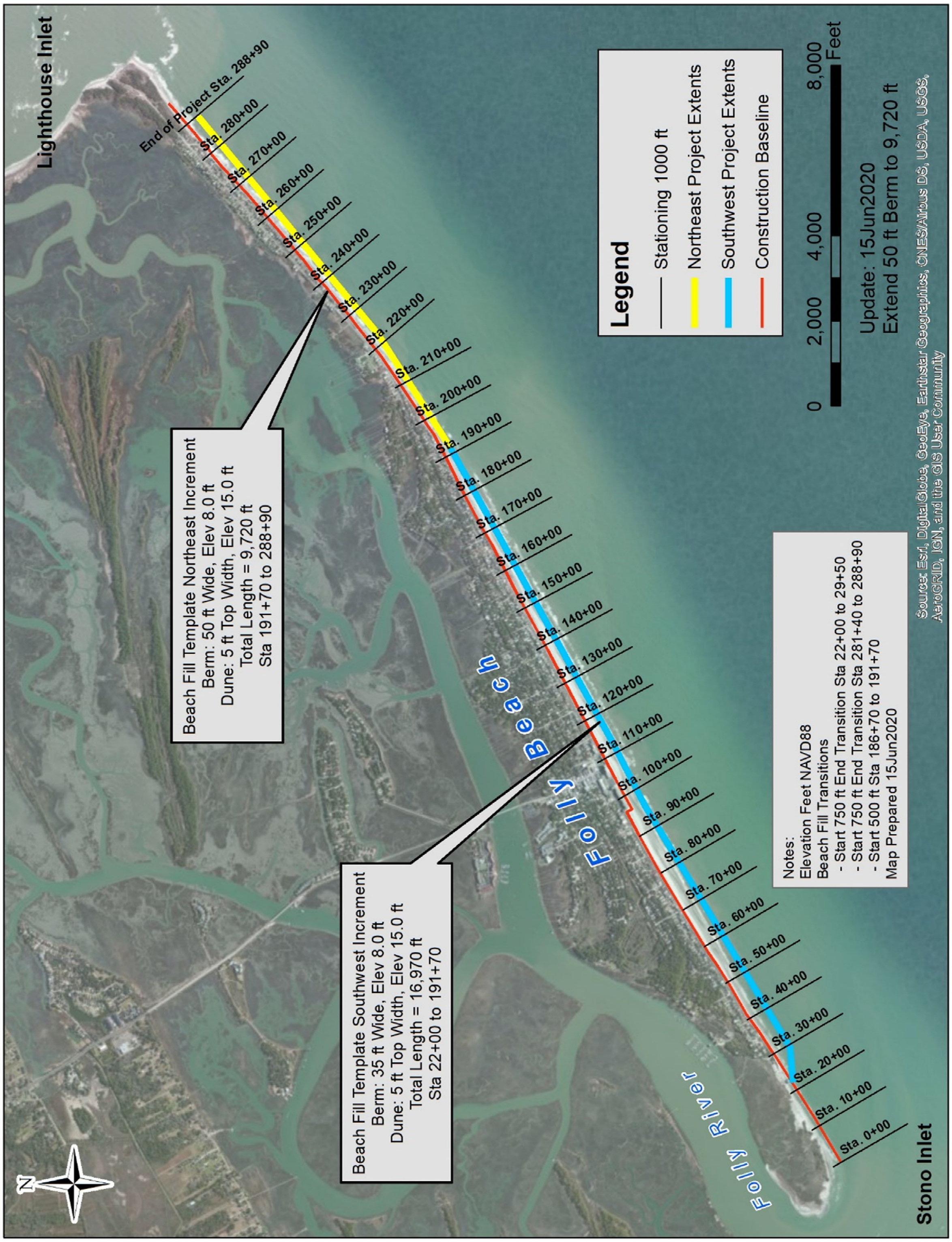

Figure 5-1. Selected Plan Project Layout

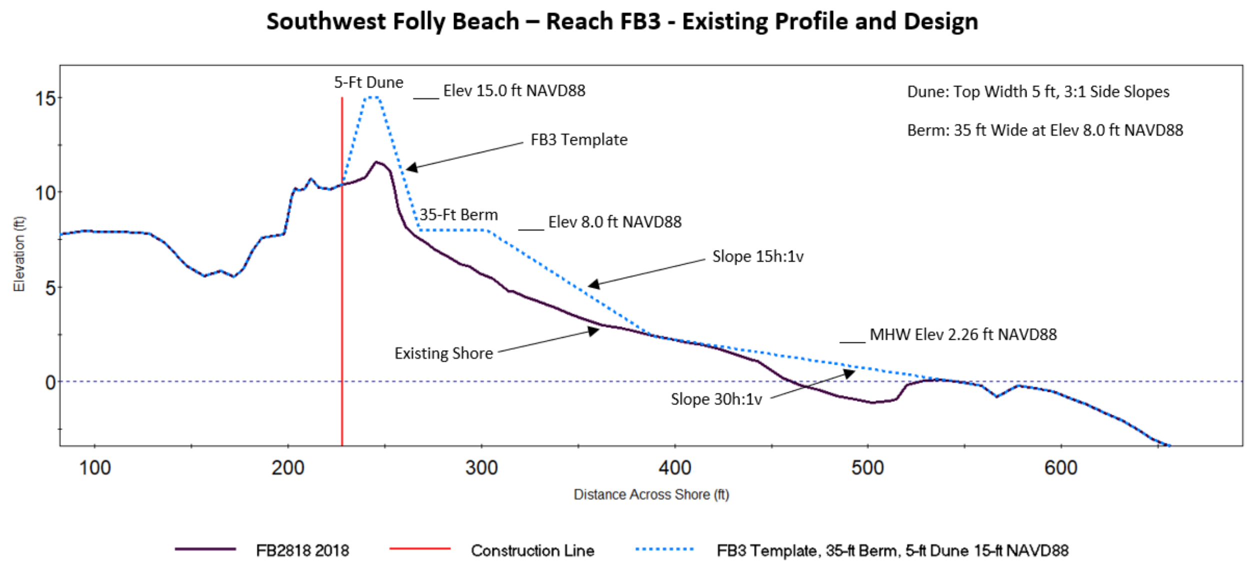

Figure 5-2. Typical Profile Southwest Segment Folly Beach

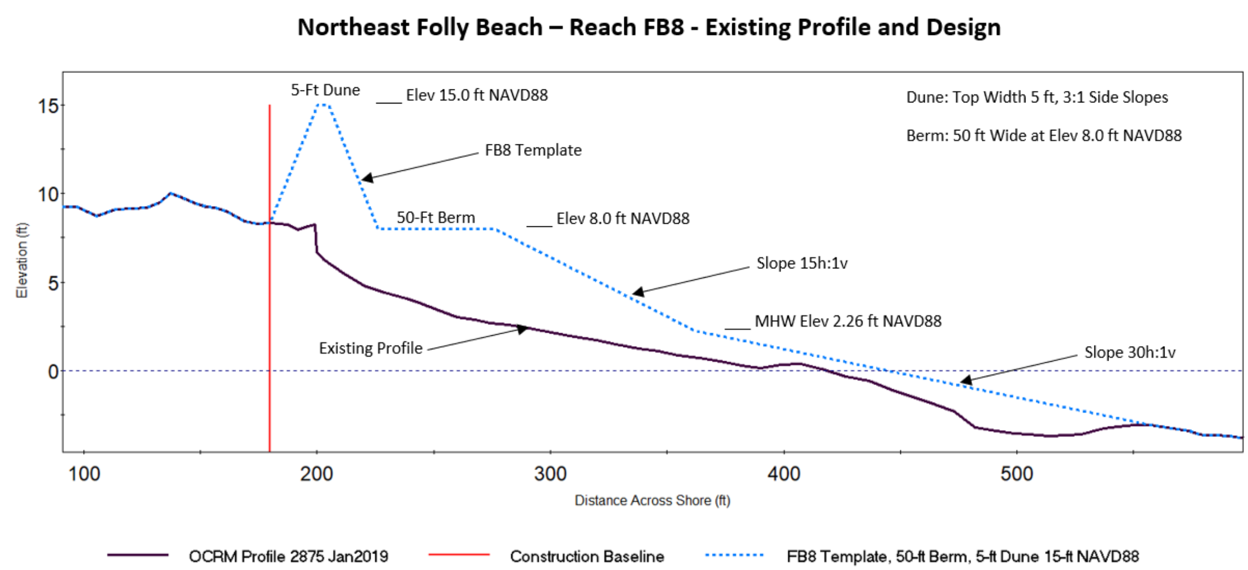

Figure 5-3. Typical Profile Northeast Segment Folly Beach

6 Borrow Area Impact Analysis

The USACE Engineering Research & Development Center's (ERDC) Coastal Hydraulics Laboratory (CHL) conducted two sand borrow area impact studies for the Folly Beach CSRM Study. The first study analyzed five offshore borrow sites. This study is complete with the results summarized below and with details provided in CHL's final report provided in Sub-Appendix C. The second CHL study focused on sediment transport and morphologic changes due to sand dredged from borrow areas within the Folly River and Stono Inlet. The final report for this study is expected in August, 2020. The Wilmington District also investigated the recharge rate for material excavated from the Folly River in 2013 with details provided in Sub-Appendix D.

6.1 Offshore Borrow Areas

Excavation of sand from locations offshore of Folly Beach for nourishment projects will cause changes in the nearshore bathymetry which will affect the wave transformation in that area. CHL conducted an analysis of the proposed borrow areas on wave propagation at Folly Beach using the Steady-state wave model (STWAVE). The software is on the USACE approved list for this application. The map in Figure 6-1 includes the location and the depths of excavation for the five borrow areas initially proposed, note that depths on the NOAA chart are in MLLW datum. The map also includes thirteen reference locations along the Folly Beach shoreline and Stono Inlet for evaluating changes in wave height and direction. The STWAVE model uses wave data from the WIS hindcast Station #63348 from 1980 to 2017 as the offshore boundary condition and bathymetry from FEMA's South Carolina Storm Surge grid.

The borrow areas were evaluated for two wave conditions; monthly mean and monthly maximum. Wave from four directions were evaluated; 60°, 115°, 170° and 225°. The mean monthly condition had a wave height of 3.6 ft and a period of 8.4 second. The monthly maximum condition had a wave height of 8.5 ft with a period of 9 seconds. The areas were also evaluated for the extreme event with a recorded wave direction of 97°, wave height of 20.3 ft and a period of 18 seconds. Figure 6-2 provides a reference for the dominant wave directions along with Kiawah Island, Stono Inlet Shoal and the Charleston Harbor Jetties.

6.1.1 Borrow Areas A and B

Borrow areas A and B (Seaward) are located about 5 miles southeast of Lighthouse Inlet. CHL evaluated this location but the borrow area was ultimately rejected because the volume of suitable sand was depleted during the 2014 Folly Beach nourishment project, no further analysis.

6.1.2 Borrow Areas E and K

Borrow Areas E and K (Stono Ebb Shoal #2) are located about 4.5 miles southeast of the east end of Folly Beach. This borrow area is likely a relict ebb shoal of Stono Inlet developed during periods of lower sea level. The mean grain size is 0.23 mm and the percent of silt and clay fines was 3.08% in Area E and 6.88% in Area K. The in-place volume for Area E is 14,000,000 CY and the volume for Area K is 500,000 CY.

6.1.3 Borrow Area F

Borrow Area F (Lighthouse) is located about 2 miles south of Lighthouse Inlet and 1.5 miles offshore the east end of Folly Beach. Excavation was shallower than the other borrow areas at a depth of -22.0 ft NAVD88. The mean grain size is 0.26 mm and the percent of silt and clay fines was 5.31%. The in-place volume for Area F is 2,800,000 CY.

6.1.4 Borrow Area G

Borrow Area G (Central Folly) is located in the center of the region about 2.5 miles offshore of Folly Beach. The mean grain size is 0.17 mm and the percent of silt and clay fines was 7.68%. The in-place volume for Area G is 8,000,000 CY. Borrow Area G was rejected as a potential borrow site because of the high fines content, no further analysis.

6.1.5 Borrow Areas I and J

Borrow Area I is located within the Stono Inlet throat and Area J is located in the inner ebb tide shoal. Excavation was assumed to be 10 feet in depth below the existing bathymetry. During the initial CHL analysis, the STWAVE results indicated that excavation of these two areas resulted in significant wave height increase to Folly Beach and to the eastern tip of Kiawah Island with a high risk of negative impacts. Wave heights increased by 1.2 feet along the perimeter of the borrow areas for the mean monthly wave conditions. Borrow Areas I and J were rejected as potential borrow sites, no further analysis.

6.1.6 Results – Offshore Borrow Area Effects

From the wave rose in Figure 6-2 approximately 84% of the wave direction at Folly Beach is between 68° (ENE) and 115° (SSE). This summary focuses on the results for borrow Area E & K and Area F from the 115° and 170° dominant wave directions with results provided in Table 6-1. Additional results are provided in CHL's report in Sub-Appendix-B. Wave heights decreased in the immediate area over the borrow sites and increased along the leeward side of the borrow site dependent on the wave direction. Generally the increased wave heights did not propagate towards the shoreline significantly higher than existing conditions. The greatest increase in wave height occurred was during the most oblique wave angle of 225°, this wave direction has a frequency of occurrence of 1.7%.

The extreme condition showed the greatest effects of borrow area excavation but the effects remained isolated within the borrow areas. Wave heights increased over 1.4 ft at all sites but the increased waves did not propagate further inshore compared to existing conditions. There were no increased wave heights along the 13 reference points along the shore.

Use of borrow Area E & K did not show significant impacts along the 13 reference points along Folly Beach or at Stono Inlet and Kiawah Island. The largest wave height increase at the reference locations for the mean monthly wave condition was 0.03 ft at locations 7 and 8. The maximum monthly wave condition showed no increase with wave heights at the reference locations compared to existing conditions.

For the frequent wave direction the use of borrow Area F had a 0.18 ft increase in the mean monthly wave height at reference location 6 for a wave direction 115°. This is a 4.3% increase above existing conditions. Locations to the east of location 6 saw a decrease in wave heights. For waves from 170° there was a 0.1 ft increase or 2.3% at location 6. There was no increase in wave heights for the maximum monthly wave conditions when using borrow area F for the 115° and 170° wave directions. There were increases and decreases along the shoreline at reference locations 5 and 7 from the infrequent oblique wave angles of 225° and 60°.

6.2 Folly River Recharge Rate

The Folly River navigation channel has routinely been dredged since the 1970's. The volume removed average about 30,000 CY with the material placed along the Charleston County Part on the southwest end Folly Beach (CSE, 2002). The first large-scale dredging of Folly River was in 1993 with 3.1 mcy removed from the river and 2.7 mcy placed along Folly Beach. An evaluation of recharge rates of South Carolina borrow sources investigated the post 1993 recovery of the Folly River using annual bathymetric surveys (Van Dolah, 1998). The study estimated an average annual recharging rate of 18% for compete refilling in 5.5 years. The study noted that Bird Key near the confluence of the Folly River and Stono Inlet was eroded following the 1993 project. The 2001 Folly Beach monitoring report of the 1993 project noted that the project likely exacerbated erosion at the southwest end of the island at the County Park (CSE, 2001). Reduced placement of material from the navigation channel likely contributed to the erosion also. A terminal groin was constructed at the southwest end of Folly Beach at the County Park in June, 2013 to address the loss of beach and damage to infrastructure at the Park. The monitoring reports noted that the rapid refilling rate of 18% may have been related loss of sand from the intertidal shoals including Bird Key and from the southwest end of Folly Beach.

An updated estimate of the Folly River recharge rate was conducted based on the May 2013 dredging of the Folly River. The 415,000 CY of material excavated from the Folly River was used to restore the beach at the County Park and to facilitate the construction of the 745 ft long terminal groin. A summary of the recharge analysis is provided in Sub-Appendix D. An average recharge rate of 12.25% was calculated over the four year period. The lower recharge rate compared to the post-1993 project rate of 18% may be related to the smaller volume excavated and the influence of the new terminal groin with the Stono Inlet system. The 12.25% recharge rate will be used in this current Folly Beach analysis until the results of the CHL analysis of Stono Inlet is complete.

6.3 Sediment Transport Folly River and Stono Inlet (Ongoing)

The primary objective of this study is to evaluate sediment transport and morphologic changes due to sand dredged from borrow areas within the Folly River and Stono Inlet and placement in nearshore beaches. The Coastal Modeling System (CMS) will be used to calculate waves, current, tide, and sediment transport within and around the immediate vicinity of the Stono Inlet, Bird Key/Skimmer Flats, Folly Island, and the eastern end of Kiawah Island. Sediment management alternatives on sand dredged and placement will be developed and comparisons between alternative results will be conducted under various forcing conditions in the nearshore area of the Stono Inlet and the Folly River. The study includes a field data collection effort of tidal and current patterns in the study area. The study is scheduled to be completed in August 2020 and will be included as Sub-Appendix E of the Coastal Engineering Appendix.

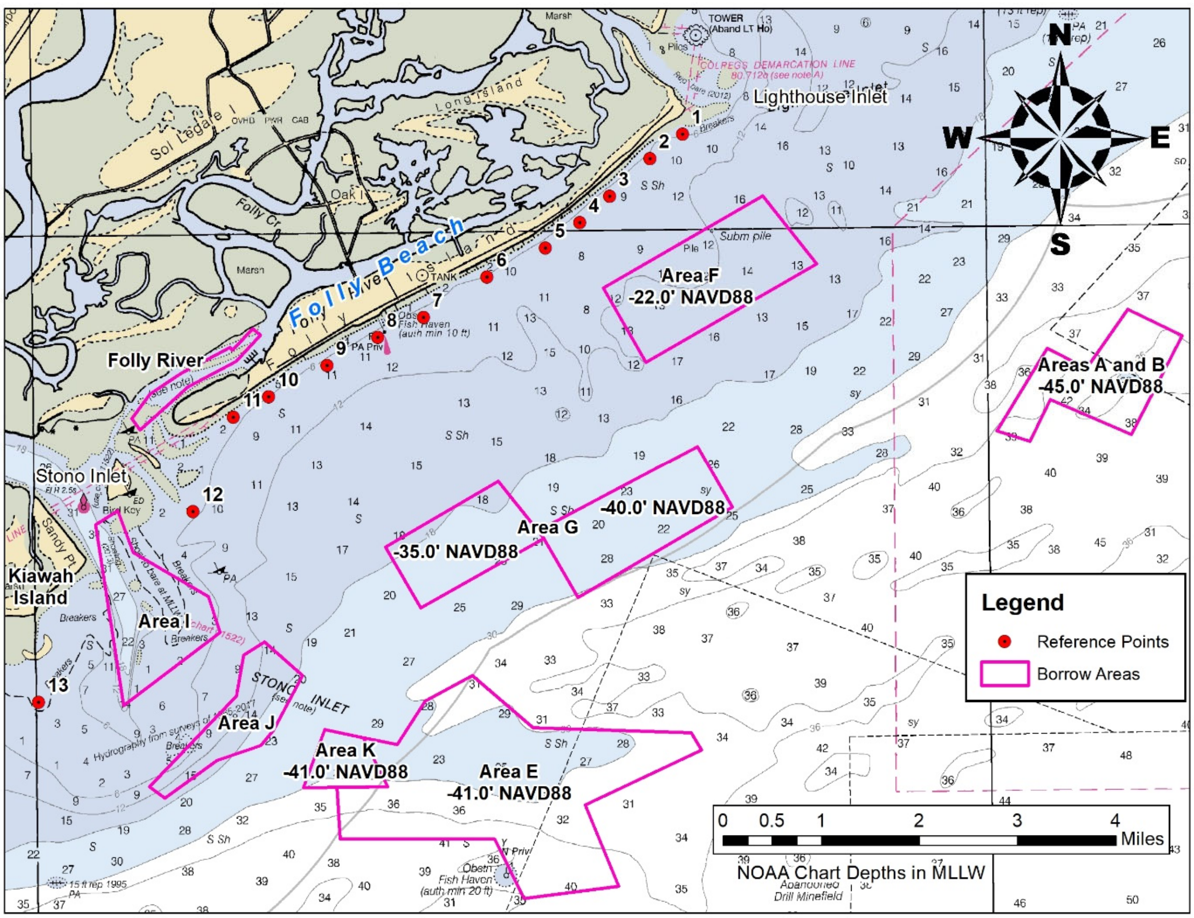

Figure 6-1. Borrow Area Impact Analysis

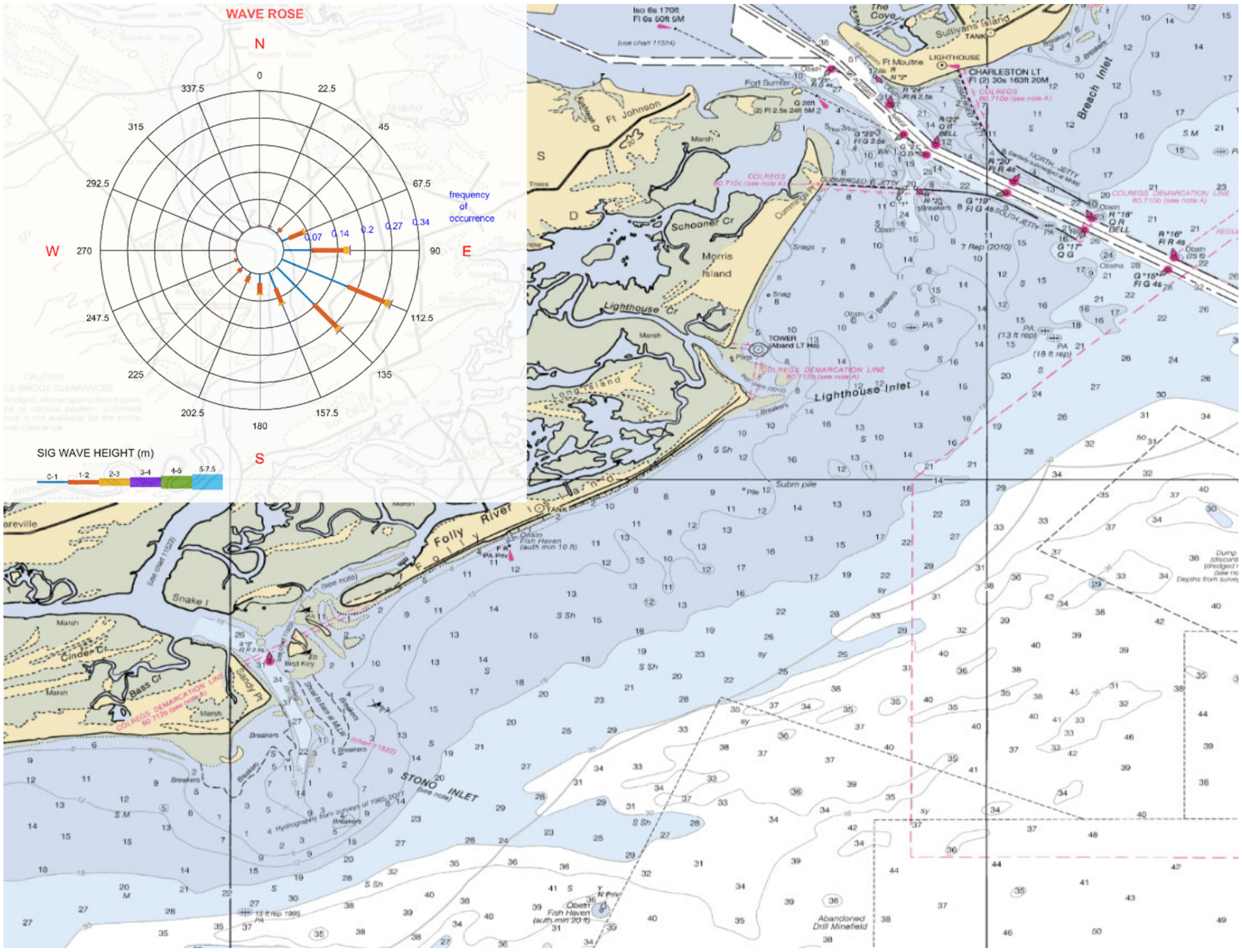

Figure 6-2. Folly Beach Wave Rose Orientation WIS Station #63348

Table 6-1. Borrow Area Impacts – Reference Points

Wave Condition & Direction	Location	Base Condition	Area F - Offshore Lighthouse			Area E & K - Offshore Stono		
		Significant Wave Height (ft)	Significant Wave Height (ft)	Difference (ft)	% Change	Significant Wave Height (ft)	Difference	% Change
Mean60	1	2.52	2.67	0.15	5.8%	2.52	0.00	0.0%
Mean60	2	2.40	2.43	0.03	1.4%	2.40	0.00	0.0%
Mean60	3	2.49	2.46	-0.03	-1.1%	2.49	0.00	0.0%
Mean60	4	2.72	2.45	-0.27	-9.8%	2.72	0.00	0.0%
Mean60	5	2.51	2.28	-0.23	-9.2%	2.51	0.00	0.0%
Mean60	6	2.90	2.72	-0.17	-5.9%	2.90	0.00	0.0%
Mean60	7	2.55	2.69	0.14	5.4%	2.55	0.00	0.0%
Mean60	8	2.36	2.54	0.18	7.5%	2.36	0.00	0.0%
Mean60	9	2.45	2.58	0.13	5.5%	2.45	0.00	0.0%
Mean60	10	2.38	2.44	0.05	2.2%	2.39	0.01	0.3%
Mean60	11	2.74	2.77	0.03	1.1%	2.76	0.02	0.6%
Mean60	12	2.55	2.56	0.01	0.3%	2.62	0.07	2.9%
Mean60	13	3.47	3.47	0.00	0.0%	3.31	-0.16	-4.6%
Mean115	1	3.84	3.82	-0.02	-0.5%	3.84	0.00	0.0%
Mean115	2	3.95	3.91	-0.04	-1.0%	3.95	0.00	0.0%
Mean115	3	4.52	4.37	-0.15	-3.4%	4.52	0.00	0.0%
Mean115	4	4.10	3.91	-0.19	-4.7%	4.11	0.01	0.2%
Mean115	5	4.08	3.81	-0.26	-6.4%	4.09	0.01	0.2%
Mean115	6	4.21	4.39	0.18	4.3%	4.23	0.02	0.5%
Mean115	7	3.92	3.99	0.07	1.9%	3.95	0.03	0.9%
Mean115	8	3.87	3.94	0.07	1.7%	3.91	0.03	0.8%
Mean115	9	3.77	3.82	0.05	1.3%	3.79	0.02	0.6%
Mean115	10	3.99	4.01	0.02	0.5%	3.99	0.00	0.0%
Mean115	11	2.77	2.77	0.00	0.0%	2.77	0.00	0.0%
Mean115	12	2.98	2.98	0.00	0.0%	2.98	0.00	0.0%
Mean115	13	4.68	4.68	0.00	0.0%	4.67	-0.01	-0.2%
Mean170	1	4.23	4.05	-0.18	-4.2%	4.24	0.01	0.3%
Mean170	2	4.21	3.94	-0.27	-6.4%	4.22	0.01	0.3%
Mean170	3	4.35	4.21	-0.14	-3.2%	4.35	0.00	0.0%
Mean170	4	3.94	3.89	-0.04	-1.1%	3.96	0.02	0.6%
Mean170	5	4.61	4.66	0.06	1.2%	4.62	0.02	0.4%
Mean170	6	4.30	4.40	0.10	2.3%	4.29	-0.01	-0.1%
Mean170	7	3.80	3.80	0.00	0.1%	3.76	-0.04	-1.0%
Mean170	8	4.01	4.01	0.00	0.0%	3.95	-0.06	-1.4%
Mean170	9	3.55	3.56	0.00	0.0%	3.50	-0.06	-1.7%
Mean170	10	3.63	3.63	0.00	0.0%	3.58	-0.05	-1.4%
Mean170	11	2.77	2.77	0.00	0.0%	2.77	0.00	0.0%
Mean170	12	2.98	2.98	0.00	0.0%	2.98	0.00	0.0%
Mean170	13	4.52	4.52	0.00	0.0%	4.52	0.01	0.2%
Mean225	1	2.80	2.47	-0.33	-11.9%	2.75	-0.06	-2.1%
Mean225	2	2.90	2.52	-0.37	-12.9%	2.82	-0.08	-2.6%
Mean225	3	2.47	2.46	-0.01	-0.4%	2.38	-0.09	-3.7%
Mean225	4	2.99	3.09	0.10	3.3%	2.89	-0.10	-3.3%
Mean225	5	2.82	3.12	0.30	10.7%	2.72	-0.11	-3.8%
Mean225	6	2.68	2.73	0.05	1.9%	2.57	-0.11	-4.0%
Mean225	7	2.43	2.43	0.00	0.0%	2.38	-0.05	-2.1%
Mean225	8	2.38	2.38	0.00	0.0%	2.36	-0.01	-0.6%
Mean225	9	2.26	2.26	0.00	0.0%	2.27	0.01	0.5%
Mean225	10	2.08	2.08	0.00	0.0%	2.12	0.04	1.8%
Mean225	11	2.34	2.34	0.00	0.0%	2.38	0.03	1.5%
Mean225	12	2.98	2.98	0.00	0.0%	2.98	0.00	0.0%
Mean225	13	4.16	4.16	0.00	0.0%	4.16	0.00	0.0%
Max60	1	4.97	4.97	0.00	0.0%	4.97	0.00	0.0%
Max60	2	4.61	4.61	0.00	0.0%	4.61	0.00	0.0%
Max60	3	5.42	5.41	0.00	0.0%	5.42	0.00	0.0%
Max60	4	6.38	5.95	-0.44	-6.8%	6.38	0.00	0.0%
Max60	5	5.94	5.53	-0.42	-7.0%	5.94	0.00	0.0%
Max60	6	4.69	4.70	0.00	0.1%	4.69	0.00	0.0%
Max60	7	6.22	6.56	0.34	5.5%	6.22	0.00	0.0%
Max60	8	5.72	5.72	0.00	0.0%	5.72	0.00	0.0%
Max60	9	5.78	5.78	0.00	0.0%	5.78	0.00	0.0%
Max60	10	5.06	5.06	0.00	0.0%	5.06	0.00	0.0%
Max60	11	2.78	2.78	0.00	0.0%	2.78	0.00	0.0%
Max60	12	2.99	2.99	0.00	0.0%	2.99	0.00	0.0%
Max60	13	5.35	5.35	0.00	0.0%	5.35	0.00	0.0%

Table 18. continued

Wave Condition & Direction	Location	Base Condition	Area F - Offshore Lighthouse			Area E & K - Offshore Stono		
		Significant Wave Height (ft)	Significant Wave Height (ft)	Difference (ft)	% Change	Significant Wave Height (ft)	Difference	% Change
Max115	2	4.61	4.61	0.00	0.0%	4.61	0.00	0.0%
Max115	3	5.42	5.41	0.00	0.0%	5.42	0.00	0.0%
Max115	4	6.38	6.38	0.00	0.0%	6.38	0.00	0.0%
Max115	5	5.95	5.94	0.00	0.0%	5.95	0.00	0.0%
Max115	6	4.69	4.69	0.00	0.0%	4.69	0.00	0.0%
Max115	7	7.16	7.16	0.00	0.0%	7.16	0.00	0.0%
Max115	8	5.72	5.72	0.00	0.0%	5.72	0.00	0.0%
Max115	9	5.77	5.77	0.00	0.0%	5.77	0.00	0.0%
Max115	10	5.06	5.06	0.00	0.0%	5.06	0.00	0.0%
Max115	11	2.78	2.78	0.00	0.0%	2.78	0.00	0.0%
Max115	12	2.99	2.99	0.00	0.0%	2.99	0.00	0.0%
Max115	13	5.35	5.35	0.00	0.0%	5.35	0.00	0.0%
Max170	1	4.97	4.97	0.00	0.0%	4.97	0.00	0.0%
Max170	2	4.61	4.61	0.00	0.0%	4.61	0.00	0.0%
Max170	3	5.42	5.42	0.00	0.0%	5.42	0.00	0.0%
Max170	4	6.38	6.38	0.00	0.0%	6.38	0.00	0.0%
Max170	5	5.95	5.95	0.00	0.0%	5.95	0.00	0.0%
Max170	6	4.69	4.69	0.00	0.0%	4.69	0.00	0.0%
Max170	7	7.16	7.16	0.00	0.0%	7.16	0.00	0.0%
Max170	8	5.72	5.72	0.00	0.0%	5.72	0.00	0.0%
Max170	9	5.78	5.78	0.00	0.0%	5.77	0.00	0.0%
Max170	10	5.06	5.06	0.00	0.0%	5.06	0.00	0.0%
Max170	11	2.78	2.78	0.00	0.0%	2.78	0.00	0.0%
Max170	12	2.99	2.99	0.00	0.0%	2.99	0.00	0.0%
Max170	13	5.34	5.34	0.00	0.0%	5.34	0.00	0.0%
Max225	1	4.98	4.98	0.00	0.0%	4.98	0.00	0.0%
Max225	2	4.62	4.61	-0.01	-0.1%	4.62	0.00	0.0%
Max225	3	5.41	5.41	0.00	-0.1%	5.41	0.00	0.0%
Max225	4	6.39	6.32	-0.07	-1.1%	6.39	0.00	0.0%
Max225	5	5.96	5.96	0.00	0.0%	5.96	0.00	0.0%
Max225	6	4.70	4.70	0.00	0.0%	4.70	0.00	0.0%
Max225	7	5.40	5.40	0.00	0.0%	5.24	-0.16	-3.0%
Max225	8	5.19	5.19	0.00	0.0%	5.13	-0.05	-1.0%
Max225	9	4.47	4.47	0.00	0.0%	4.49	0.03	0.6%
Max225	10	4.04	4.04	0.00	0.0%	4.15	0.11	2.8%
Max225	11	2.78	2.78	0.00	0.0%	2.78	0.00	0.0%
Max225	12	2.99	2.99	0.00	0.0%	2.99	0.00	0.0%
Max225	13	5.35	5.35	0.00	0.0%	5.35	0.00	0.0%
Extreme	1	5.14	5.14	0.00	0.0%	5.14	0.00	0.0%
Extreme	2	4.76	4.76	0.00	0.0%	4.76	0.00	0.0%
Extreme	3	5.62	5.62	0.00	0.0%	5.62	0.00	0.0%
Extreme	4	6.66	6.66	0.00	0.0%	6.66	0.00	0.0%
Extreme	5	6.19	6.19	0.00	0.0%	6.19	0.00	0.0%
Extreme	6	4.84	4.84	0.00	0.0%	4.84	0.00	0.0%
Extreme	7	7.53	7.53	0.00	0.0%	7.53	0.00	0.0%
Extreme	8	5.95	5.95	0.00	0.0%	5.95	0.00	0.0%
Extreme	9	6.01	6.01	0.00	0.0%	6.01	0.00	0.0%
Extreme	10	5.24	5.24	0.00	0.0%	5.24	0.00	0.0%
Extreme	11	2.83	2.83	0.00	0.0%	2.83	0.00	0.0%
Extreme	12	3.05	3.05	0.00	0.0%	3.05	0.00	0.0%
Extreme	13	5.54	5.54	0.00	0.0%	5.54	0.00	0.0%

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Sub-Appendix A:

Development of Storm Suite

Storm Suite Development – Folly Beach, SC

Data

Oceanweather (OWI) GROW-FINE U.S. East Coast: Global Reanalysis of Ocean Waves – U.S. East Coast 2018 (GF-EC) reanalysis data was used to develop a storm suite for the region. This dataset consists of 147 historical tropical events over the period 1924– 2017 and 48 extra-tropical cyclones over the period 1957 – 2016. The modeling system consists of the 2-Dimensional hydrodynamic model ADCIRC (ADvanced CIRCulation) and the OWI high-resolution 3rd generation spectral wave model known as OWI3G. This data has been validated (OWI 2018) and previously used in the development of storm suites.

For the Folly Beach, SC storm suite, output point 10452 was used (Figure 1). This output location is located about 4.5 miles southeast of Folly Beach, SC (32.6° N, 79.9° W) at a model depth of 10.25 m. A number of time series of variables were output at this location including: Date, Water Level, Significant Wave Height and Wave Period which were needed for input into the cross-shore change model.

For all datum conversions NOAA Station 8665530, Charleston, Cooper River Entrance was used.

Tropical Storm Selection

The storm selection process followed the general direction of Gravens and Sanderson (2018) Technical Note. In the Technical Note (TN) data from the North Atlantic Comprehensive Coastal Study (NACCS) were used. The NACCS data was developed using a high-fidelity numerical hydrodynamic and wind wave modeling system similar to that used in the OWI study. The main difference is that the NACCS study also examined the water level return period so the associated probability of occurrence for different water levels was available. In the absence of this data for the OWI dataset, instead of 'binning' the storms based on return period, the data were based binned based on an evaluation of storm surge and wave height elevation as discussed below.

The 147 tropical storms in the OWI dataset were separated based on the time/date of occurrence and output interval at the save point. In doing so, 144 unique events were identified. This is because there are a few instances were storms overlap in time, creating longer continuous time series that feature signals from two events. Of the 144 storm time series they were first "de-tided" to remove the influence of the astronomical tide. To accomplish this the U-Tide (Codiga, 2011) Matlab software package was used. Using the NOAA Charleston (8665530) station predicted tide levels, U-Tide was run to create a model of predicted tide level. This model was applied to the date/time of each instance of surge within the OWI record and subtracted from the overall water level to obtain the surge height. Next the peak surge and wave height for each storm was determined and all storms which produced a peak surge height less than 2.0 ft and peak wave height less than 2.0 ft were discarded. While these cut off values are somewhat subjective with the goal of reducing the storm suite to a manageable number of storms, they represent values that are likely to lead to minimal impacts on the shoreline. The Preliminary FEMA Flood Insurance Study (FIS) for Folly Beach (FEMA 2016) this reports 10, 50, 100, and 500 year return period stillwater levels. Along Folly Beach the 10 year return period stillwater level is approximately 5.5

ft NAVD. Likewise NOAA reports exceedance levels at the Charleston Station (8665530) which show a 10 year return period of about 4 ft NAVD. Setting a minimum surge height of 2.0 ft, allows for elimination of many storms with negligible impacts while still ensuring that storms with a return period much more frequent than 10 years is accounted for. This initial screening left 30 storm events for evaluation with peak surge heights between approximately 2.0 and 4.5 ft and peak wave heights between 2 and 28 ft. The storms were then binned based on maximum surge height into 0.5 ft increments. The distribution of storms within the bins is shown in Table 1 and a histogram is shown in Figure 2. Within each bin the hydrographs of each storm were examined. A subsample of the storms were chosen based on the shape of the hydrograph (peaked versus long duration, etc.) and the corresponding wave height (high wave, low wave and average wave conditions). For bins with only a few storms, all storms in the bin were selected. After this evaluation 21 of the 30 storms were selected.

Each of the selected storms was modulated to reflect three statistically defined tide ranges (high, medium, and low amplitude) at four surge-tide phases. The statistically defined tide range reflect the upper quartile, middle half and lower quartile of the tidal ranges. The three tidal ranges and four phase shifts result in 12 plausible total water elevation time series for a single representative storm.

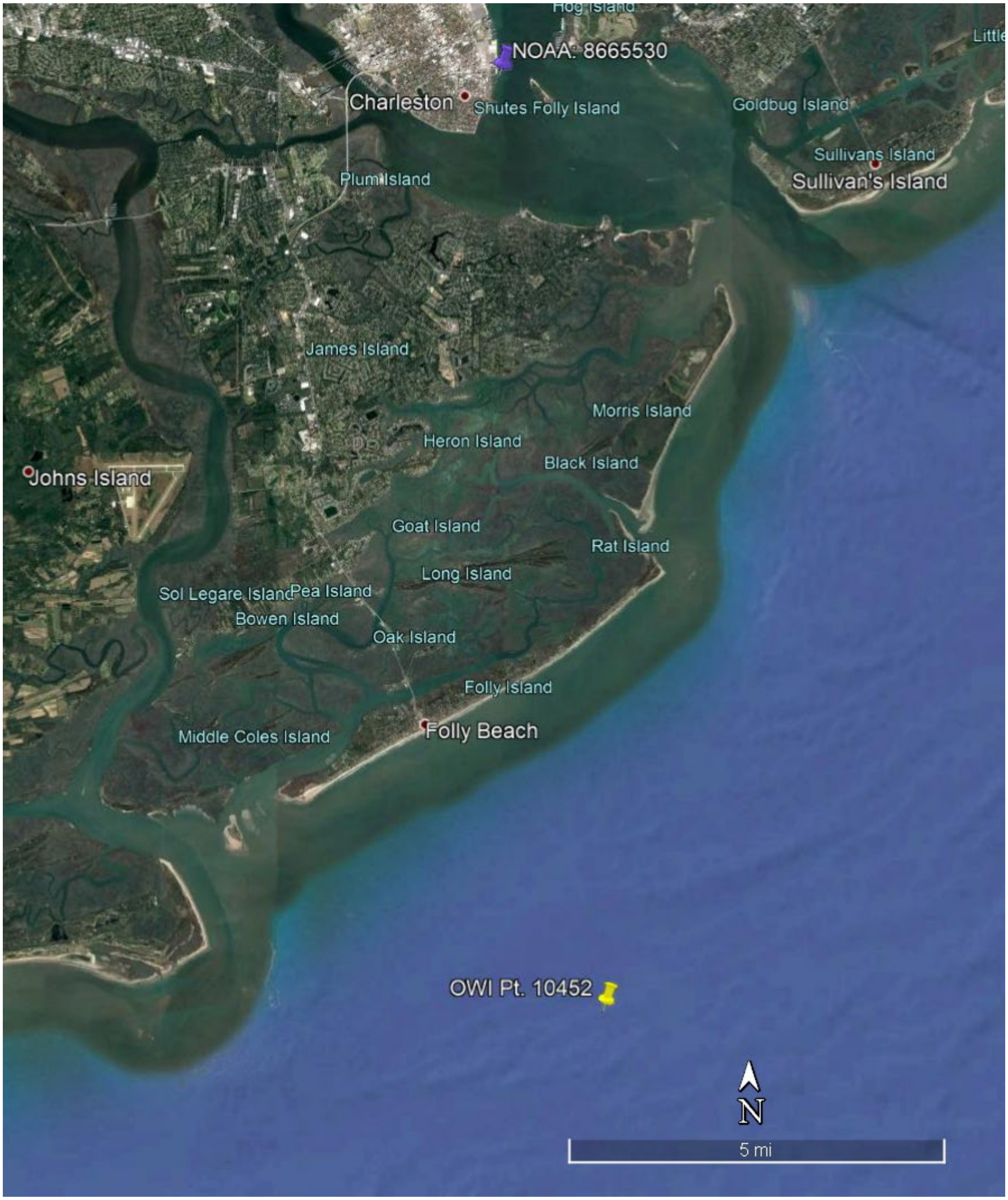

Figure 1: Oceanweather GFEC 2018 grid point 10452 which was used for development of the Folly Beach, SC storm suite. Also pictured is NOAA Station 8665530 which was used to develop the predicted tides and establish datum conversions for the study

Table 1: Distribution of tropical storms by bin

Surge Height (ft)	Number of Storms	Chosen Storms
2.0 – 2.5	12	7
2.5 – 3.0	9	6
3.0 – 3.5	5	4
3.5 – 4.0	1	1
4.0 – 4.5	0	0
4.5 – 5.0	3	3
5.0 – 5.5	0	0
5.5 – 6.0	0	0
6.0 – 6.5	0	0
6.5 – 7.0	0	0
7.0 – 7.5	0	0
7.5 – 8.0	0	0
8.0 – 8.5	0	0
8.5 – 9.0	0	0
9.0 – 9.5	0	0
9.5 – 10.0	0	0
10.0 – 10.5	0	0
10.5 – 11.0	0	0
11.0 – 11.5	0	0
11.5 – 12.0	0	0
12.0 – 12.5	0	0
12.5 – 13.0	0	0
Total	30	21

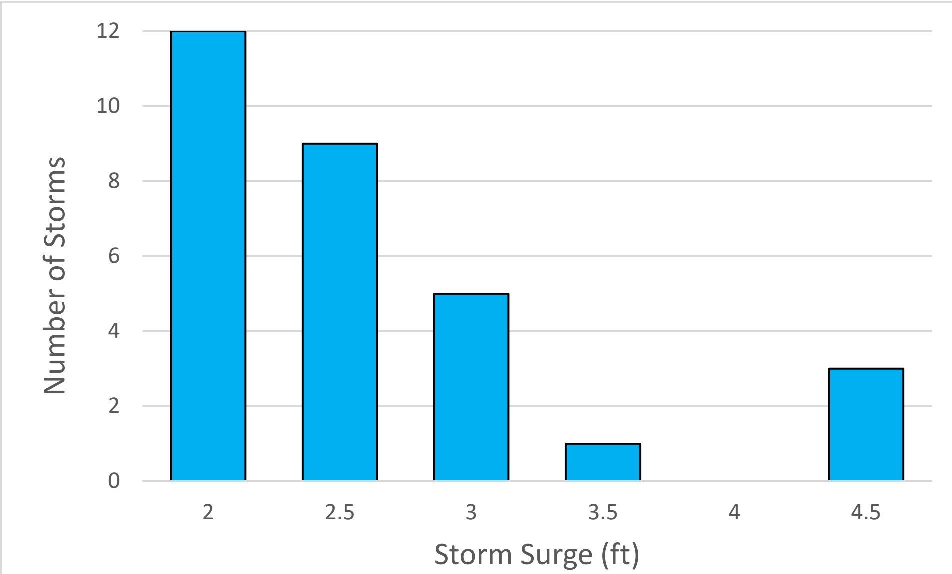

Figure 2: Histogram showing the distribution of peak surge height for tropical storms

Extra-Tropical Storm Selection

The Extra-Tropical storm selection process mirrors the Tropical Storm selection process for Folly Beach. For Folly Beach a total of 48 storms were identified in the record. After applying the same filters of 2.0 ft peak surge and 2.0 peak wave height as applied for the tropical storms the 48 extra-tropical storms was reduced to 25 storms. The remaining storms were binned (Figure 3) and the shape of the hydrograph and peak wave heights were analyzed to ensure the storm suite contained a diverse array of storms. This resulted in a total of 16 extra-tropical storms being selected for the Folly Beach storm suite. A summary of the storm breakdown is presented in Table 2. Similar to the tropical storms, the extra-tropical storms were modulated by the twelve tide conditions resulting in 192 total extra-tropical storm hydrographs.

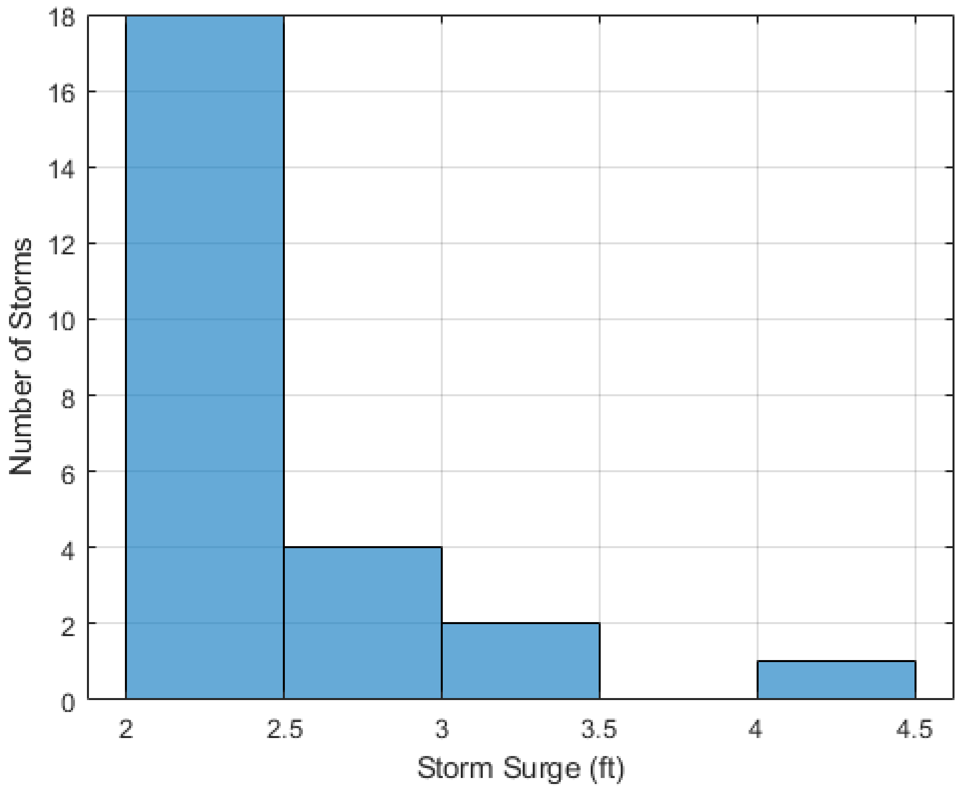

Figure 3: Histogram showing the distribution of peak surge height for extra-tropical storms

Table 2: Distribution of extra-tropical storms by bin

Surge Height (ft)	Number of Storms	Chosen Number
2.0 – 2.5	18	9
2.5 - 3.0	4	4
3.0 - 3.5	2	2
3.5 - 4.0	0	0
4.0 - 4.5	1	1
Total	25	16

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Sub-Appendix B:

Folly Beach Shoreline Change Rate Analysis

GenCade Planform Rates

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MEMORANDUM

To: John Hazelton, P.E., Kevin Conner, P.E., USACE Wilmington District Office

From: Jeff Shelden, P.E., Yong Chen, Ph.D, P.E., Brian Joyner, P.E.

Date: June 16, 2020

Subject: Folly Beach Shoreline Change Rate Analysis

M&N Job No.: 10514-01

1. INTRODUCTION

1.1. STUDY PURPOSE AND SCOPE

Moffatt & Nichol (M&N) was contracted by USACE Water Resources Section, Wilmington District Office to conduct the Folly Beach shoreline change rate analysis. The objective of this memo is to compile and query historical data necessary to develop and calibrate a planform evolution model and to conduct analytical calculations relative to post-nourishment shoreline change rates of Future With Project (FWP) scenarios in the various reaches of the project area.

The currently authorized federal coastal storm risk management project at Folly Beach, South Carolina, was initially constructed in 1993 and to date has been nourished seven times including initial construction. Due to a sediment deficiency and the desire to optimize the project, a General Revaluation Report was authorized to locate additional offshore borrow sources and determine optimal project templates for the project.

A component of the feasibility study is the Beach-fx economic model of economic damages over time to structures and infrastructure along the town's shoreline. The project area being evaluated in Beach-fx consists of approximately 5.47 miles of shoreline (See Figure 1-1). Among other inputs, Beach-fx requires estimates of shoreline change rates for existing conditions, and Future With Project conditions.

1.2. ENGINEERING STUDY APPROACH

Existing Data Collection and Review

M&N compiled and reviewed existing available data sets regarding profile conditions, shoreline positions, waves, tides and sediment characteristics in the study area. The existing available data sets include:

- Beach profiles (see Figure 1-2) and other survey data
- Existing groin locations (see Figure 1-3), length and elevation
- Historical reports and data sets describing beach and nearshore sediment characteristics
- Tidal levels at NOAA tidal station of Charleston, Cooper River Entrance, SC, ID: 8665530
- USACE WIS wind and wave hindcast data sets
- NOAA WaveWatch3 (WW3) wind and wave hindcast data sets
- Wave data sets at NOAA buoy #41004
- Oceanweather hindcast data at station 10452
- Wind data sets at NDBC FBIS1

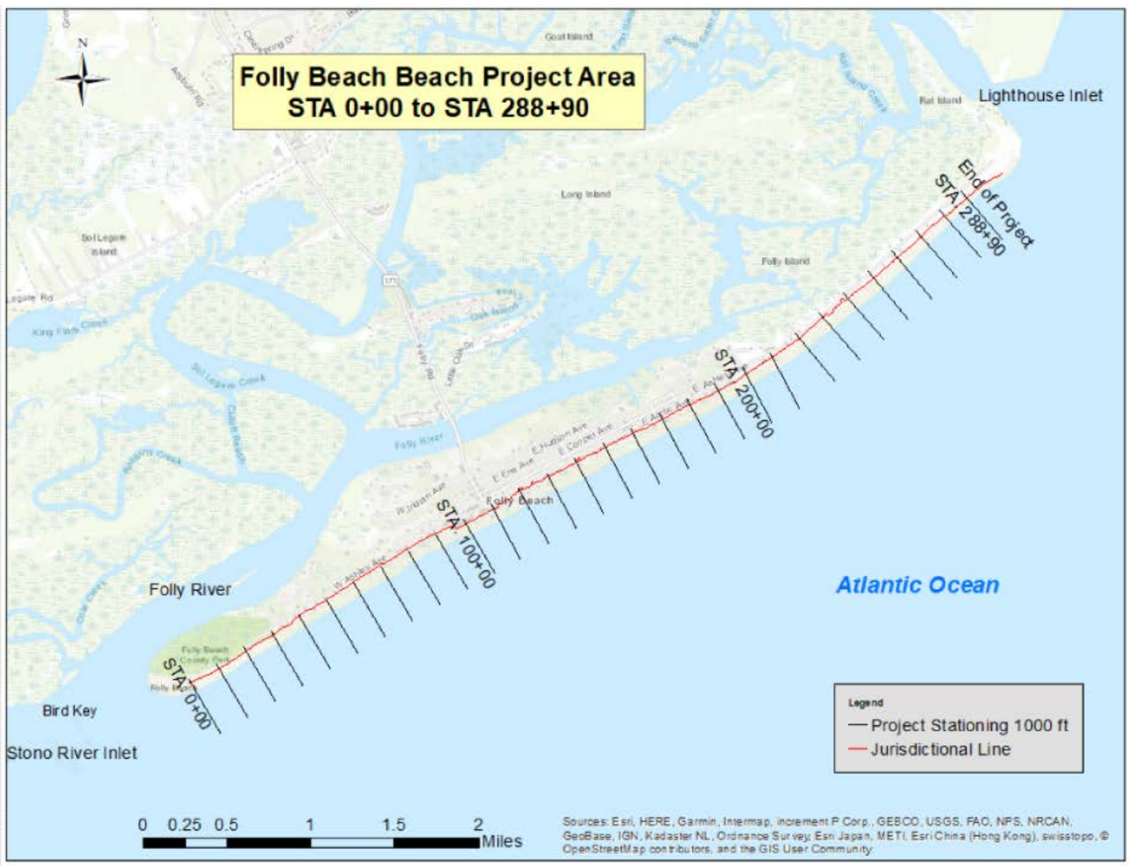

Figure 1-1: Folly Beach Project Area

Figure 1-2: Monument Locations

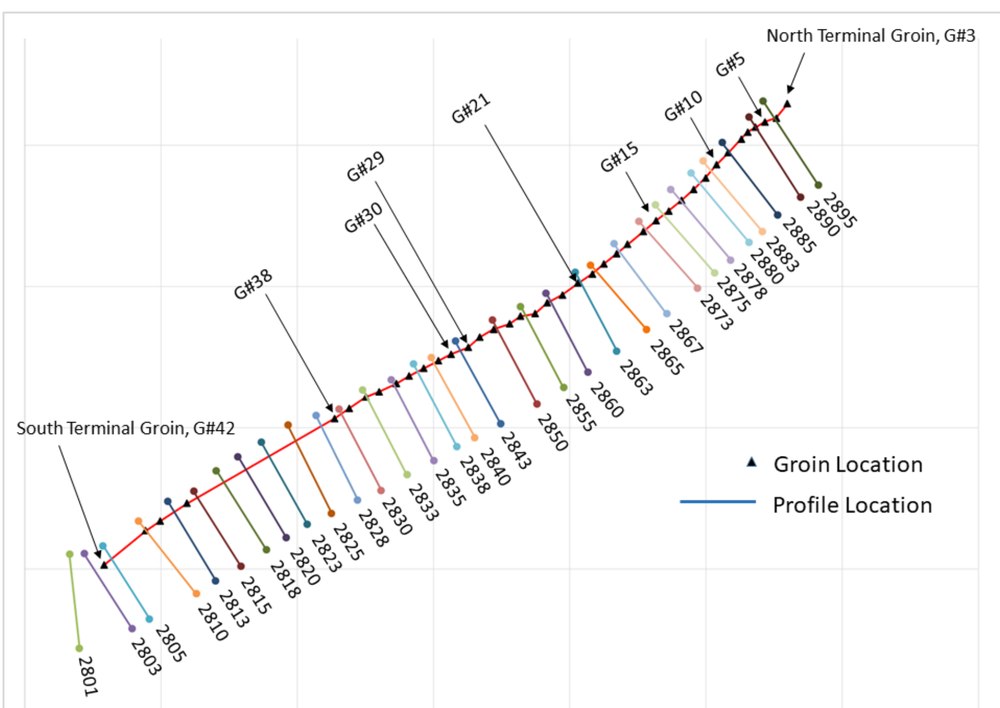

Figure 1-3: Monument Locations and Groin Locations

Wave Transformation Modeling

Evaluation of the shoreline change rates depends on expected wave conditions and associated longshore sediment transport rates. M&N applied a numerical spectral wave model, the MIKE 21 Spectral Waves software by DHI, to transform a continuous time series of offshore wave conditions to a high-resolution grid of nearshore locations along the study area.

The spectral wave model was calibrated and validated using the NDBC buoy wave data, Oceanweather data, and WIS wave data. The calibrated and validated spectral wave model was used to transform time series of offshore waves to the nearshore project site.

One-Line Shoreline Model Calibration

M&N applied the USACE GenCade one-line shoreline evolution model for the Folly Beach shoreline change rate analysis. The GenCade shoreline model was developed utilizing the shoreline locations, existing groin fields at Folly Beach including the terminal groin on the north and south ends of Folly Island, and model simulated nearshore wave conditions. The shoreline model was calibrated and validated using the historical shoreline positions and historical longshore sediment transport rates.

Estimation of Shoreline Change Rates of Future With Project Scenarios

Four Future With Project scenarios were designed by USACE and provided to M&N. M&N applied the calibrated/validated shoreline evolution model to estimate post-nourishment shoreline position changes in representative segments of the project shoreline for representative "typical annual" wave conditions. M&N utilized the results to estimate and recommend representative shoreline change rates for each of the Beach-fx reaches for each of the Future With Project scenarios. The following project features were evaluated:

- Beach nourishment project constructed in January 2024
- Beach nourishment project constructed in January 2036
- Beach nourishment project constructed in January 2048
- Beach nourishment project constructed in January 2060

2. DATA COLLECTION AND REVIEW

M&N collected and reviewed the existing data sets including water levels, winds, waves, beach profiles and beach nourishment projects as presented in Table 2-1.

Table 2-1: Timeline of the Historical Data

	Year	80	90	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18
Water level	NOAA 8665530																							
Wind	NDBC FBIS1																							
	WIS Wind																							
	WW3 Wind																							
Wave	WIS Wave																							
	WW3 Wave																							
	NDBC 41004																							
	Oceanweather GROW-FINE																							
Profile																								
Beach nourishment																								
Possible beach nourishment																								
Potential shoreline calibration period																								

The following periods for the shoreline change model calibration and validation were recommended by M&N and approved by the USACE, in order to avoid the near-term effects of beach nourishment projects on the measured shorelines:

- December 2008 to March 2010
- March 2010 to December 2012
- December 2016 to December 2017

Figure 2-1 shows the collected wave data locations. In Figure 2-1, the OW10452 represents the Oceanweather data station 10452, WIS63348 represents USACE WIS wave data station 63348, the NDBC41004 represents NDBC buoy 41004 data location, and WW3 represents WaveWatch 3 data location.

Figure 2-1: Wave Data Locations

3. Spectral Wave Modeling

The wave transformation study was conducted utilizing the MIKE 21 Spectral Waves (SW) model (DHI, 2014) to calculate wave conditions approaching Folly Beach. MIKE 21 SW simulates the growth, decay and transformation of wind-generated waves and swells in offshore and nearshore coastal areas. M&N developed and calibrated a spectral wave model, then utilized the wave model to transform waves from offshore to the nearshore project area.

The model domain computational mesh resolution and model bathymetry are illustrated in Figure 3-1 and Figure 3-2. The horizontal mesh resolution varies between approximately 2.5 miles offshore and approximately 100 feet at study area.

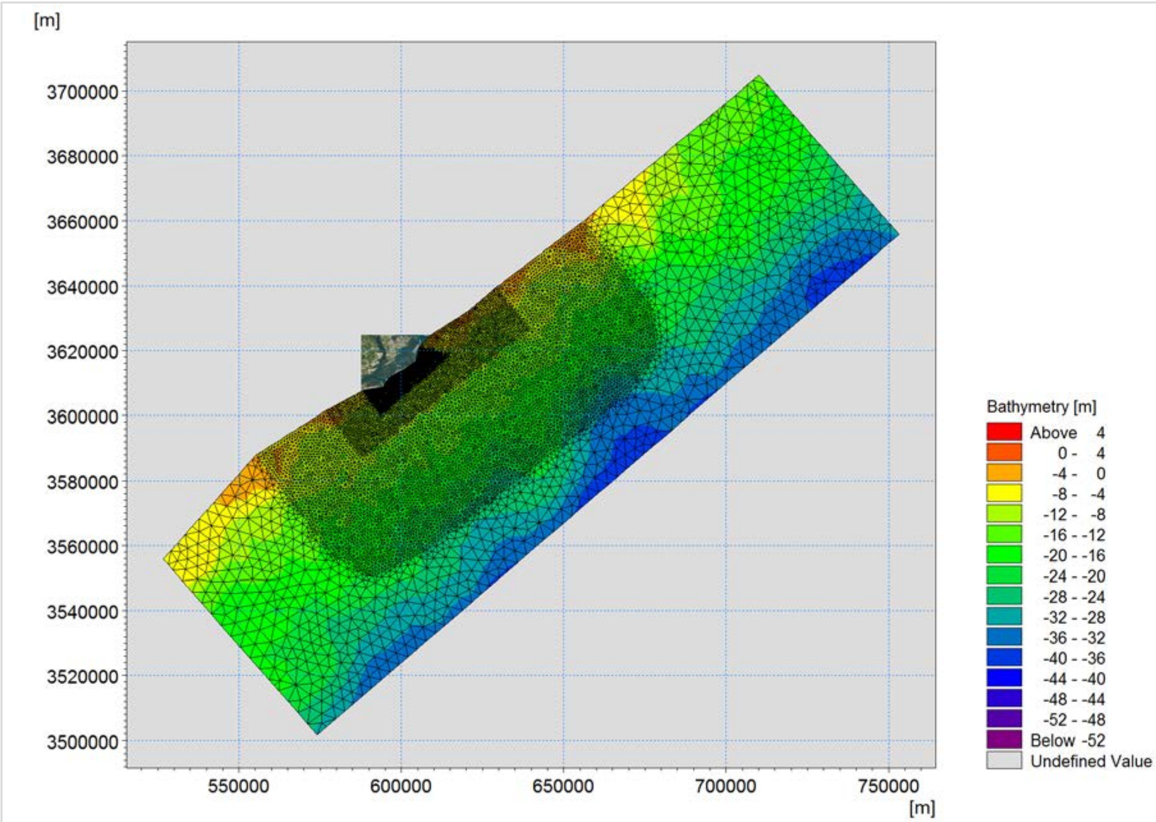

Figure 3-1: Spectral Wave Model Mesh (Entire Area)

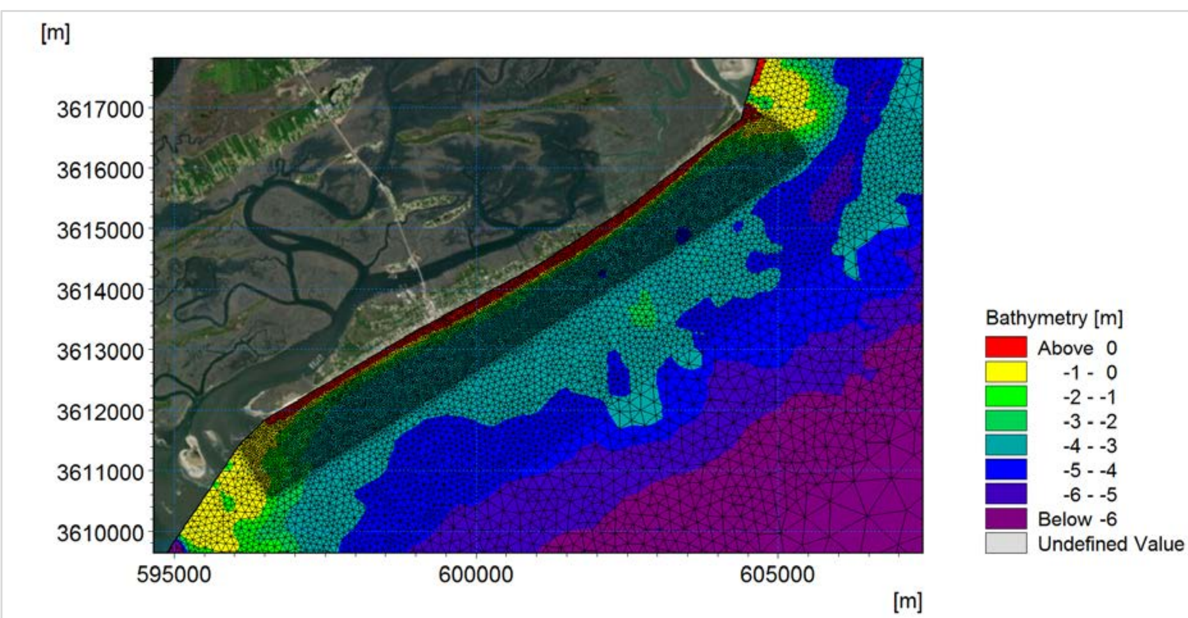

Figure 3-2: Spectral Wave Model Mesh (Project Site)

3.1. Wave Model Calibration and Validation

The MIKE 21 SW wave model used NOAA hydrographic data, profile data, water level time series, and wind and wave data as inputs to the wave transformation simulation. The calibrated model parameters for the spectral wave model are presented in Table 3-1. For the wave model calibration, the NDBC 41004 buoy data were used as open boundary conditions. The calculated wave heights, wave periods and wave directions were compared with the Oceanweather data at station 10452 for two selected storms as shown in Figure 3-3 through Figure 3-8.

Table 3-1: MIKE 21 Spectral Wave Model Parameters

Parameter Name	Type	Value
Frequency discretization logarithmic	Number of frequencies	12
	Minimum frequency	0.07 Hz
	Frequency factor	1.15
Directional discretization	Directional sector, number of directions	18
Wind forcing	Coupled, Charnock parameter	0.012
Wave breaking	Functional form, Ruessink et al. (2003)	1
Bottom friction	Friction factor, f_w	0.03
White Capping	Constant	3.0, 0.6
Solution method	Newton-Raphson iteration, low order	

Generally, the M&N calculated wave heights, wave periods and wave directions agree with the Oceanweather hindcasted wave data at station 10452. The Oceanweather wave data curves show some data smoothing. In the wave model calibration, the measured wave data were used as open boundary conditions. Therefore, the M&N calculated wave conditions could be more accurate compared to the Oceanweather hindcasted wave data.

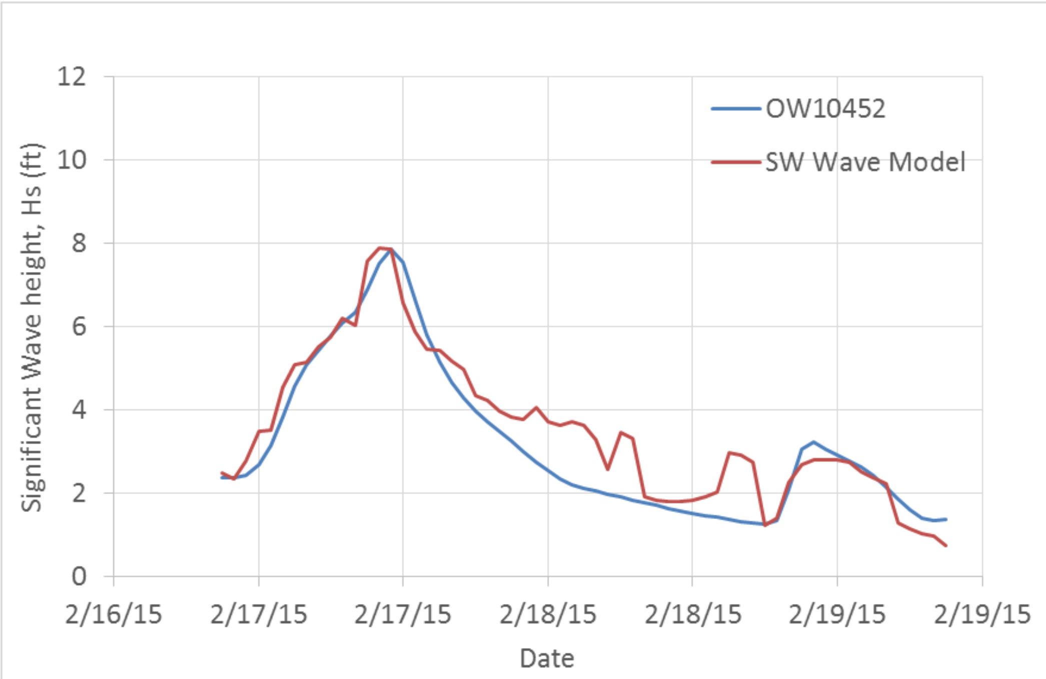

Figure 3-3: Calculated Wave Heights Compared to OW10452 Wave Heights (Open Boundary Conditions: NDBC 41004 Buoy Data)

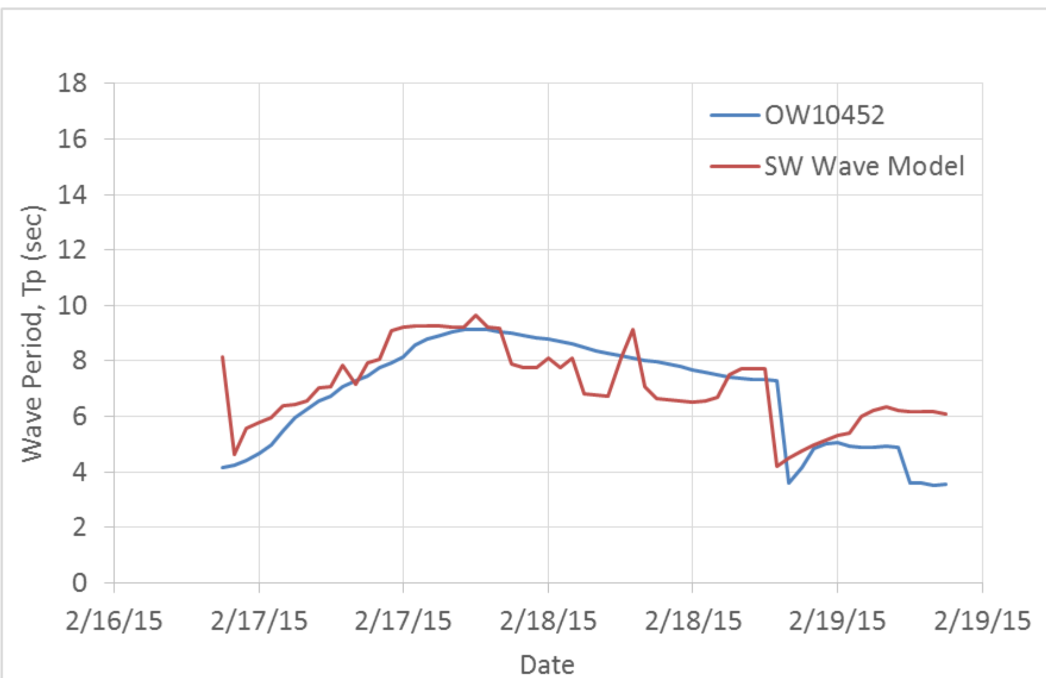

Figure 3-4: Calculated Wave Periods Compared to OW10452 Wave Periods (Open Boundary Conditions: NDBC 41004 Buoy Data)

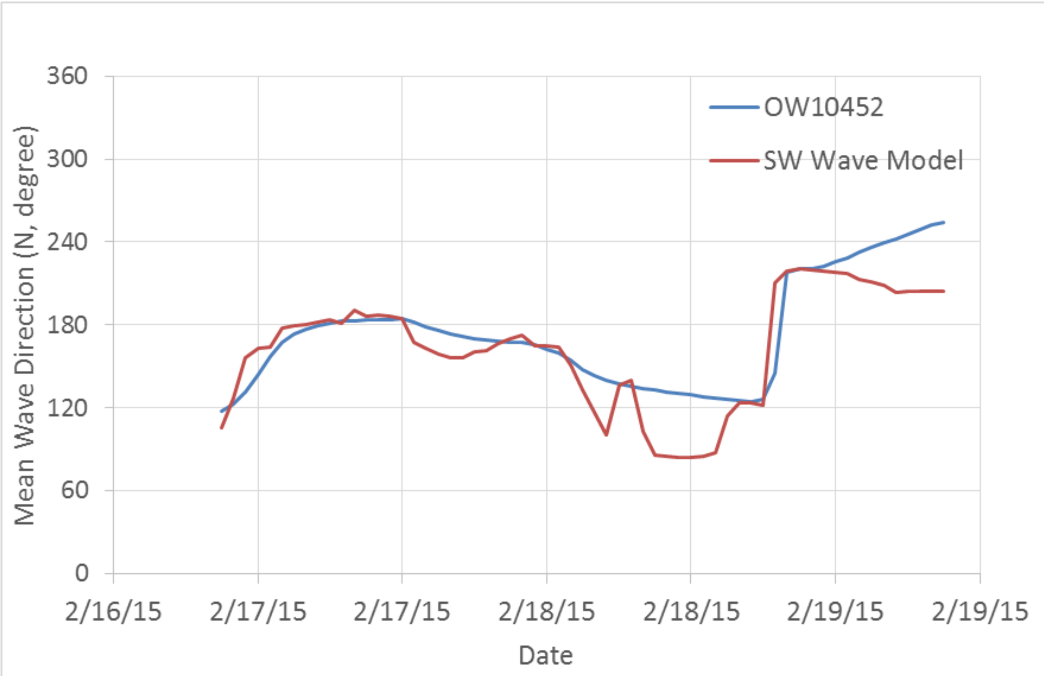

Figure 3-5: Calculated Wave Directions Compared to OW10452 Wave Directions (Open Boundary Conditions: NDBC 41004 Buoy Data)

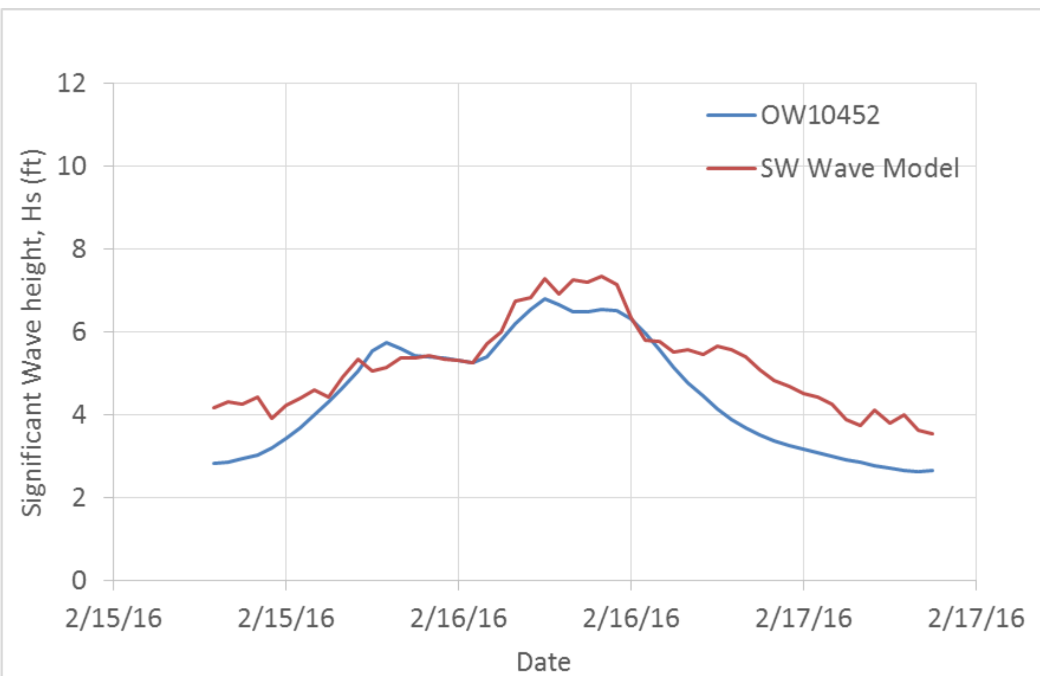

Figure 3-6: Calculated Wave Heights Compared to OW10452 Wave Heights (Open Boundary Conditions: NDBC 41004 Buoy Data)

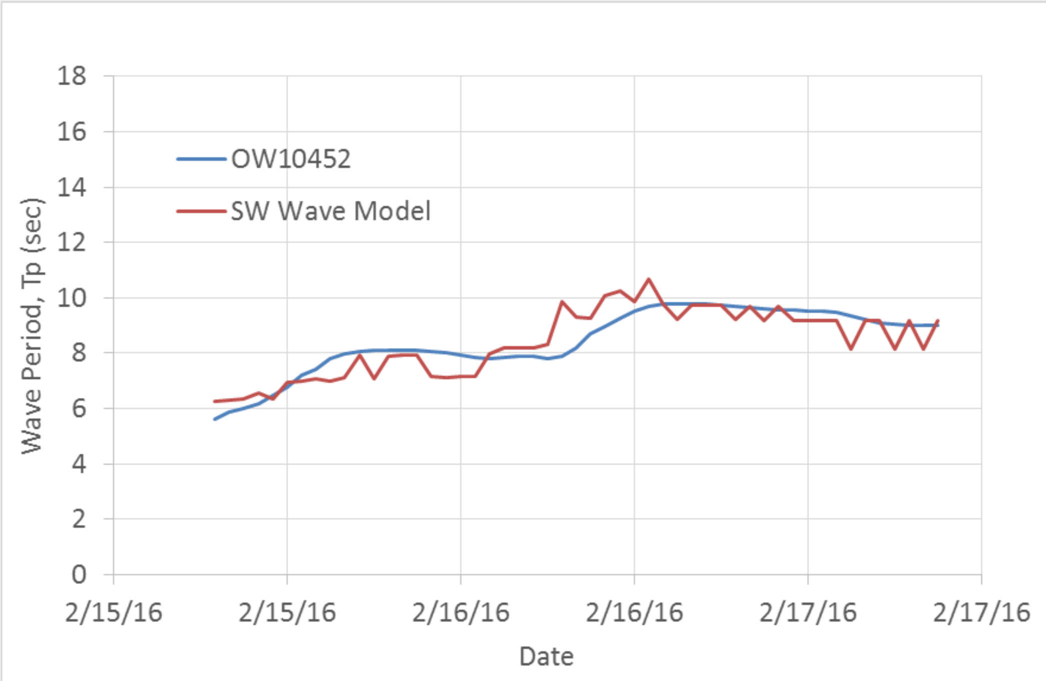

Figure 3-7: Calculated Wave Periods Compared to OW10452 Wave Periods (Open Boundary Conditions: NDBC 41004 Buoy Data)

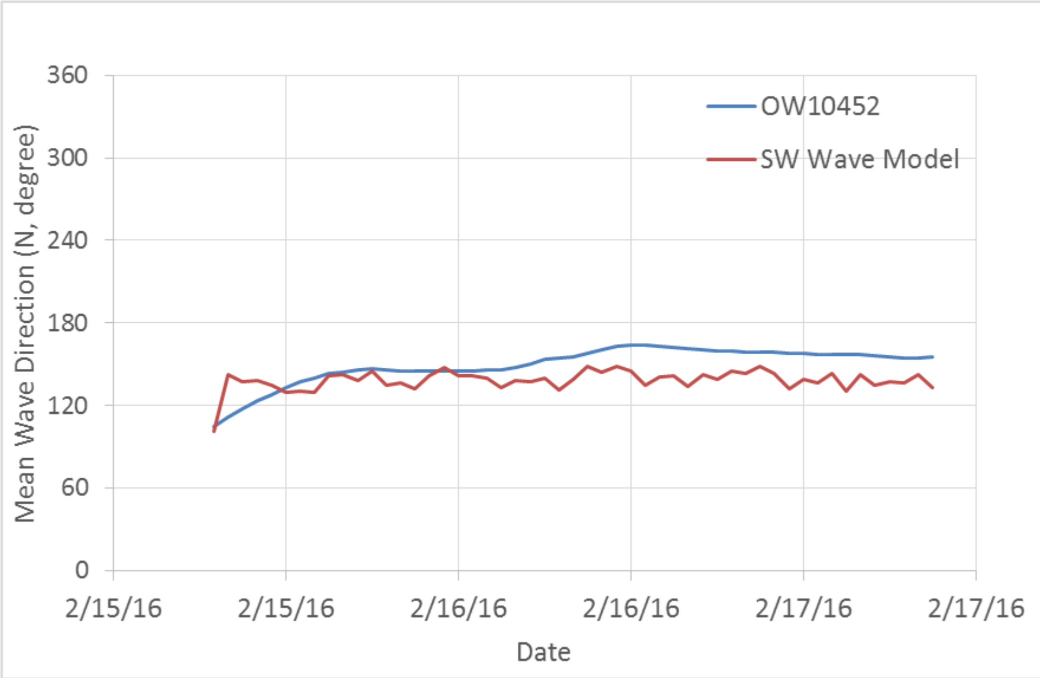

Figure 3-8: Calculated Wave Directions Compared to OW10452 Wave Directions (Open Boundary Conditions: NDBC 41004 Buoy Data)

The same wave model parameters were validated for the following two cases:

- Using the NDBC 41004 buoy data as open boundary conditions, and comparing calculated wave climates to the WIS wave data at station 63348 (see Figure 3-9 through Figure 3-14)
- Using the WW3 wave data as open boundary conditions, and comparing calculated wave climates to the NDBC 41004 buoy data (see Figure 3-15 through Figure 3-20)

Generally, the wave model calibration and validation results indicate the degree to which the wave transformation model agrees with the wave gauge data and existing wave model data. Figure 3-9 and Figure 3-18 show large peak wave height discrepancies in a short duration. In Figure 3-9, the measured data had a short-duration higher peak wave height while the WIS data had a smoothed lower peak wave height. In Figure 3-18, the calculated storm shape matches well to the measured data, however, the measured data caught a short-duration higher peak wave height. The wave model wave height results indicate that directly applying measured wave data as open boundary conditions would get more accurate short-duration peak wave heights at nearshore area.

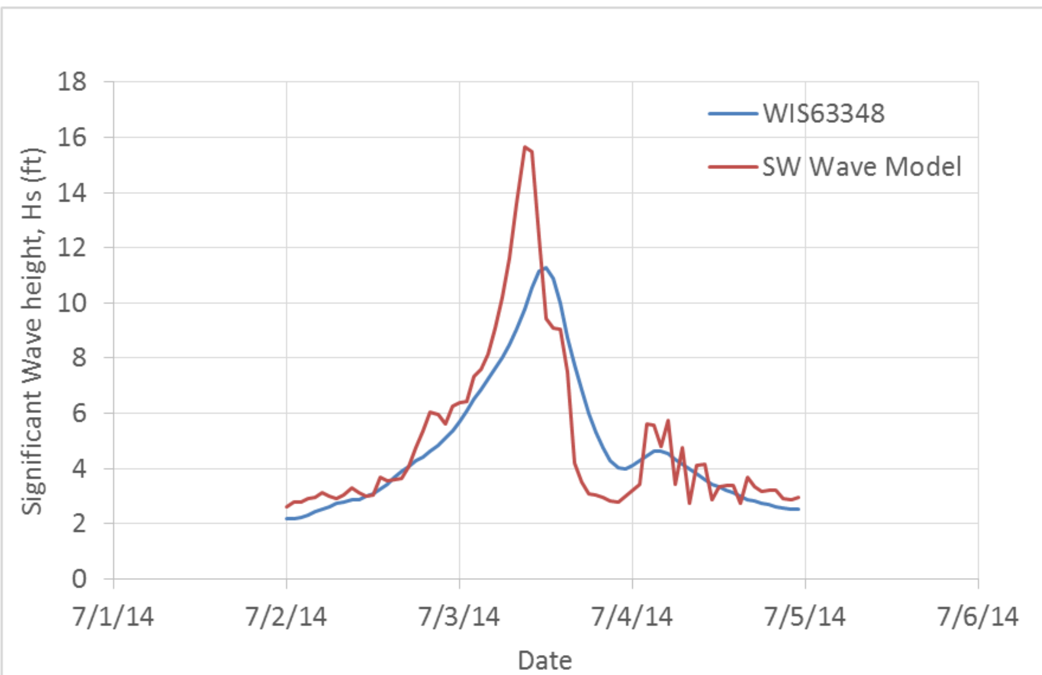

Figure 3-9: Calculated Wave Heights Compared to WIS63348 Wave Heights (Open Boundary Conditions: NDBC 41004 Buoy Data)

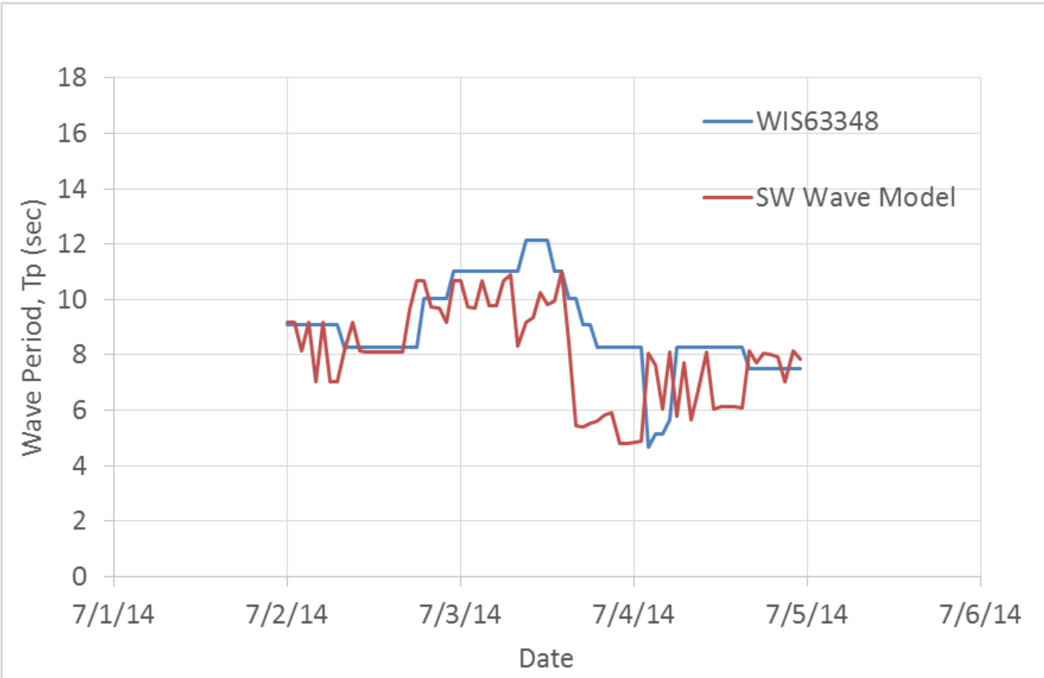

Figure 3-10: Calculated Wave Periods Compared to WIS63348 Wave Periods (Open Boundary Conditions: NDBC 41004 Buoy Data)

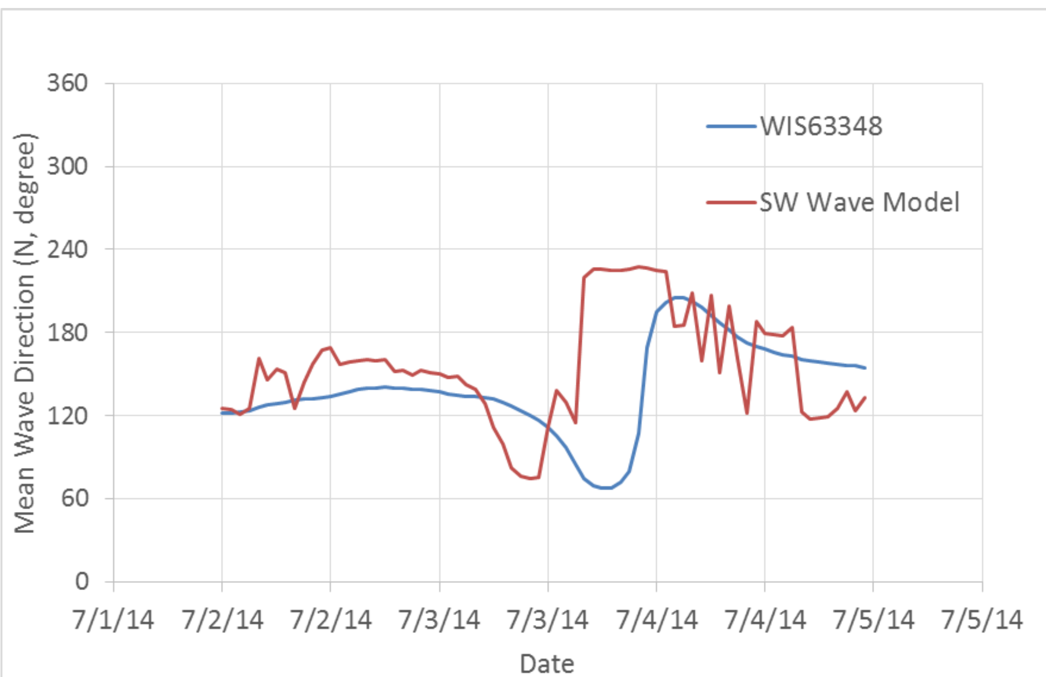

Figure 3-11: Calculated Wave Directions Compared to WIS63348 Wave Directions (Open Boundary Conditions: NDBC 41004 Buoy Data)

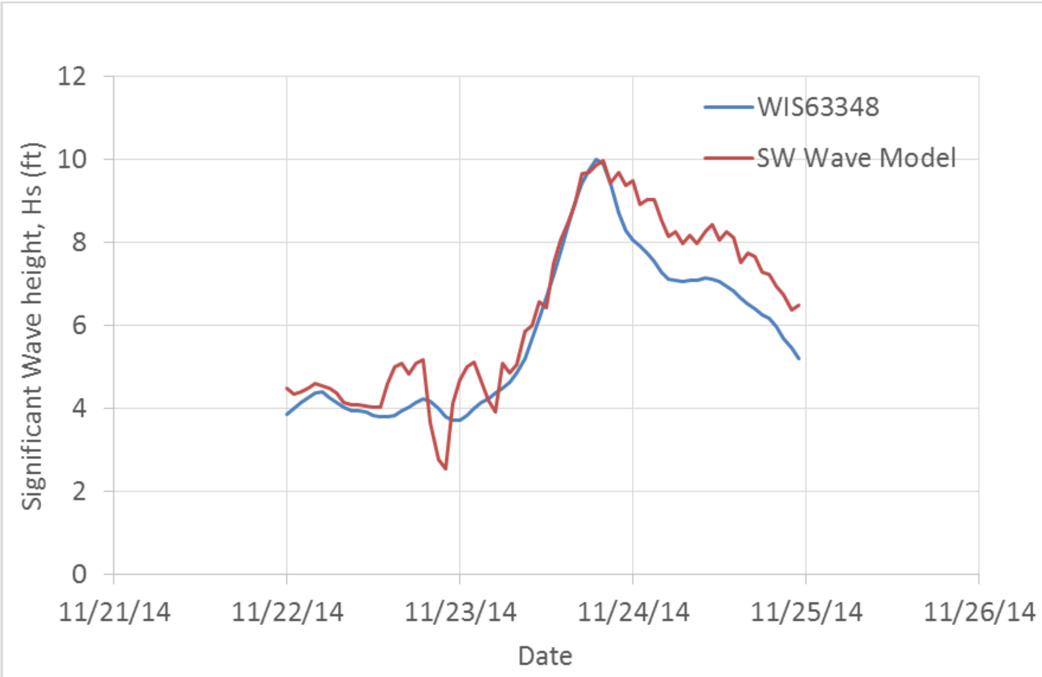

Figure 3-12: Calculated Wave Heights Compared to WIS63348 Wave Heights (Open Boundary Conditions: NDBC 41004 Buoy Data)

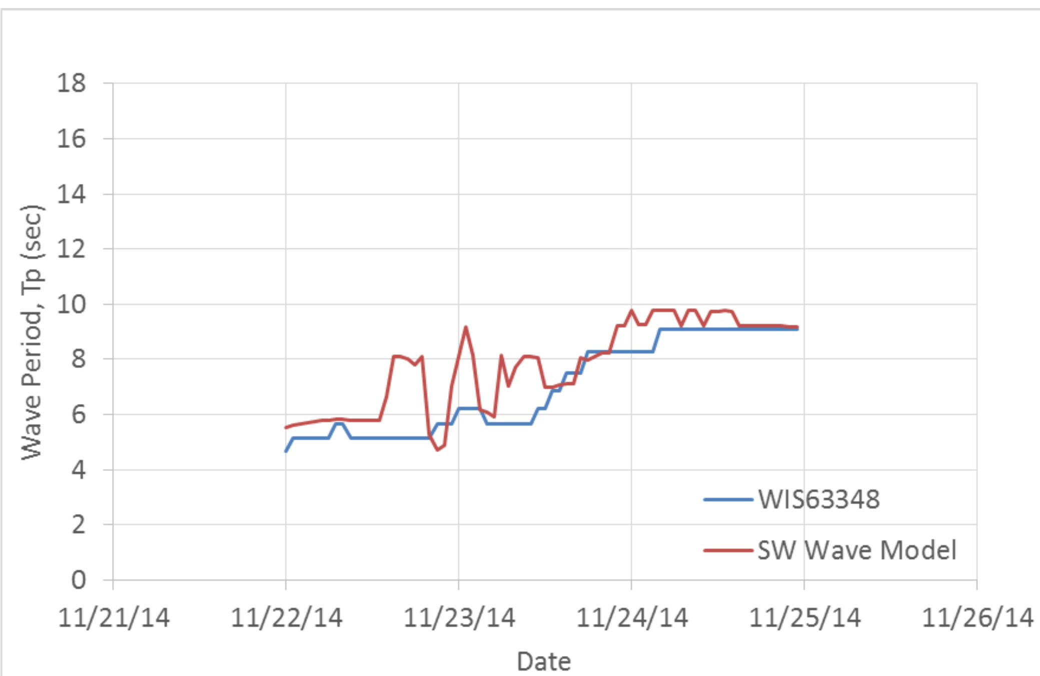

Figure 3-13: Calculated Wave Periods Compared to WIS63348 Wave Periods (Open Boundary Conditions: NDBC 41004 Buoy Data)

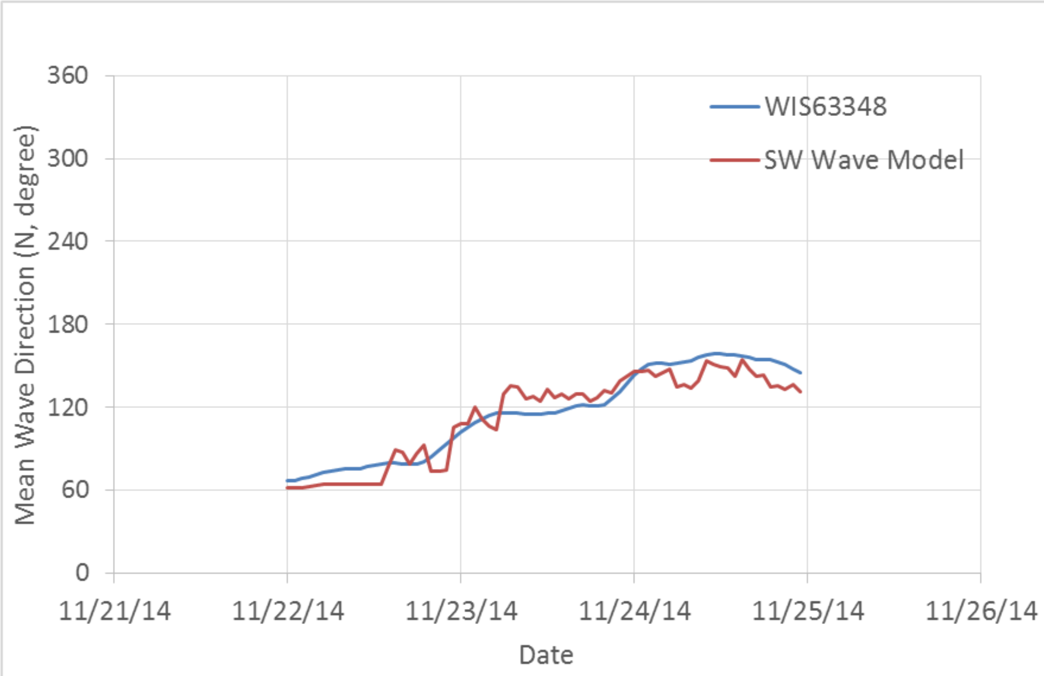

Figure 3-14: Calculated Wave Directions Compared to WIS63348 Wave Directions (Open Boundary Conditions: NDBC 41004 Buoy Data)

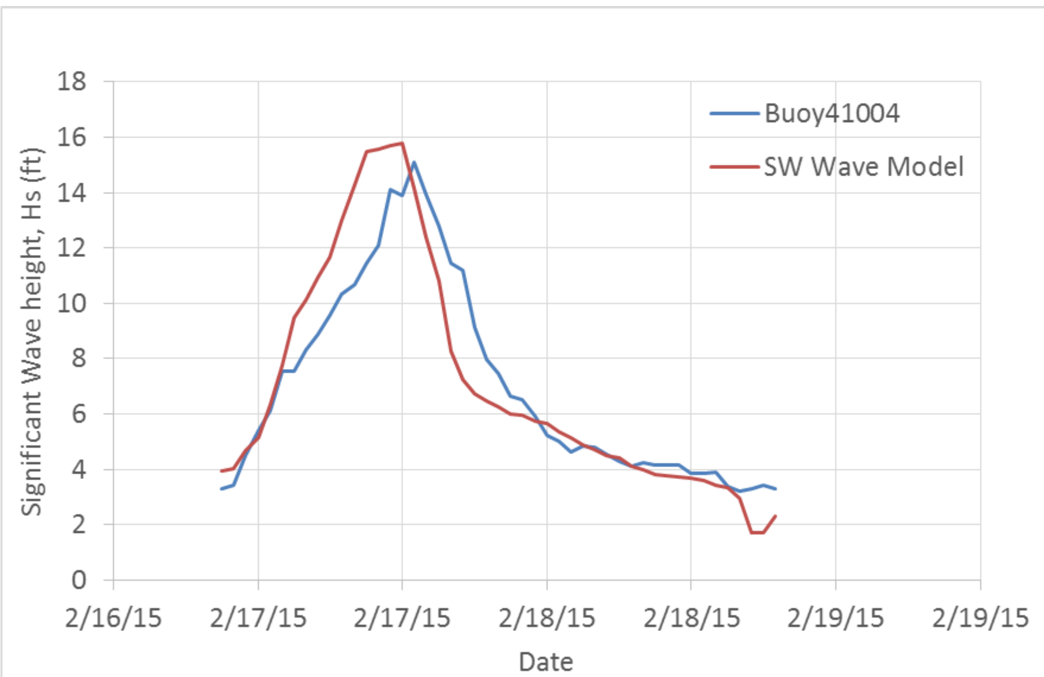

Figure 3-15: Calculated Wave Heights Compared to Buoy41004 Wave Heights (Open Boundary Conditions: NDBC 41004 Buoy Data)

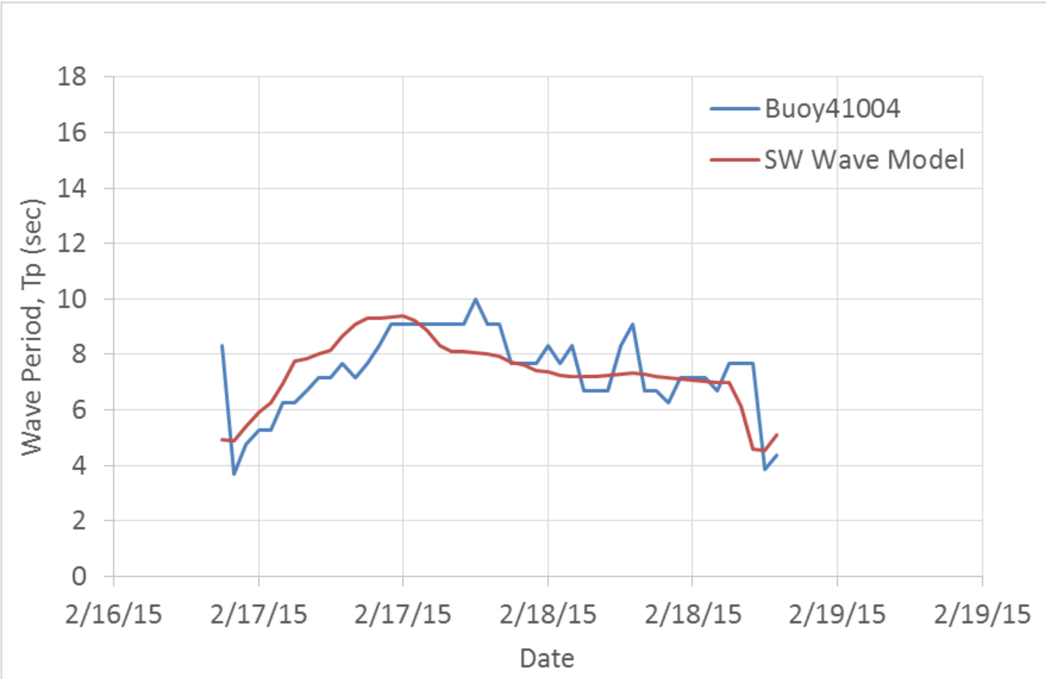

Figure 3-16: Calculated Wave Periods Compared to Buoy41004 Wave Heights (Open Boundary Conditions: NDBC 41004 Buoy Data)

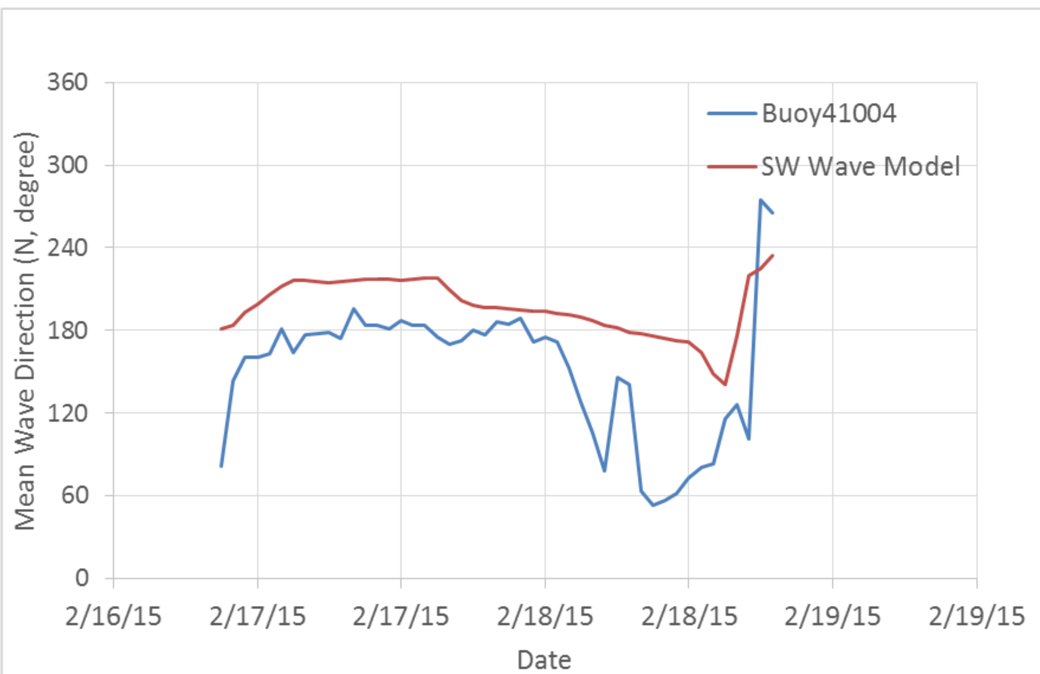

Figure 3-17: Calculated Wave Directions Compared to Buoy41004 Wave Directions (Open Boundary Conditions: NDBC 41004 Buoy Data)

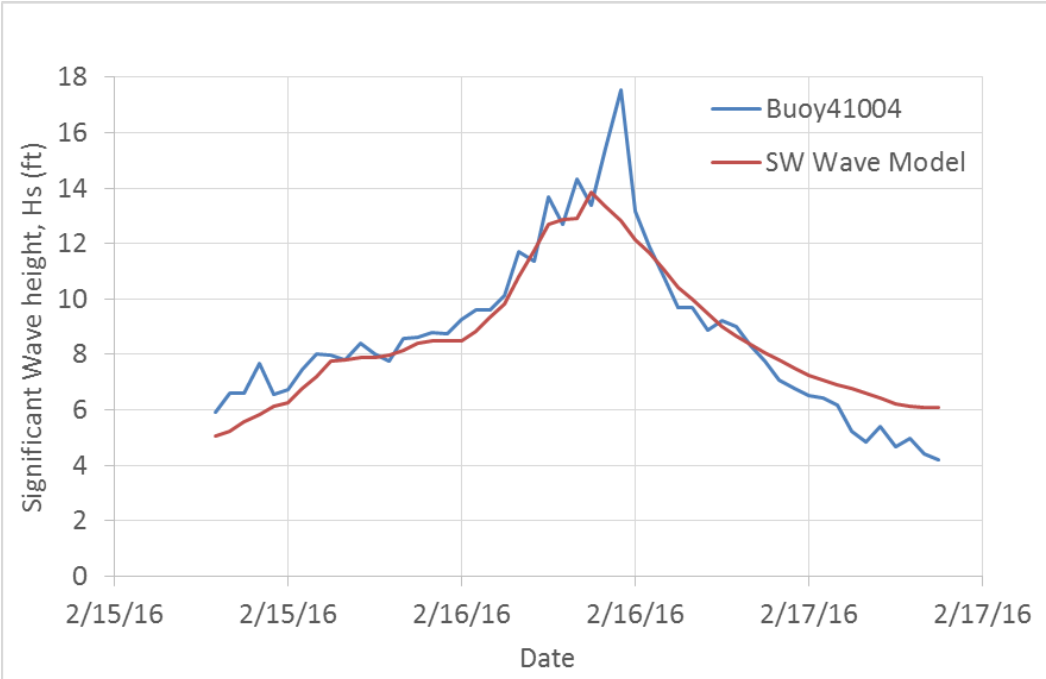

Figure 3-18: Calculated Wave Heights Compared to Buoy41004 Wave Heights (Open Boundary Conditions: WaveWatch 3 Data)

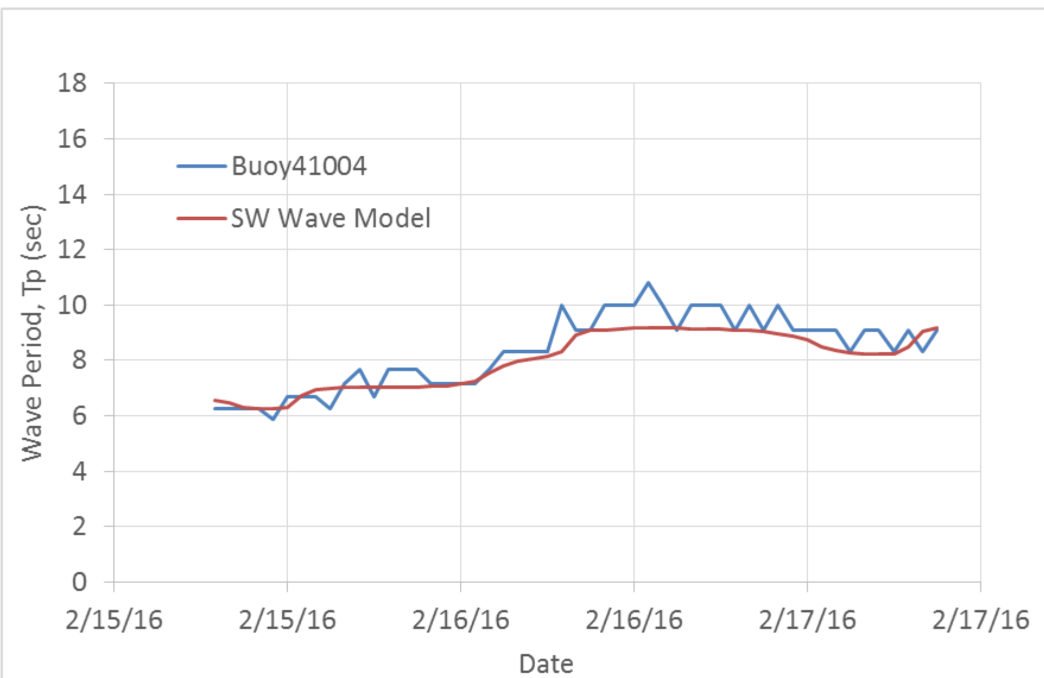

Figure 3-19: Calculated Wave Periods Compared to Buoy41004 Wave Periods (Open Boundary Conditions: WaveWatch 3 Data)

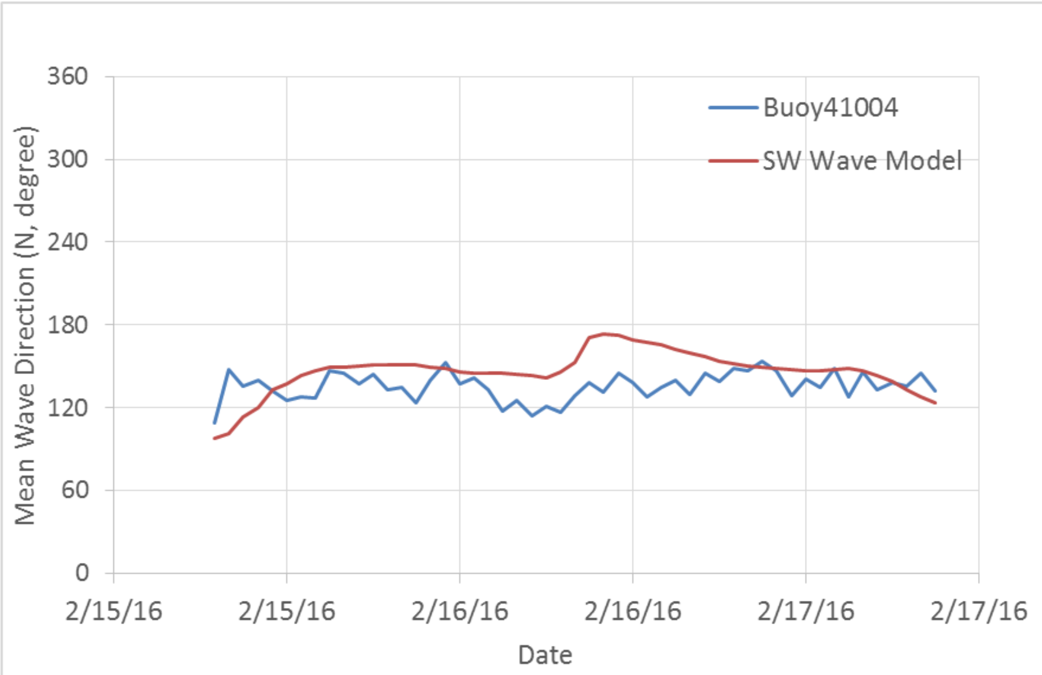

Figure 3-20: Calculated Wave Directions Compared to Buoy41004 Wave Directions (Open Boundary Conditions: WaveWatch 3 Data)

3.2. Wave Model Transformation

The calibrated and validated spectral wave model was applied for wave transformation from offshore to nearshore project site. Based on wave model calibration and validation, applying measured wave data as wave model open boundary conditions would get more accurate short-period peak wave heights at nearshore area compared to using model data, such as WaveWatch 3. For the long-term wave transformation simulations, NDBC measured wave data was used for the open boundary conditions in the time periods that it was available. When NDBC measured data was not available, the WaveWatch 3 data was used to provide wave model open boundary conditions. The wave transformation model was thus run for the following time periods:

- Offshore WaveWatch 3 wave data from January 2008 to December 2014
- NDBC 41004 wave data from April 2014 to December 2019

The model simulated nearshore wave conditions were extracted along the 4.0 meters (13.1 feet) mean sea level (MSL) depth contours at 22 locations along the Folly Beach. The nearshore wave data, which include both storm and non-storm wave conditions, were utilized as representative wave conditions to evaluate long-term shoreline changes.

4. ONE-LINE SHORELINE MODEL CALIBRATION

The USACE GenCade shoreline evolution model was used to estimate the shoreline change rates for the Folly Beach shoreline study. The GenCade model is a one-line, one-dimensional shoreline change model developed by the USACE's Coastal Inlets Research Program (CIRP) to combine and improve upon the capabilities of previous shoreline response models Cascade and GENESIS. The GenCade shoreline model calculates shoreline changes based on differential wave-driven longshore sediment transport rates.

A GenCade shoreline model was developed for the Folly Beach as illustrated in Figure 4-1.The total shoreline length simulated within the shoreline model is approximately 6.3 miles. The shoreline at mean high water level (MHW) was represented by grid points with a spacing of 20.0 feet in the alongshore direction. The GenCade shoreline model was calibrated using the measured shorelines in December 2016 and December 2017.

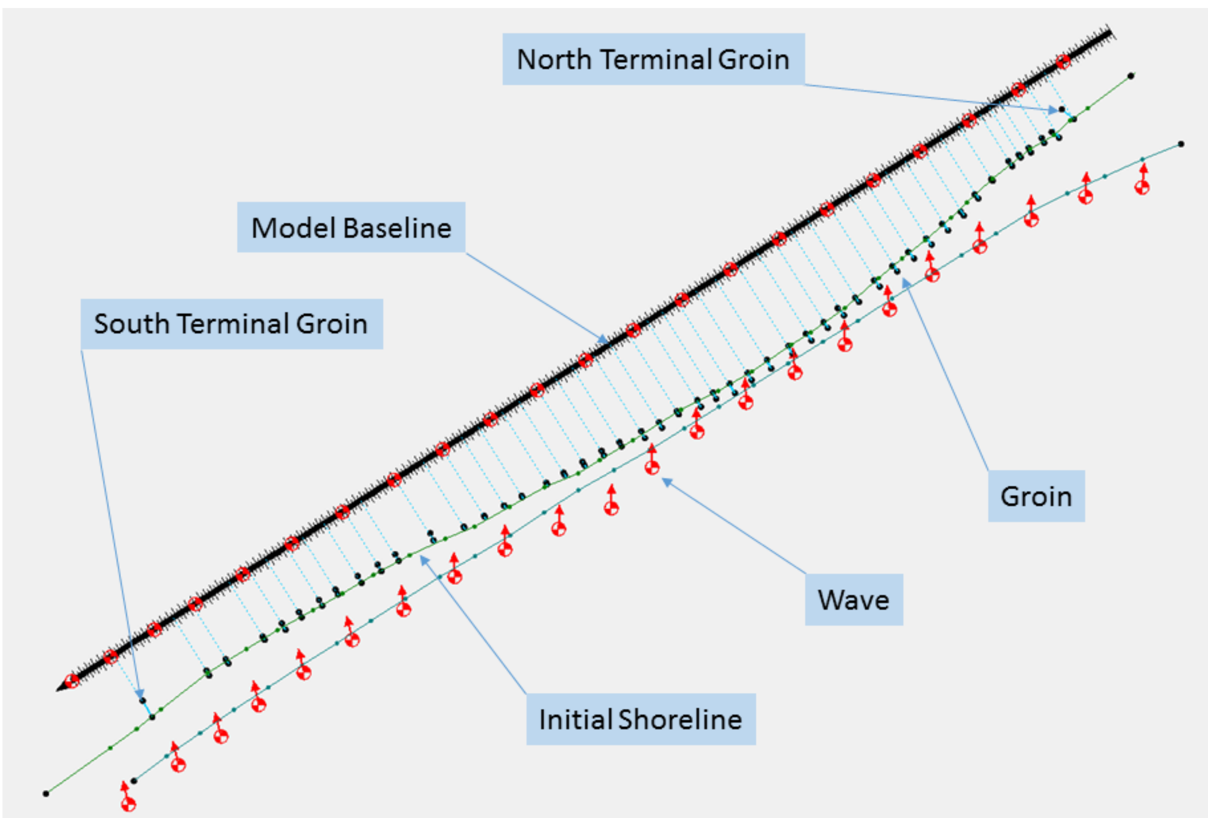

Figure 4-1: GenCade Model Setup

The GenCade model setup parameters are presented in Table 4-1.

Table 4-1: Calibrated GenCade Model Setup Parameters

No.	Parameter Name	Value
1	Cell size	20 ft
2	Grain size	0.17 mm
3	Average berm height	7.5 ft
4	Closure depth	10 ft
5	Longshore sand transport coefficient, K1	0.15
6	Longshore sand transport coefficient, K2	0.25
7	Lateral boundary for Northeast boundary	Moving
8	Lateral boundary for Southwest boundary	Pinned

The grain size was selected from the 1994 Coastal Engineering Journal article about Folly Beach (Billy et.al, 1994). The average berm height and the closure depth were determined from the historical survey profiles. The default longshore sand transport coefficient K1 is 0.5, and the default longshore sand transport coefficient K2 is 0.25. The groin permeability parameters were initially estimated considering the groin elevations provided by USACE, aerial images, and engineering judgement. Then the estimated groin permeability parameters were adjusted and calibrated using the measured shoreline locations. The final calibrated groin permeability parameters are presented in Table 4-2.

In the GenCade shoreline model, the sand bypassing is assumed to take place if the water depth at the tip of the structure is less than the depth of active longshore transport.

In the Coastal Engineering Manual, the “closure depth” is defined using the concept of “the seaward limit of effective profile fluctuation over long-term (seasonal or multi-year) time scales.” The USACE GenCade Model Theory and User’s Guide states that “The depth of closure, the seaward limit beyond which the profile does not exhibit significant change in depth, must be specified by the user. Empirically, the location of the closure depth is difficult to identify precisely, as small bathymetric change in deeper water is extremely difficult to measure. This situation usually results in a depth of closure located somewhere in a wide range of values, requiring judgement to be exercised to specify a single value.” M&N applied the closure depth values of 10 feet and 15 feet to estimate shoreline change rates. Based on the shoreline model calibration and validation, using the closure depth of 10 feet resulted in better shoreline change results from the GenCade shoreline model.

Table 4-2: Calibrated GenCade Shoreline Model Groin Permeability Values

Groin	Permeability	Groin	Permeability
#3	0.3	#30	0.1
#4	0.5	#31	0.1
#5	0.8	#32	0.1
#6	0.8	#33	0.1
#7	0.8	#34	0.1
#8	0.8	#35	0.1
#9	0.8	#36	0.1
#10	0.5	#37	0.1
#11	0.5	#38	0.1
#12	0.5	#39	0.8
#13	0.5	#40	0.8
#14	0.5	#41	0.8
#15	0.5	#42	0.8
#16	0.5	#43	0.8
#17	0.5	#44	0.8
#18	0.8	#45	0.8
#19	0.5	#46	0.8
#20	0.5	#47	0.8
#21	0.5	#48	0.8
#22	0.5	#49	0.8
#23	0.5	#50	0.3
#24	0.5		
#25	0.5		
#26	0.5		
#27	0.6		
#28	0.6		
#29	0.6		

Figure 4-2 illustrates the comparisons between the observed (blue dots) annual shoreline changes at each survey transect and model simulated shoreline changes (solid red line) at the MHW water location between December 2016 and December 2017. The purple dots show the groin locations in the figures. In general, the simulated shoreline changes are in reasonable agreement with the observed shoreline changes at most locations along the Folly Beach.

The same shoreline model parameters presented in Table 4-1 and Table 4-2 were validated for two periods: a) March 2010 to December 2012, and b) December 2008 to March 2010.

Figure 4-3 shows the comparisons between the observed and model simulated annual shoreline changes at each survey transect between March 2010 and December 2012. For this period, the shoreline model simulated shoreline change rates are underestimated compared to the measured data. However, the model simulated trends of shoreline erosion and accretion are similar with the measured data.

Figure 4-4 shows the comparisons between the observed and model simulated annual shoreline changes at each survey transect between December 2008 and March 2010. In general, the simulated shoreline changes are in agreement with the observed shoreline changes at most locations along the Folly Beach shoreline between December 2008 and March 2010.

The calculated net longshore sediment transport rates during December 2016 and December 2017 are illustrated in Figure 4-5. In Figure 4-5 the positive sediment transport is from northeast to southwest, and the negative sediment transport is from southwest to northeast. The shoreline model simulated net longshore sediment transport rates are between -32,000 cy/yr (sediment transport to northeast) and 99,000 cy/yr (sediment transport to southwest) during December 2016 and December 2017.

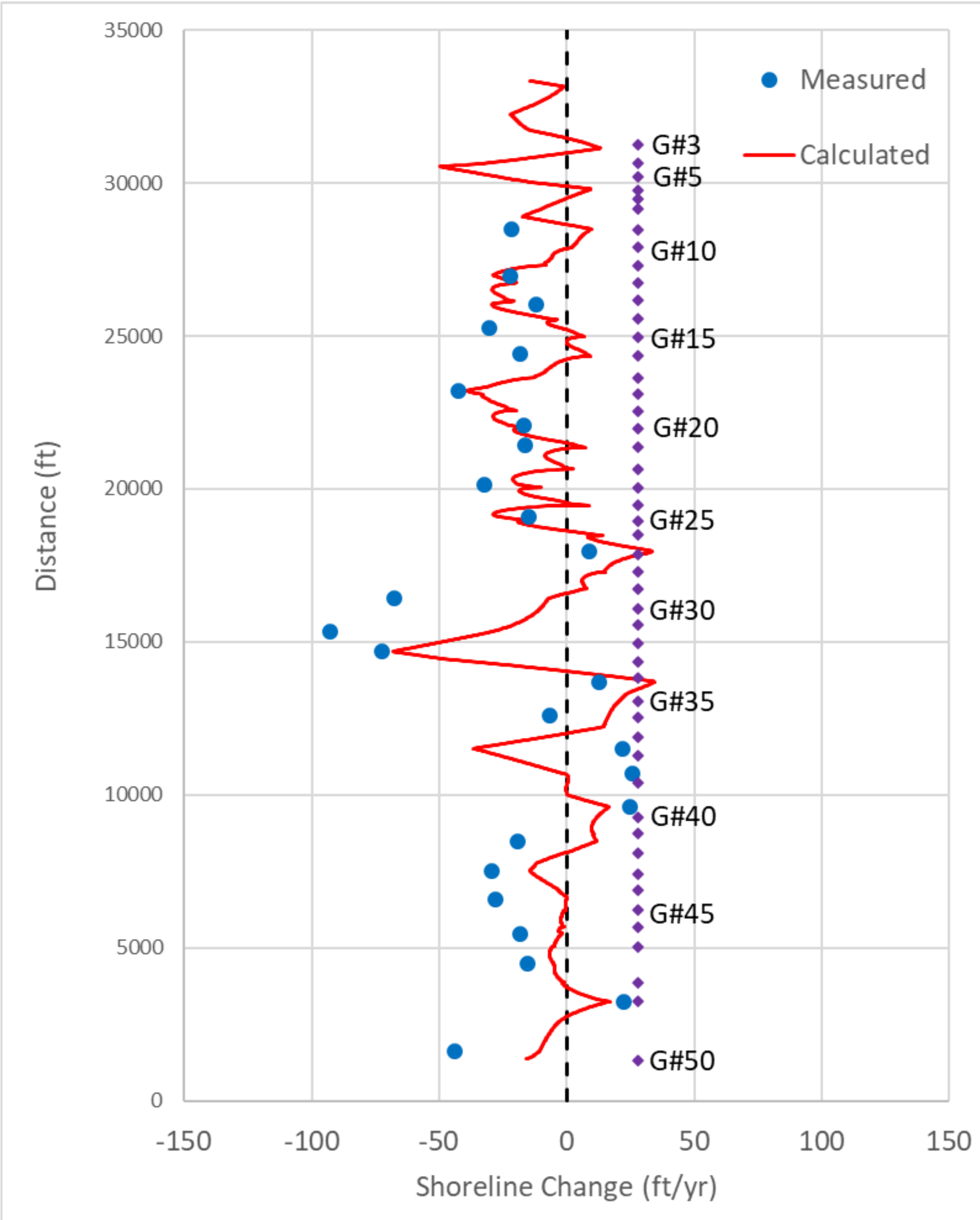

Figure 4-2: Shoreline Model Calibration (Dec. 2016 to Dec. 2017)

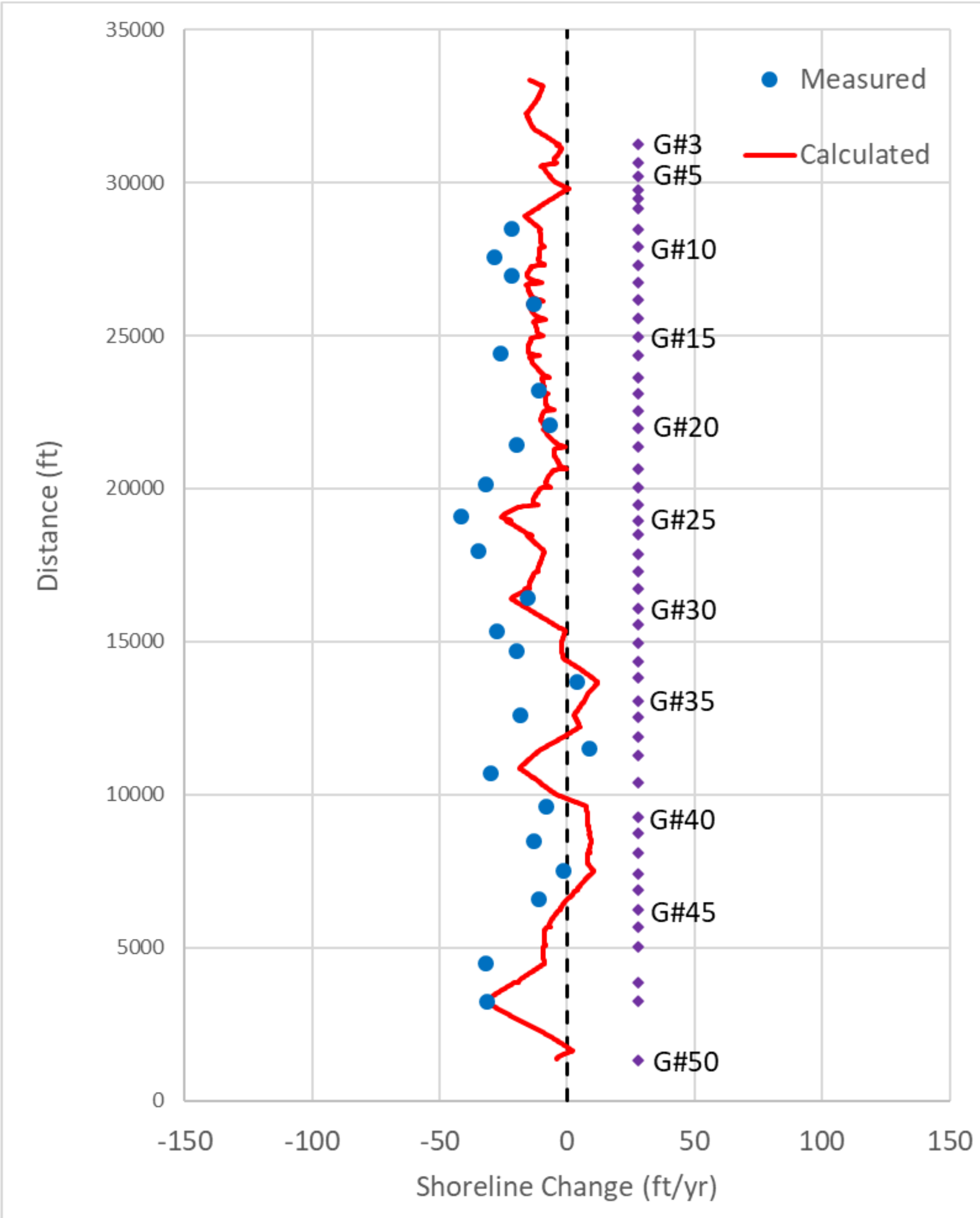

Figure 4-3: Shoreline Model Validation (Mar. 2010 to Dec. 2012)

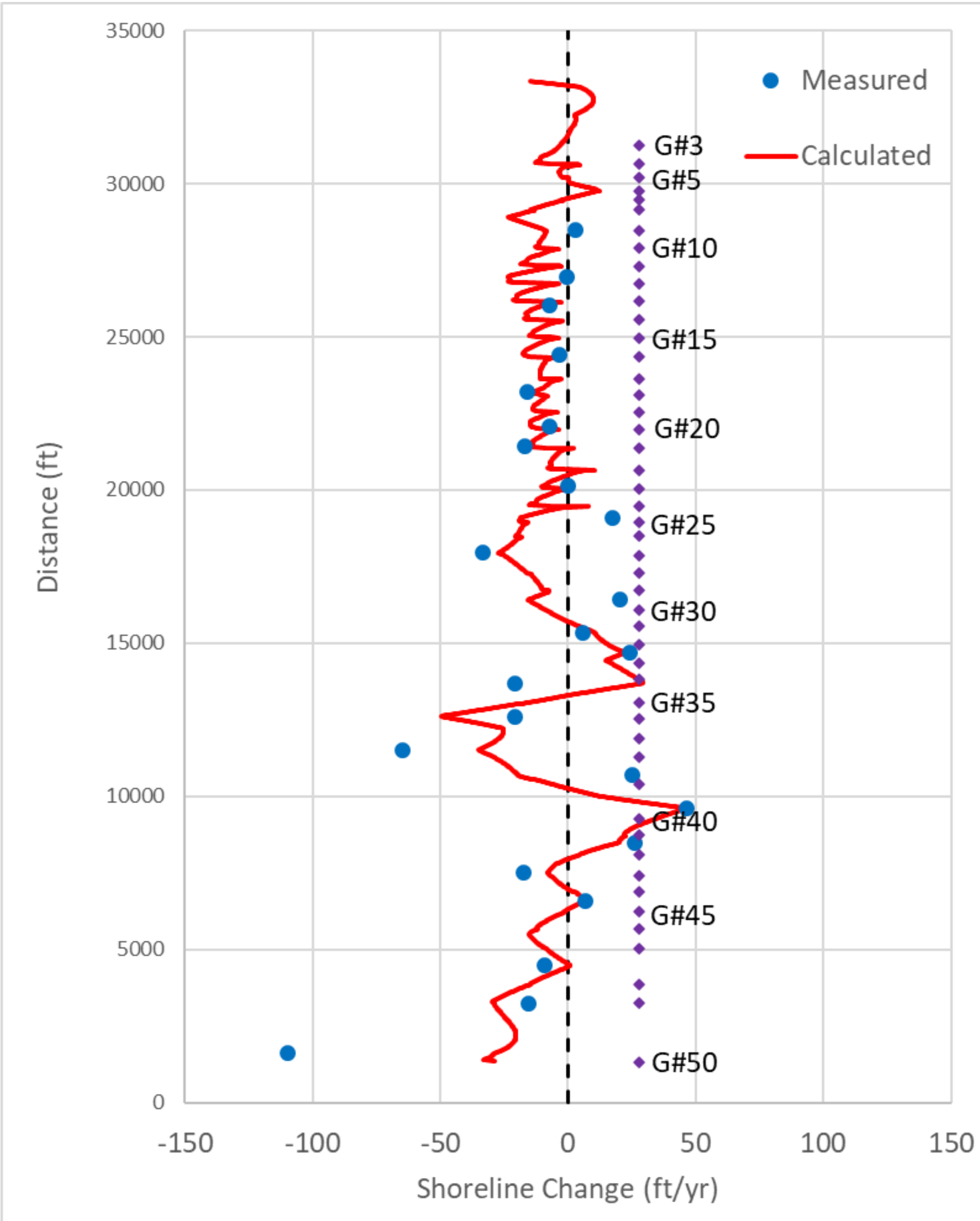

Figure 4-4: Shoreline Model Validation (Dec. 2008 to Mar. 2010)

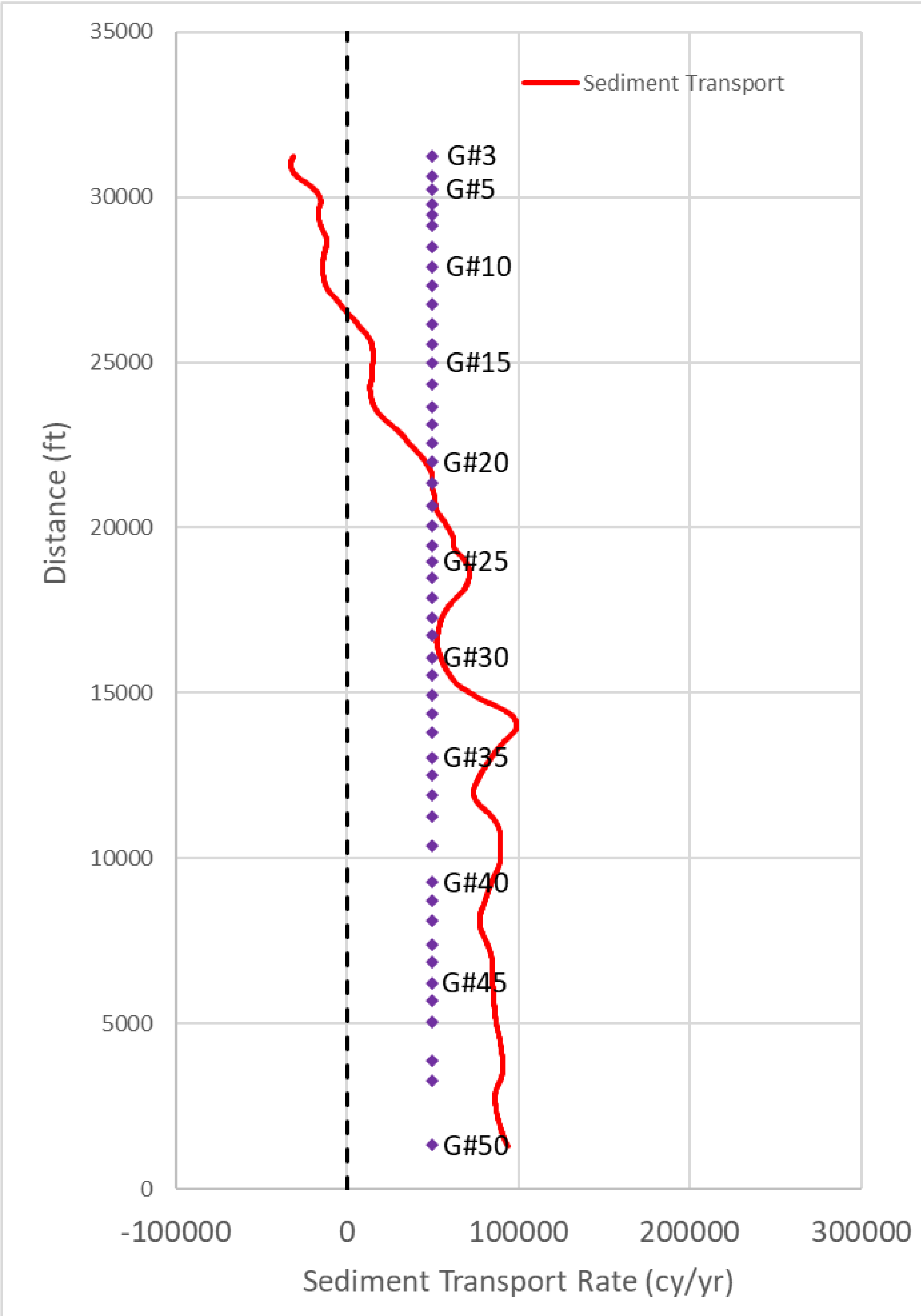

Figure 4-5: Calculated Net Longshore Sediment Transport Rates (Dec. 2016 to Dec. 2017)

5. Estimation of Shoreline Change Rates of Future With Project Scenarios

Four future beach nourishment projects were developed by USACE. The future beach nourishment template and the beach reaches for Beach-fx model are illustrated in Figure 5-1. Table 5-1 and Table 5-2 present the detailed beach nourishment design and future project schedule. The project interval of the future beach nourishment projects will be 12 years. The grain sizes from the proposed sand sources will be in the range of 0.16 mm and 0.20 mm.

The calibrated GenCade shoreline model was used to estimate the shoreline change rates for the Future With Project scenarios.

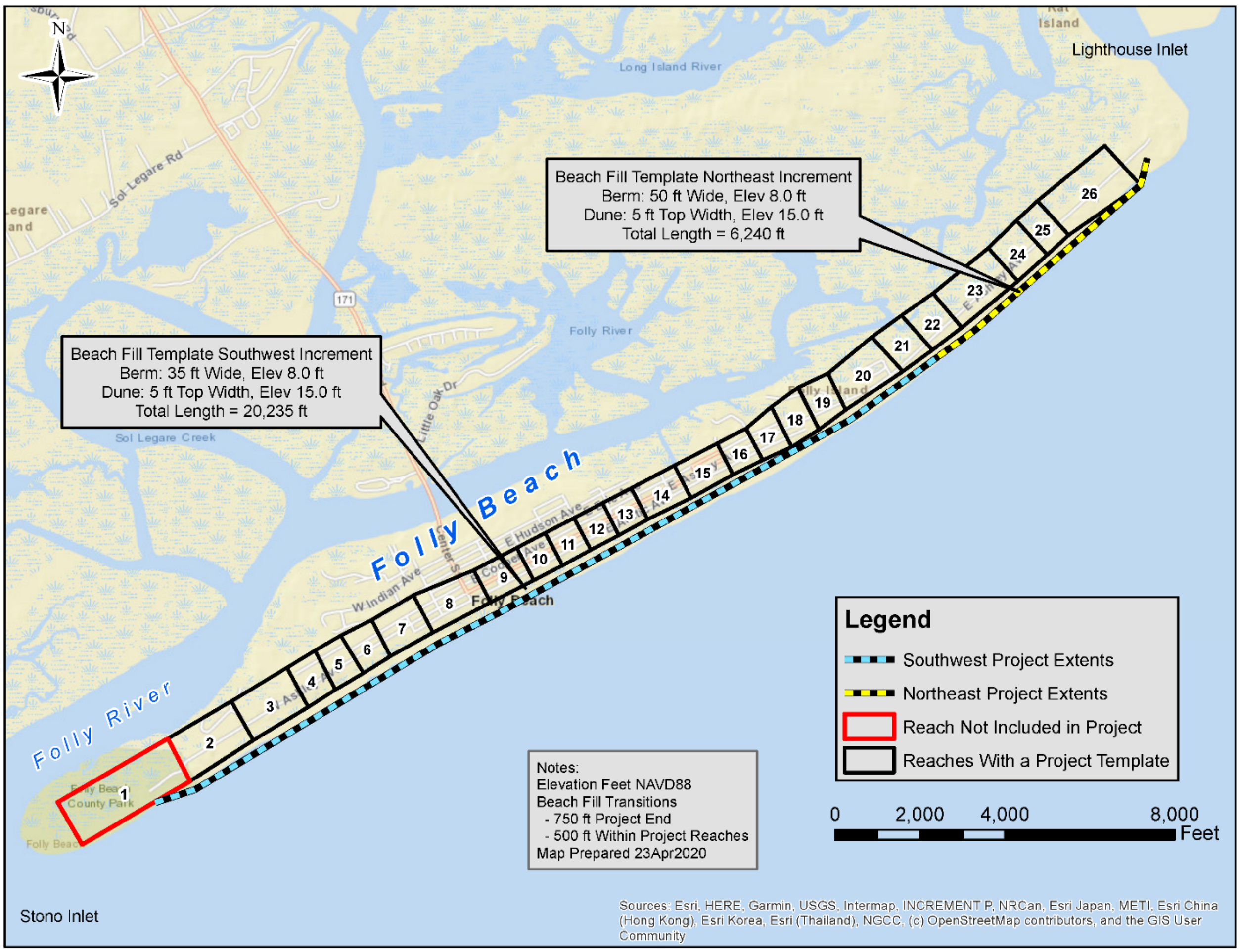

Figure 5-1: Beach Nourishment Template and Beach-fx Model Reaches

Table 5-1: Beach Nourishment Design

Design	Beach-fx Reach 2 to Beach-fx Reach 21	Beach-fx Reach 22 to Beach-fx Reach 26
Dune elevation	15.0 ft, NAVD	15.0 ft, NAVD
Top dune width	5.0 ft	5.0 ft
Dune slope	1v:5h	1v:5h
Berm elevation	8.0 ft, NAVD	8.0 ft, NAVD
Berm width	35.0 ft	50.0 ft
Foreshore slope to MHW	1v:15h	1v:15h
Offshore slope to existing profile	1v:30h	1v:30h

Table 5-2: Beach Nourishment Schedule

Project	Date	Grain Size (d_{50}, mm)
Nourishment #1	January 2024	0.20
Nourishment #2	January 2036	0.19
Nourishment #3	January 2048	0.19
Nourishment #4	January 2060	0.16

The 12-year time series (2008 - 2019) nearshore wave conditions were extracted from the spectral wave model results. The annual longshore sediment transport rates were estimated using a profile-based model of longshore sediment transport (LITDRIFT, developed by DHI). The estimated annual longshore sediment transport rates are between approximately 60,000 cy/yr and 158,000 cy/yr from 2008 to 2019. The estimated 2010 annual longshore sediment transport rate represents the lowest rate between 2008 and 2019. Thus, the time series wave conditions in 2010 were selected as representative waves to represent milder (non-storm) wave climates for the shoreline model since storms will be modeled in Beach-fx. The 2010 time series waves were repeated every year for 12-year period for the GenCade shoreline model.

The procedure of the shoreline change simulations is summarized as below:

- January 2024 beach nourishment project: A shoreline model was developed based on the December 2018 shoreline and the proposed January 2024 beach nourishment project. The shoreline changes from January 1, 2024 to December 31, 2035 were calculated.

- January 2036 beach nourishment project: A shoreline model was developed based on the simulated December 31, 2035 shoreline and the proposed January 2036 beach nourishment project. The shoreline changes from January 1, 2036 to December 31, 2047 were calculated.

- January 2048 beach nourishment project: A shoreline model was developed based on the simulated December 31, 2047 shoreline and the proposed January 2048 beach nourishment project. The shoreline changes from January 1, 2048 to December 31, 2059 were calculated.

- January 2060 beach nourishment project: A shoreline model was developed based on the simulated December 31, 2059 shoreline and the proposed January 2060 beach nourishment project. The shoreline changes from January 1, 2060 to December 31, 2071 were calculated.

The simulated shoreline change rates for the Future With Project scenarios were analyzed for both the Beach-fx model reaches and the SBEACH model reaches as illustrated in Figure 5-2. The estimated annual and average shoreline change rates for the Beach-fx model reaches are presented in Table 5-3 through Table 5-8. The estimated annual and average shoreline change rates for the SBEACH model reaches are presented in Table 5-9 through Table 5-14.

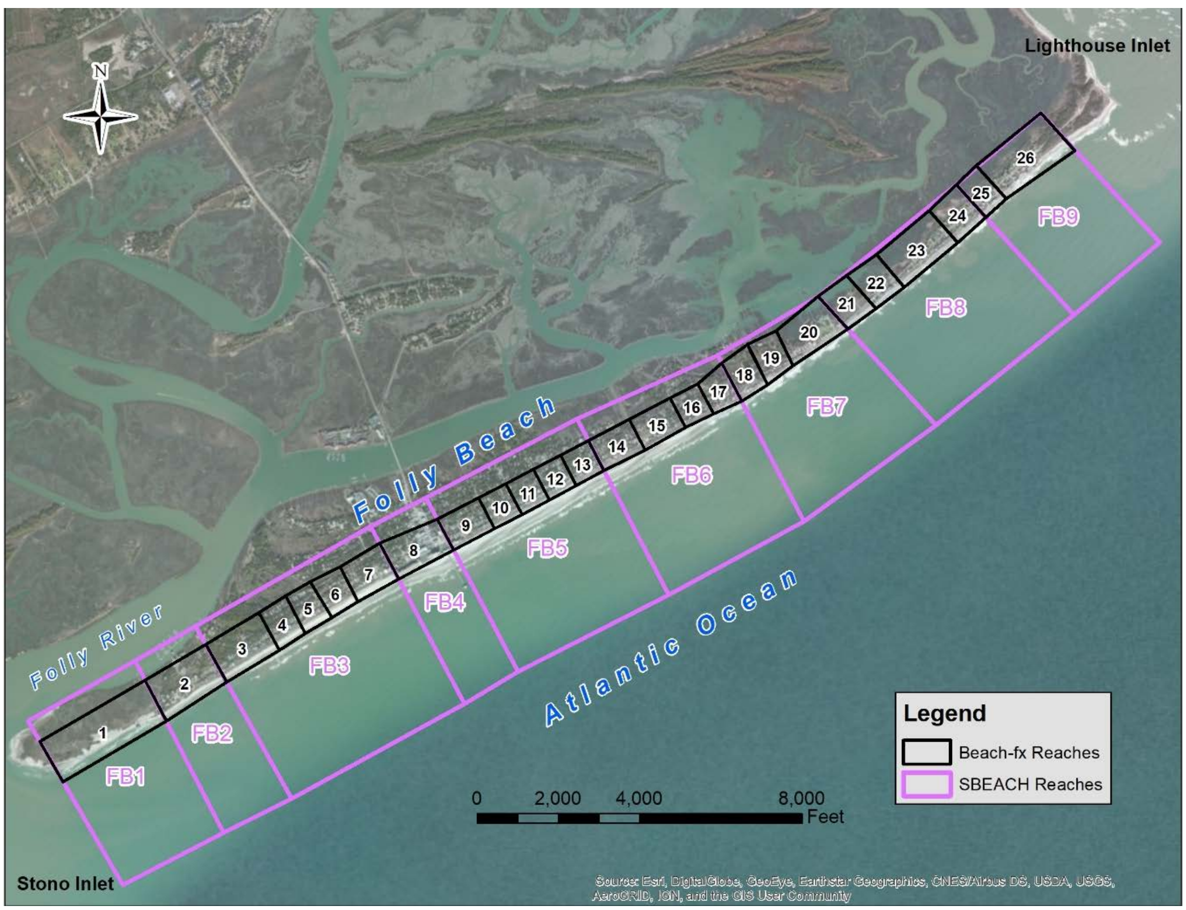

Figure 5-2: Beach-fx Model Reaches and SBEACH Model Reaches

Table 5-3: Annual Shoreline Change Rates for 2024 Beach Nourishment Project at Beach-fx Model Reaches

Beach -fx Reach	Shoreline Change Rates (ft/yr)											
	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
R#2	-3.0	-6.3	-7.5	-6.7	-4.1	-1.3	0.9	2.2	2.9	3.1	3.1	3.0
R#3	-1.2	1.2	2.0	1.8	1.2	0.9	1.0	1.2	1.5	1.7	1.9	1.9
R#4	8.4	8.6	7.7	6.0	4.4	3.5	2.7	2.1	1.8	1.6	1.5	1.5
R#5	12.5	13.7	9.6	6.9	5.2	3.7	2.8	2.1	1.7	1.4	1.2	1.1
R#6	30.5	12.9	7.2	4.8	3.6	2.7	2.1	1.6	1.3	1.0	0.8	0.7
R#7	2.8	-1.3	-1.1	-0.5	0.1	0.3	0.3	0.3	0.2	0.1	0.0	-0.1
R#8	-33.8	-14.3	-7.6	-4.7	-3.3	-2.5	-2.0	-1.7	-1.5	-1.4	-1.3	-1.3
R#9	18.5	2.7	-1.5	-2.8	-3.2	-3.2	-3.1	-2.9	-2.7	-2.6	-2.5	-2.4
R#10	18.3	6.2	0.3	-2.0	-3.0	-3.3	-3.3	-3.3	-3.1	-3.0	-2.9	-2.9
R#11	-4.4	-3.1	-2.8	-3.2	-3.4	-3.5	-3.5	-3.4	-3.4	-3.3	-3.2	-3.1
R#12	-29.6	-10.6	-6.2	-4.4	-3.6	-3.3	-3.2	-3.1	-3.1	-3.2	-3.2	-3.3
R#13	-11.0	-10.0	-6.2	-4.3	-3.4	-3.0	-2.9	-3.0	-3.1	-3.2	-3.3	-3.4
R#14	0.3	-1.9	-2.2	-2.2	-2.2	-2.4	-2.6	-2.8	-3.0	-3.2	-3.3	-3.4
R#15	8.5	4.8	1.6	-0.4	-1.7	-2.6	-3.2	-3.6	-3.9	-4.1	-4.3	-4.2
R#16	6.9	2.1	-0.6	-2.4	-3.5	-4.3	-4.8	-5.1	-5.3	-5.4	-5.5	-5.8
R#17	-3.6	-5.0	-5.6	-5.9	-6.2	-6.3	-6.4	-6.4	-6.4	-6.4	-6.4	-6.8
R#18	-18.6	-13.5	-11.8	-10.7	-9.9	-9.3	-8.9	-8.6	-8.5	-8.3	-8.2	-7.9
R#19	-19.1	-18.0	-15.5	-13.7	-12.6	-11.8	-11.3	-10.9	-10.5	-10.3	-10.1	-9.8
R#20	-21.2	-17.2	-15.9	-14.9	-14.2	-13.6	-13.1	-12.7	-12.4	-12.0	-11.7	-11.5
R#21	-3.5	-12.0	-13.2	-13.5	-13.6	-13.5	-13.4	-13.2	-13.0	-12.7	-12.4	-12.1
R#22	-12.6	-11.4	-12.1	-12.5	-12.7	-12.8	-12.8	-12.7	-12.5	-12.2	-12.0	-11.8
R#23	-13.4	-11.9	-11.6	-11.7	-11.8	-11.9	-11.8	-11.6	-11.4	-11.2	-11.0	-10.8
R#24	-9.3	-10.2	-11.5	-11.7	-11.5	-11.2	-11.0	-10.7	-10.6	-10.4	-10.2	-10.2
R#25	-4.8	-11.5	-12.4	-11.8	-11.1	-10.5	-10.1	-9.8	-9.7	-9.7	-9.8	-10.0
R#26	-21.7	-13.0	-9.3	-7.6	-6.9	-6.7	-6.6	-6.9	-7.2	-7.6	-8.1	-8.5

Table 5-4: Annual Shoreline Change Rates for 2036 Beach Nourishment Project at Beach-fx Model Reaches

Beach -fx Reach	Shoreline Change Rates (ft/yr)											
	2036	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**	**2046**	**2047**
R#2	4.2	-1.1	-4.3	-5.3	-4.3	-1.8	0.5	1.9	2.7	2.9	2.9	2.8
R#3	2.1	2.3	1.8	0.7	-0.1	-0.6	-0.6	-0.3	0.1	0.5	0.8	1.0
R#4	2.2	1.5	1.4	1.4	0.9	0.5	0.2	0.1	0.0	0.1	0.2	0.4
R#5	0.1	0.9	0.9	0.8	0.8	0.6	0.4	0.3	0.2	0.1	0.2	0.2
R#6	1.1	0.4	0.3	0.4	0.5	0.6	0.5	0.4	0.3	0.2	0.1	0.1
R#7	-0.4	-0.7	-0.3	0.1	0.3	0.4	0.4	0.3	0.1	0.0	-0.1	-0.2
R#8	-2.9	-0.1	0.5	0.5	0.3	0.1	-0.1	-0.3	-0.4	-0.5	-0.6	-0.7
R#9	7.7	3.6	1.4	0.1	-0.6	-1.0	-1.3	-1.4	-1.4	-1.4	-1.5	-1.5
R#10	5.1	1.5	-1.1	-2.0	-2.3	-2.4	-2.3	-2.3	-2.2	-2.1	-2.2	-2.2
R#11	2.9	-5.5	-5.0	-4.5	-3.9	-3.5	-3.1	-2.9	-2.7	-2.6	-2.5	-2.5
R#12	-30.7	-11.5	-7.5	-5.5	-4.4	-3.8	-3.4	-3.2	-3.2	-3.1	-3.0	-3.0
R#13	-13.1	-10.5	-6.9	-5.1	-4.1	-3.6	-3.3	-3.2	-3.2	-3.3	-3.3	-3.3
R#14	0.1	-2.3	-2.6	-2.6	-2.6	-2.8	-2.9	-3.0	-3.2	-3.3	-3.4	-3.5
R#15	8.5	4.8	1.6	-0.6	-1.9	-2.8	-3.4	-3.8	-4.1	-4.2	-4.4	-4.3
R#16	7.3	2.3	-0.5	-2.3	-3.6	-4.3	-4.9	-5.2	-5.4	-5.5	-5.6	-5.9
R#17	-3.3	-4.9	-5.5	-5.9	-6.1	-6.3	-6.4	-6.5	-6.5	-6.5	-6.5	-6.8
R#18	-18.9	-13.6	-11.7	-10.6	-9.9	-9.3	-8.9	-8.6	-8.5	-8.3	-8.2	-8.0
R#19	-19.4	-18.2	-15.6	-13.8	-12.6	-11.9	-11.3	-10.9	-10.5	-10.3	-10.1	-9.9
R#20	-21.3	-17.4	-16.0	-15.0	-14.3	-13.7	-13.2	-12.8	-12.4	-12.1	-11.8	-11.5
R#21	-3.5	-12.0	-13.3	-13.6	-13.7	-13.6	-13.5	-13.3	-13.0	-12.8	-12.5	-12.2
R#22	-12.7	-11.5	-12.2	-12.6	-12.8	-12.9	-12.9	-12.8	-12.6	-12.3	-12.0	-11.9
R#23	-13.4	-11.9	-11.6	-11.8	-11.9	-11.9	-11.8	-11.6	-11.4	-11.3	-11.1	-10.9
R#24	-9.4	-10.3	-11.5	-11.7	-11.5	-11.3	-11.0	-10.8	-10.6	-10.4	-10.3	-10.3
R#25	-5.0	-11.6	-12.4	-11.9	-11.2	-10.5	-10.1	-9.9	-9.8	-9.8	-9.9	-10.1
R#26	-21.5	-13.0	-9.2	-7.6	-6.9	-6.7	-6.6	-6.9	-7.3	-7.7	-8.2	-8.6

Table 5-5: Annual Shoreline Change Rates for 2048 Beach Nourishment Project at Beach-fx Model Reaches

Beach -fx Reach	Shoreline Change Rates (ft/yr)											
	2048	2049	2050	2051	2052	2053	2054	2055	2056	2057	2058	2059
R#2	3.8	-1.3	-4.3	-5.1	-3.9	-1.3	0.8	2.1	2.8	2.9	2.9	2.7
R#3	1.3	1.6	1.1	0.2	-0.5	-0.9	-0.8	-0.5	0.0	0.4	0.7	0.9
R#4	1.2	0.8	0.8	0.6	0.4	0.1	-0.1	-0.2	-0.2	0.0	0.1	0.3
R#5	-0.6	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.0	0.0	0.1	0.1
R#6	0.5	-0.1	-0.1	0.1	0.3	0.3	0.3	0.2	0.2	0.1	0.0	0.0
R#7	-0.5	-0.8	-0.3	0.2	0.4	0.5	0.4	0.3	0.2	0.1	0.0	-0.1
R#8	-2.3	0.7	1.2	1.1	0.8	0.4	0.2	-0.1	-0.2	-0.4	-0.5	-0.6
R#9	10.1	5.0	2.3	0.8	-0.1	-0.6	-0.9	-1.1	-1.2	-1.3	-1.3	-1.4
R#10	6.4	2.0	-0.7	-1.7	-2.1	-2.1	-2.1	-2.0	-2.0	-2.0	-2.1	-2.1
R#11	0.4	-6.0	-5.2	-4.5	-3.8	-3.3	-3.0	-2.7	-2.6	-2.5	-2.4	-2.4
R#12	-31.7	-12.3	-7.9	-5.8	-4.6	-3.9	-3.5	-3.3	-3.2	-3.0	-3.0	-2.9
R#13	-13.4	-11.0	-7.3	-5.4	-4.4	-3.8	-3.5	-3.3	-3.3	-3.3	-3.3	-3.3
R#14	0.1	-2.4	-2.8	-2.8	-2.8	-2.9	-3.0	-3.1	-3.3	-3.4	-3.4	-3.5
R#15	8.5	4.8	1.5	-0.6	-2.0	-2.9	-3.5	-3.9	-4.1	-4.3	-4.4	-4.4
R#16	7.3	2.3	-0.5	-2.4	-3.6	-4.4	-4.9	-5.2	-5.4	-5.6	-5.7	-5.9
R#17	-3.3	-4.9	-5.5	-5.9	-6.2	-6.3	-6.4	-6.5	-6.5	-6.5	-6.5	-6.9
R#18	-18.9	-13.6	-11.7	-10.6	-9.9	-9.3	-8.9	-8.7	-8.5	-8.4	-8.3	-8.0
R#19	-19.4	-18.2	-15.6	-13.8	-12.6	-11.9	-11.3	-10.9	-10.5	-10.3	-10.2	-9.9
R#20	-21.3	-17.4	-16.0	-15.0	-14.3	-13.7	-13.2	-12.8	-12.4	-12.1	-11.8	-11.5
R#21	-3.5	-12.0	-13.3	-13.6	-13.7	-13.6	-13.5	-13.3	-13.1	-12.8	-12.5	-12.2
R#22	-12.7	-11.5	-12.2	-12.6	-12.8	-12.9	-12.9	-12.8	-12.6	-12.3	-12.0	-11.9
R#23	-13.4	-11.9	-11.6	-11.8	-11.9	-11.9	-11.8	-11.6	-11.4	-11.3	-11.1	-10.9
R#24	-9.4	-10.3	-11.5	-11.7	-11.5	-11.3	-11.0	-10.8	-10.6	-10.4	-10.3	-10.3
R#25	-5.0	-11.6	-12.4	-11.9	-11.2	-10.5	-10.1	-9.9	-9.8	-9.8	-9.9	-10.1
R#26	-21.5	-13.0	-9.2	-7.6	-6.9	-6.7	-6.6	-6.9	-7.3	-7.7	-8.2	-8.6

Table 5-6: Annual Shoreline Change Rates for 2060 Beach Nourishment Project at Beach-fx Model Reaches

Beach -fx Reach	Shoreline Change Rates (ft/yr)											
	2060	2061	2062	2063	2064	2065	2066	2067	2068	2069	2070	2071
R#2	4.0	-1.4	-4.8	-6.3	-6.8	-6.2	-3.7	-0.5	1.4	2.2	2.1	1.6
R#3	1.2	1.5	0.9	0.0	-0.9	-1.6	-2.0	-2.0	-1.4	-0.7	-0.3	0.0
R#4	0.8	0.5	0.6	0.5	0.2	-0.2	-0.5	-0.7	-0.9	-1.0	-0.7	-0.5
R#5	-0.9	0.0	0.2	0.2	0.2	0.1	0.0	-0.2	-0.5	-0.6	-0.6	-0.5
R#6	0.3	-0.3	-0.2	0.0	0.2	0.3	0.2	0.1	-0.1	-0.3	-0.4	-0.4
R#7	-0.4	-0.8	-0.3	0.2	0.4	0.4	0.4	0.3	0.1	-0.1	-0.2	-0.4
R#8	-2.1	0.9	1.4	1.2	0.8	0.5	0.2	-0.1	-0.2	-0.4	-0.5	-0.7
R#9	10.6	5.2	2.3	0.7	-0.1	-0.7	-0.9	-1.0	-1.2	-1.2	-1.3	-1.4
R#10	6.2	1.7	-0.9	-1.8	-2.1	-2.2	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
R#11	-0.8	-6.5	-5.5	-4.6	-3.9	-3.3	-2.9	-2.7	-2.5	-2.3	-2.3	-2.2
R#12	-32.2	-12.5	-8.0	-5.7	-4.5	-3.8	-3.5	-3.2	-2.9	-2.8	-2.7	-2.7
R#13	-13.3	-10.8	-7.1	-5.1	-4.1	-3.5	-3.2	-3.1	-3.0	-2.9	-2.9	-3.0
R#14	1.2	-2.0	-2.4	-2.4	-2.5	-2.6	-2.7	-2.8	-2.9	-3.0	-3.1	-3.2
R#15	8.8	5.5	2.1	-0.1	-1.6	-2.5	-3.1	-3.5	-3.8	-4.0	-4.1	-4.2
R#16	8.5	3.0	0.1	-1.9	-3.1	-3.9	-4.5	-4.8	-5.0	-5.2	-5.2	-5.3
R#17	-2.1	-4.5	-5.1	-5.5	-5.8	-5.9	-6.1	-6.1	-6.2	-6.2	-6.2	-6.5
R#18	-20.0	-13.7	-11.7	-10.3	-9.6	-9.0	-8.6	-8.4	-8.2	-8.1	-8.0	-7.7
R#19	-20.6	-18.8	-16.0	-13.9	-12.6	-11.8	-11.3	-10.8	-10.5	-10.2	-10.0	-9.8
R#20	-21.6	-17.8	-16.4	-15.4	-14.6	-14.0	-13.4	-13.0	-12.6	-12.2	-11.8	-11.5
R#21	-3.2	-12.2	-13.6	-14.0	-14.1	-14.0	-13.8	-13.6	-13.3	-13.0	-12.6	-12.3
R#22	-12.9	-11.6	-12.3	-12.8	-13.1	-13.2	-13.2	-13.0	-12.7	-12.4	-12.1	-12.0
R#23	-13.5	-12.0	-11.7	-11.9	-12.0	-12.0	-11.9	-11.7	-11.5	-11.4	-11.2	-11.0
R#24	-9.4	-10.4	-11.6	-11.8	-11.7	-11.4	-11.2	-11.0	-10.9	-10.7	-10.6	-10.6
R#25	-5.6	-11.7	-12.5	-12.0	-11.5	-10.8	-10.4	-10.3	-10.2	-10.2	-10.4	-10.7
R#26	-21.0	-12.7	-9.1	-7.5	-6.9	-6.7	-6.8	-7.1	-7.5	-8.0	-8.5	-9.0

Table 5-7: Total 12 Years Average Shoreline Change Rates for the Future with Project Scenarios at Beach-fx Model Reaches

Beach-fx Reach	Average Shoreline Change Rates (ft/yr)			
	Jan2024 Fill	Jan2036 Fill	Jan2048 Fill	Jan2060 Fill
R#2	-1.1	0.1	0.2	-1.5
R#3	1.3	0.6	0.3	-0.4
R#4	4.1	0.7	0.3	-0.2
R#5	5.2	0.5	0.1	-0.2
R#6	5.8	0.4	0.2	-0.1
R#7	0.1	0.0	0.0	0.0
R#8	-6.3	-0.4	0.0	0.1
R#9	-0.5	0.2	0.9	0.9
R#10	-0.2	-1.2	-0.9	-0.9
R#11	-3.3	-3.0	-3.2	-3.3
R#12	-6.4	-6.9	-7.1	-7.0
R#13	-4.7	-5.3	-5.4	-5.2
R#14	-2.4	-2.7	-2.8	-2.4
R#15	-1.1	-1.2	-1.3	-0.9
R#16	-2.8	-2.8	-2.8	-2.3
R#17	-6.0	-5.9	-6.0	-5.5
R#18	-10.3	-10.4	-10.4	-10.3
R#19	-12.8	-12.9	-12.9	-13.0
R#20	-14.2	-14.3	-14.3	-14.5
R#21	-12.2	-12.2	-12.2	-12.5
R#22	-12.4	-12.4	-12.4	-12.6
R#23	-11.7	-11.7	-11.7	-11.8
R#24	-10.7	-10.8	-10.8	-10.9
R#25	-10.1	-10.2	-10.2	-10.5
R#26	-9.2	-9.2	-9.2	-9.2

Table 5-8: Last 8 Years Average Shoreline Change Rates for Future with Project Scenarios at Beach-fx Model Reaches

Beach-fx Reach	Average Shoreline Change Rates (ft/yr)			
	Jan2024 Fill	**Jan2036 Fill**	**Jan2048 Fill**	**Jan2060 Fill**
R#2	1.2	1.0	1.1	-1.2
R#3	1.4	0.1	-0.1	-1.1
R#4	2.4	0.3	0.0	-0.5
R#5	2.4	0.3	0.1	-0.3
R#6	1.7	0.3	0.2	0.0
R#7	0.1	0.2	0.2	0.1
R#8	-1.9	-0.3	0.0	-0.1
R#9	-2.8	-1.3	-1.0	-1.0
R#10	-3.1	-2.2	-2.1	-2.0
R#11	-3.3	-3.0	-2.8	-2.8
R#12	-3.3	-3.4	-3.4	-3.3
R#13	-3.2	-3.4	-3.5	-3.2
R#14	-2.8	-3.1	-3.2	-2.8
R#15	-3.4	-3.6	-3.7	-3.3
R#16	-5.0	-5.0	-5.1	-4.6
R#17	-6.4	-6.5	-6.5	-6.1
R#18	-8.7	-8.7	-8.7	-8.5
R#19	-10.9	-10.9	-11.0	-10.9
R#20	-12.7	-12.7	-12.7	-12.9
R#21	-13.0	-13.1	-13.1	-13.3
R#22	-12.4	-12.5	-12.5	-12.7
R#23	-11.4	-11.5	-11.5	-11.6
R#24	-10.7	-10.8	-10.8	-11.0
R#25	-10.1	-10.2	-10.2	-10.6
R#26	-7.3	-7.3	-7.3	-7.6

Table 5-9: Annual Shoreline Change Rates for 2024 Beach Nourishment Project at SBEACH Model Reaches

SBEACH Reach	Shoreline Change Rates (ft/yr)											
	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
FB#1	-32.8	-28.1	-21.3	-12.2	-3.0	2.4	4.7	5.0	4.6	4.0	3.3	2.8
FB#2	-3.1	-6.0	-7.3	-6.6	-4.1	-1.3	0.8	2.1	2.8	3.1	3.1	3.0
FB#3	8.0	5.4	4.1	3.1	2.4	1.8	1.5	1.3	1.2	1.1	1.1	1.1
FB#4	-33.6	-14.1	-7.5	-4.7	-3.3	-2.5	-2.0	-1.7	-1.6	-1.4	-1.4	-1.3
FB#5	0.3	-2.5	-3.1	-3.3	-3.3	-3.3	-3.2	-3.1	-3.1	-3.0	-3.0	-3.0
FB#6	3.3	0.3	-1.4	-2.5	-3.2	-3.7	-4.0	-4.3	-4.5	-4.6	-4.7	-4.8
FB#7	-20.1	-16.6	-14.8	-13.7	-12.8	-12.2	-11.7	-11.3	-11.0	-10.8	-10.5	-10.2
FB#8	-10.4	-11.4	-12.0	-12.2	-12.3	-12.2	-12.1	-11.9	-11.7	-11.5	-11.3	-11.1
FB#9	-17.6	-12.5	-9.9	-8.5	-7.8	-7.5	-7.4	-7.5	-7.7	-8.1	-8.4	-8.8

Table 5-10: Annual Shoreline Change Rates for 2036 Beach Nourishment Project at SBEACH Model Reaches

SBEACH Reach	Shoreline Change Rates (ft/yr)											
	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047
FB#1	-34.8	-30.0	-23.4	-15.9	-5.9	1.7	5.1	5.8	5.5	4.7	3.9	3.1
FB#2	4.1	-0.8	-4.0	-5.1	-4.2	-1.8	0.4	1.8	2.6	2.9	2.9	2.7
FB#3	1.0	1.0	0.8	0.6	0.4	0.2	0.1	0.1	0.1	0.2	0.3	0.3
FB#4	-2.8	0.0	0.6	0.5	0.3	0.0	-0.2	-0.3	-0.5	-0.6	-0.7	-0.7
FB#5	-4.3	-3.8	-3.4	-3.1	-2.9	-2.7	-2.6	-2.5	-2.5	-2.4	-2.4	-2.4
FB#6	3.4	0.2	-1.5	-2.6	-3.3	-3.8	-4.2	-4.4	-4.6	-4.7	-4.8	-4.9
FB#7	-20.3	-16.7	-14.9	-13.7	-12.9	-12.2	-11.8	-11.4	-11.1	-10.8	-10.6	-10.3
FB#8	-10.5	-11.5	-12.0	-12.3	-12.3	-12.3	-12.2	-12.0	-11.8	-11.6	-11.4	-11.2
FB#9	-17.5	-12.5	-9.8	-8.5	-7.8	-7.5	-7.4	-7.6	-7.8	-8.2	-8.5	-8.9

Table 5-11: Annual Shoreline Change Rates for 2048 Beach Nourishment Project at SBEACH Model Reaches

SBEACH Reach	Shoreline Change Rates (ft/yr)											
	2048	2049	2050	2051	2052	2053	2054	2055	2056	2057	2058	2059
FB#1	-34.0	-29.1	-22.4	-14.5	-4.4	2.7	5.5	6.0	5.5	4.6	3.8	2.9
FB#2	3.7	-1.0	-4.0	-4.9	-3.8	-1.4	0.7	2.0	2.6	2.9	2.8	2.6
FB#3	0.4	0.4	0.4	0.3	0.1	-0.1	-0.1	-0.1	0.0	0.1	0.2	0.3
FB#4	-2.2	0.8	1.3	1.1	0.8	0.4	0.1	-0.1	-0.2	-0.4	-0.5	-0.6
FB#5	-4.1	-3.7	-3.3	-3.0	-2.8	-2.6	-2.5	-2.4	-2.4	-2.3	-2.3	-2.4
FB#6	3.4	0.2	-1.6	-2.7	-3.4	-3.9	-4.3	-4.5	-4.7	-4.8	-4.8	-4.9
FB#7	-20.3	-16.7	-14.9	-13.7	-12.9	-12.3	-11.8	-11.4	-11.1	-10.8	-10.6	-10.3
FB#8	-10.5	-11.5	-12.0	-12.3	-12.3	-12.3	-12.2	-12.0	-11.8	-11.6	-11.4	-11.2
FB#9	-17.5	-12.5	-9.8	-8.5	-7.8	-7.5	-7.4	-7.6	-7.8	-8.2	-8.5	-8.9

Table 5-12: Annual Shoreline Change Rates for 2060 Beach Nourishment Project at SBEACH Model Reaches

SBEACH Reach	Shoreline Change Rates (ft/yr)											
	2060	2061	2062	2063	2064	2065	2066	2067	2068	2069	2070	2071
FB#1	-34.3	-29.7	-23.7	-18.5	-13.8	-6.5	3.6	7.7	7.6	5.7	3.2	1.3
FB#2	3.9	-1.1	-4.5	-6.1	-6.6	-6.1	-3.7	-0.7	1.3	2.1	2.0	1.6
FB#3	0.2	0.3	0.3	0.2	-0.1	-0.3	-0.5	-0.6	-0.6	-0.5	-0.4	-0.3
FB#4	-1.9	1.0	1.5	1.2	0.8	0.4	0.2	-0.1	-0.2	-0.4	-0.6	-0.7
FB#5	-4.3	-3.8	-3.3	-3.0	-2.7	-2.5	-2.4	-2.3	-2.2	-2.2	-2.2	-2.2
FB#6	4.3	0.8	-1.1	-2.3	-3.0	-3.5	-3.9	-4.1	-4.3	-4.4	-4.5	-4.6
FB#7	-21.0	-17.1	-15.2	-13.9	-13.0	-12.3	-11.8	-11.4	-11.1	-10.8	-10.5	-10.2
FB#8	-10.5	-11.6	-12.2	-12.5	-12.6	-12.5	-12.4	-12.2	-12.0	-11.7	-11.5	-11.3
FB#9	-17.2	-12.3	-9.8	-8.5	-7.9	-7.6	-7.6	-7.8	-8.1	-8.5	-8.9	-9.3

Table 5-13: Total 12 Years Average Shoreline Change Rates of Future with Project Scenarios at SBEACH Reaches

SBEACH Reach	Average Shoreline Change Rates (ft/yr)			
	Jan2024 Fill	Jan2036 Fill	Jan2048 Fill	Jan2060 Fill
FB#1	-5.9	-6.7	-6.1	-8.1
FB#2	-1.1	0.1	0.2	-1.5
FB#3	2.7	0.4	0.2	-0.2
FB#4	-6.3	-0.4	0.0	0.1
FB#5	-2.8	-2.9	-2.8	-2.8
FB#6	-2.8	-2.9	-3.0	-2.6
FB#7	-13.0	-13.1	-13.1	-13.2
FB#8	-11.7	-11.7	-11.7	-11.9
FB#9	-9.3	-9.3	-9.3	-9.5

Table 5-14: Last 8 Years Average Shoreline Change Rates of Future with Project Scenarios at SBEACH Reaches

SBEACH Reach	Average Shoreline Change Rates (ft/yr)			
	Jan2024 Fill	Jan2036 Fill	Jan2048 Fill	Jan2060 Fill
FB#1	3.0	3.0	3.3	1.1
FB#2	1.2	0.9	1.1	-1.3
FB#3	1.4	0.2	0.1	-0.4
FB#4	-1.9	-0.3	-0.1	-0.1
FB#5	-3.1	-2.6	-2.4	-2.3
FB#6	-4.2	-4.4	-4.4	-4.0
FB#7	-11.3	-11.4	-11.4	-11.4
FB#8	-11.8	-11.8	-11.8	-12.0
FB#9	-7.9	-8.0	-8.0	-8.2

It was noted that:

a) the shoreline change rate at Beach-fx model reach 8 is higher for the January 2024 project, and

b) the shoreline change rates at Beach-fx model reach 12 are higher for all four future beach nourishment projects.

These are discussed as below:

a) Higher shoreline change rate at Beach-fx model reach 8

The shoreline model for 2024 beach nourishment project was developed based on the December 2018 shoreline and the proposed January 2024 beach nourishment project. There is a significant shoreline orientation difference at Beach-fx model reach 8 compared to the adjacent shoreline orientations (see Figure 5-3). This shoreline orientation at Beach-fx model reach 8 will increase the longshore sediment transport rates along Beach-fx model reach 8. Therefore, the annual shoreline change rates for the January 2024 beach nourishment will be higher at the Beach-fx model reach 8 until the shoreline transitions to a more stable equilibrium orientation.

Figure 5-3: Location of Beach-fx Model Reach 8, and Shoreline on January 10, 2019

b) Higher shoreline change rates at Beach-fx model reach 12

The Beach-fx model reach 12 includes transect 2838 while transect 2040 is located in Beach-fx model reach 13. Figure 5-4 and Figure 5-5 illustrate the USACE's initial beach fill design at transects 2838 and 2840. After USACE reviewed the initial beach fill design, USACE recommended to modify the beach fill design to provide more beach fill volumes at transects 2838 and 2840 (see Figure 5-6 and Figure 5-7). The modified beach fill design changed the shoreline orientation at Beach-fx model reach 12, and thus increased shoreline change rates along Beach-fx model reach 12 as the shoreline transitions to a more stable equilibrium orientation.

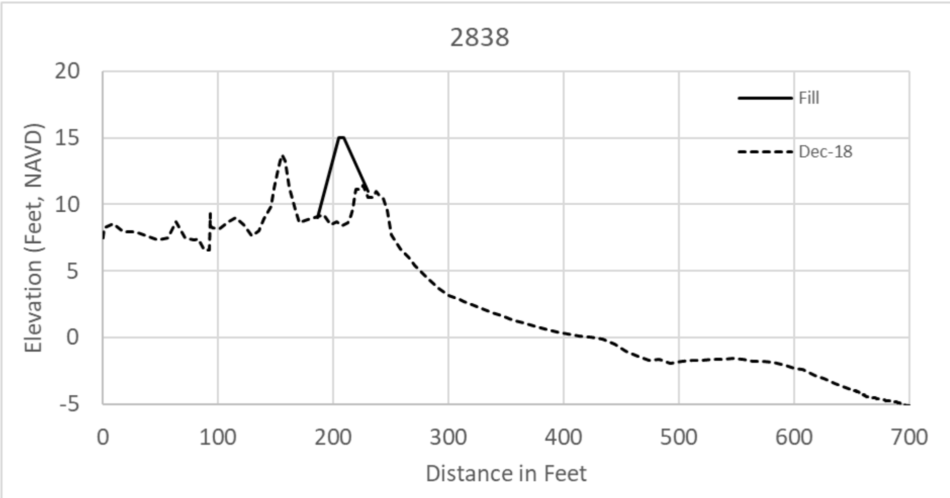

Figure 5-4: Initial Beach Fill Design at Transect 2838

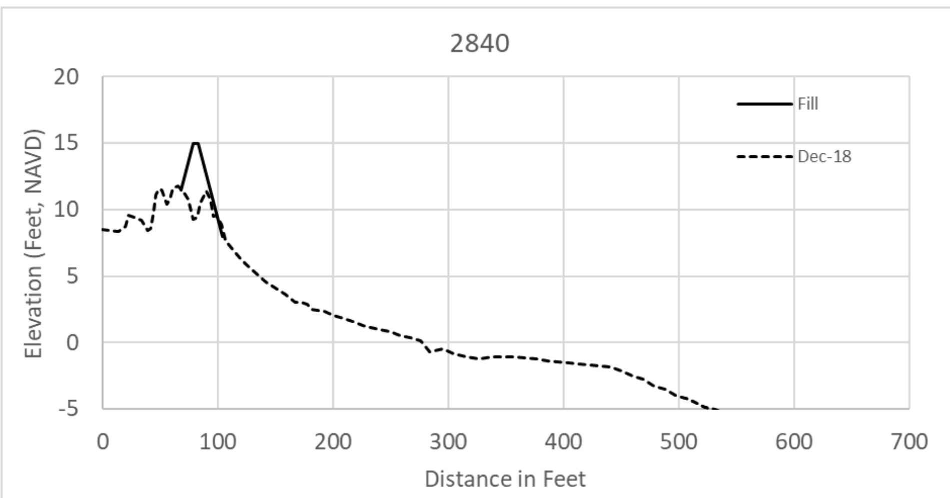

Figure 5-5: Initial Beach Fill Design at Transect 2840

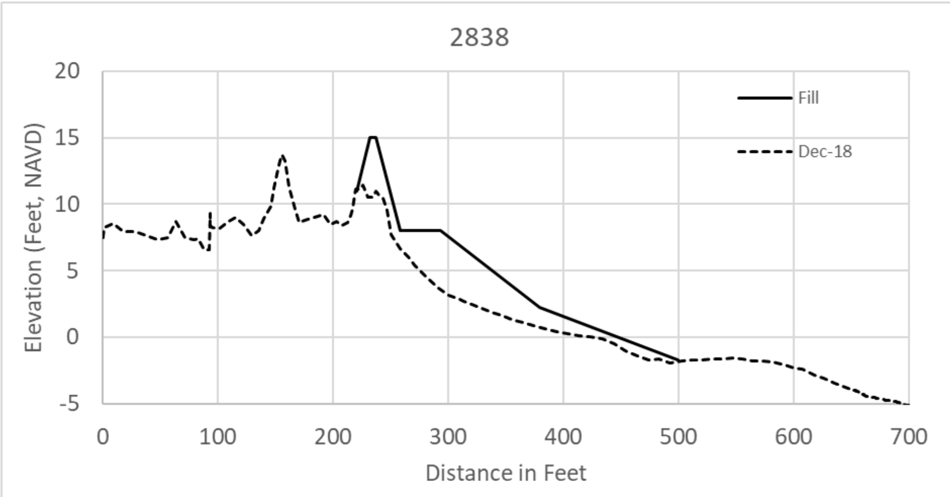

Figure 5-6: Modified Beach Fill Design at Transect 2838

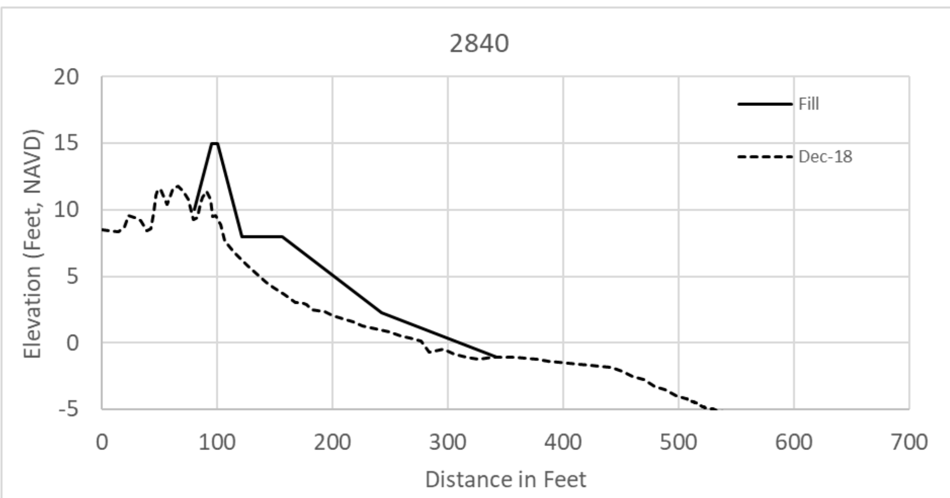

Figure 5-7: Modified Beach Fill Design at Transect 2840

6. Conclusion

A spectral wave model was developed to transform a time series of waves from offshore to nearshore at the Folly Beach project site. The spectral wave model was calibrated and validated using Oceanweather hindcast wave data at station 10452, USACE WIS wave data at station 63348, and NOAA buoy 41004 wave data. A 12-year time series of offshore wave data from

2008 to 2019 was transformed to nearshore at the project site using the calibrated spectral wave model.

A GenCade shoreline model was developed to simulate Folly Beach shoreline change rates. The spectral wave model simulated time series nearshore wave conditions were utilized as input forces for the GenCade shoreline model. The shoreline model was calibrated and validated using the historical measured shoreline locations for three different periods. The calibrated shoreline model was applied to simulate long-term Folly Beach shoreline change rates for the USACE proposed four future beach nourishment projects in January 2024, January 2036, January 2048, and January 2060. The shoreline model simulated shoreline change rates presented in Table 5-3 through Table 5-14 at each reach were recommended for the USACE Beach-fx economic model and SBEACH storm profile model.

7. References

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Sub-Appendix C:

Folly Beach

Offshore Borrow Area Analysis

February 2020

Effects of four potential borrow areas on wave propagation at Folly Beach, South Carolina

by S.C. Dillon

INTRODUCTION: The USACE Wilmington District (SAW) requested assistance in conducting a wave assessment for four proposed borrow areas near Folly Beach, South Carolina. Folly Beach (32°39’18.65”N 79°56’25.32”W) is located southwest of Charleston harbor near Charleston, South Carolina. The excavation of these sites will cause changes in the nearshore bathymetry, which will affect the wave transformation in the area. An assessment of the effects these borrow areas have on the nearshore wave propagation will help SAW evaluate each potential borrow area site. To complete this assessment, the STeady-state WAVE (STWAVE) model (Smith et al. 2001, Massey et al. 2011), which is a phase-averaged spectral model for wave generation, propagation and transformation, was used to simulate wave transformation in the Folly Beach area.

STWAVE: STWAVE is a steady-state spectral wave model for nearshore wave generation, propagation, transformation, and dissipation. STWAVE numerically solves the steady-state conservation of spectral wave action along backward-traced wave rays:

$$(C_g)_i \frac{\partial}{\partial x_i} \frac{C C_g \cos \alpha E(\sigma, \theta)}{\sigma} = \sum \frac{S}{\sigma} \qquad (1)$$

Where *i* is tensor notation for *x*- and *y*- components, C_g is group celerity, θ is wave direction, *C* is wave celerity, σ is wave angular frequency, *E* is wave energy density, and *S* is energy source and sink terms. Source and sink mechanisms include surf-zone wave breaking, wind input, wave-wave interaction, whitecapping, and bottom friction. STWAVE is formulated on a Cartesian grid, with the x-axis oriented in the cross shore direction (I) and the y-axis oriented alongshore (J), generally parallel with the shoreline. Angles are measured counterclockwise from the grid x-axis.

GRID DEVELOPMENT: In order to capture the effects of each borrow area, four STWAVE grids were developed, which extended alongshore from Sullivan’s Island to Kiawah Island and seaward to a depth of 90 ft. (25 m). The Cartesian grid resolution of all four grids was approximately 164 ft. (50 m) and is comprised of 643 cells in the cross-shore direction (I) and 817 cells in the alongshore direction (J). The projection of the grid is in State Plane South Carolina (FIPS 3900), with a vertical datum relative to NAD83 (meters). The properties of all four STWAVE domains are provided in Table 1.

Table 1. STWAVE Grid Properties

Horizontal Projection	Vertical Projection	Grid Origin (x,y) [m]	Azimuth [deg]	Δx/Δy [ft]	Number of Cells	
					I	J
State Plane South Carolina FIPS 3900	NAD83	(742990.0, 83070.0)	125.2	164	643	817

The outlines of the potential borrow area sites are shown in Figure 1. The four borrow areas include Stono Inlet, which is the most westward borrow area sites and is located near Stono Inlet. This area is proposed to be excavated to a depth of -41ft. The Central site is located adjacent to the Stono Inlet sites and offshore of Folly Beach. The Central borrow area site is proposed to be excavated to a depth of -35ft in the upper right quadrant and to a depth of -40ft in the lower left quadrant of the area. The Lighthouse borrow area is located between the Central site and Lighthouse Inlet, and is proposed to be excavated to a depth of -22ft. Finally, the last borrow area, Seaward, is located seaward of South Carolina's offshore territory and offshore from the Lighthouse Inlet site and is proposed to be excavated to a depth of -45 ft. The topography and bathymetry data to populate the STWAVE domain were obtained from the South Carolina Storm Surge Study - FEMA grid. The bathymetry was modified for each proposed borrow area site by deepening each site to the proposed dredge depth as described above and shown in Figure 1. Depictions of the modified depths as represented in the STWAVE domains are included in Appendix A.

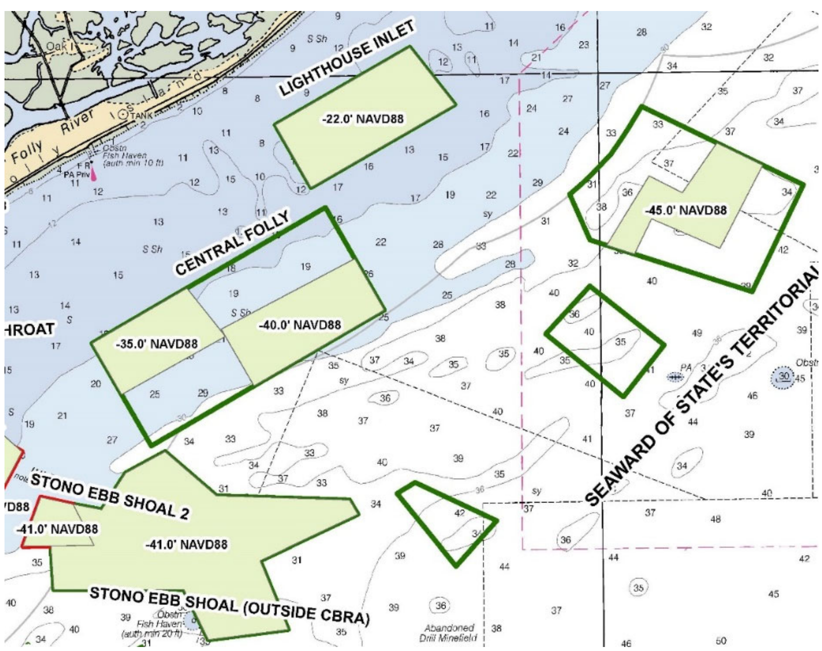

Figure 1: Dredge depths (shown in light green) of the four potential borrow areas offshore of Folly Beach, SC.

OFFSHORE BOUNDARY SPECTRA: To determine the boundary forcing conditions for STWAVE a wave assessment was conducted for the Folly Beach area, to capture the mean monthly, maximum monthly and extreme events using the wave data from the Wave Information Study (WIS) hindcast. The hindcast data provides a record of 37 years, from 1980 to 2017. Stations 63350 and 63348 were chosen as the primary stations of interest due to their close proximity to Folly Beach.

A comparison of the mean monthly wave heights and the max monthly wave heights for all four seasons for both stations is included in Appendix B. These histograms show that the mean monthly wave height, across all seasons, is less than 6.5 ft. (2 m) with the most frequent mean monthly wave height at approximately 3.6 ft. (1.1m). The histograms also show that the most frequent max monthly wave height is approximately 8.5 ft. (2.6 m).

A comparison of the mean monthly wave periods and the max monthly wave periods, show that the average max monthly wave period is approximately 9 seconds and the average mean monthly wave period is approximately 8.4 seconds.

The extreme plots for both stations are shown in Appendix C. For station 63348, the extreme wave heights range from 17.7 to 20.17 ft. (5.38 to 6.15 m) for the top 10 events with peak wave periods ranging from 12-18 seconds. For station 63350, the top 10 extreme events contained wave heights ranging from 17.2 to 18.7 ft. (5.25 to 5.70 m) with peak periods of 14 to 18 seconds.

Onshore propagation for the area is between 60 and 225 degrees.

In order to encompass the climate of the area nine conditions were identified for inclusion as boundary forcing for STWAVE. The chosen conditions, shown in Table 2, included a mean monthly condition composed of a wave height of 3.6 ft. (1.1 m) with an 8.4-sec. period, and a max monthly condition with an 8.5 ft. (2.6 m) wave height and 9-sec. period. Also chosen was the highest extreme event, which occurred for WIS station 63348, and had a 20.3 ft. (6.2 m) wave height and an 18-sec. period. Both the mean and maximum monthly condition spectra were simulated with a mean direction ranging from 60 to 225 degrees, for a total of four directions, and the extreme event was simulated at 97 degrees (as occurred in the extreme event).

The resolved spectra for each condition was represented by 35 frequency bands, ranging from 0.37 Hz (2.7 sec) to 0.03 Hz (33.3 sec), and 72 angle bands, from an angle of 0 degrees to 355 degrees with respect to the x-axis. Frequency and angular resolution were 0.01 Hz and 5 degrees, respectively.

Table 2: *STWAVE Conditions for Simulation*

	Wave Height (ft)	Period (sec)	Direction (deg)	Number of STWAVE Simulations:
Mean Monthly	3.6	8.4	60°, 115°, 170°, 225°	4
Max Monthly	8.5	9	60°, 115°, 170°, 225°	4
Extreme Event	20.3	18	97°	1
Total number of STWAVE simulations per borrow area:				**9**

MODEL EXECUTION: Each STWAVE simulation conducted used the full-plane mode of STWAVE to allow for wave generation and transformation in a 360-degree plane. The full-plane version of STWAVE uses an iterative solution process that requires user-defined convergence criteria to signal a suitable solution. Boundary spectra information is propagated from the boundary throughout the domain and iteratively executes until it reaches a convergent state. The convergence criteria includes the maximum number of iterations to perform per time-step, the relative difference in significant wave height between iterations, and the minimum percent of cells that must satisfy the convergence criteria (i.e., have values less than the relative difference.) Convergence parameters were selected based on a previous study by Massey et al. (2011) in which the sensitivity of the solution to the final convergence criteria was examined. The relative difference and minimum percent of cells were set as (0.1, 100.0) and (0.1, 99.8) for the initial and final iterations, respectively. STWAVE was set up with parallel in-space execution whereby each computational grid was divided into different partitions (in both the x- and y-direction), with each partition executing on a different computer processor. The number of partitions in the x direction was 13, while the number of partitions in the y direction was 17. The maximum number of initial and final iterations was set to a value of 20 iterations, higher than the largest partition size.

Thirteen locations were identified within the STWAVE grid to save significant wave height, peak period, mean period and mean wave direction from each of the 9 wave conditions simulated. The x y coordinates of these locations are included in Table 3 and depicted in Figure 2.

Table 3: Location of Save Points inside STWAVE domain

	x [m]	y [m]		x [m]	y [m]
pt1	713942	94557.7	**pt7**	709691	91561.9
pt2	713410	94183.2	**pt8**	708922	91264.5
pt3	712732	93583	**pt9**	708088	90798.9
pt4	712259	93126.8	**pt10**	707172	90275.7
pt5	711686	92723.5	**pt11**	706571	89913.3
pt6	710742	92241.2	**pt12**	705917	88412
			pt13	703363	85266

Figure 2: Save point locations

RESULTS: Three types of figures were generated for each borrow area and boundary condition: a spectral wave height plot (Appendix D), a spectral wave height difference plot (Appendix E), and a plot depicting the significant wave height, mean period, peak period, and STWAVE wave angle, at each save point for each condition (Appendix F).

Mean Monthly Condition: The mean monthly wave condition, 3.6 ft. wave height and 8.4 sec. period, showed, as expected, the least effects caused by the borrow areas. Due to the low energy of this condition, the differences in depth caused by the excavation of the borrow areas will be minimal compared to the higher energy events. Overall, each borrow area site increased and decreased the wave heights on average ~0.5 ft. in the area of each site, with increases occurring on the perimeter and decreases in the center. The greatest impact was observed at the Central borrow area in the 60° wave direction, with decreases at the borrow area and toward shore of ~1.0 ft and slight increases of ~0.5-1.0 ft. in the perimeter, as shown in figure 3. The decrease most significantly affected the eastern shores of Folly Beach, while the increases affected Kiawah Island and the central shores of Folly Beach. The Seaward borrow area site had the least effects on the wave height. The results showed only slight increases and decreases of less than 0.5ft, which were widely distributed from the borrow area site.

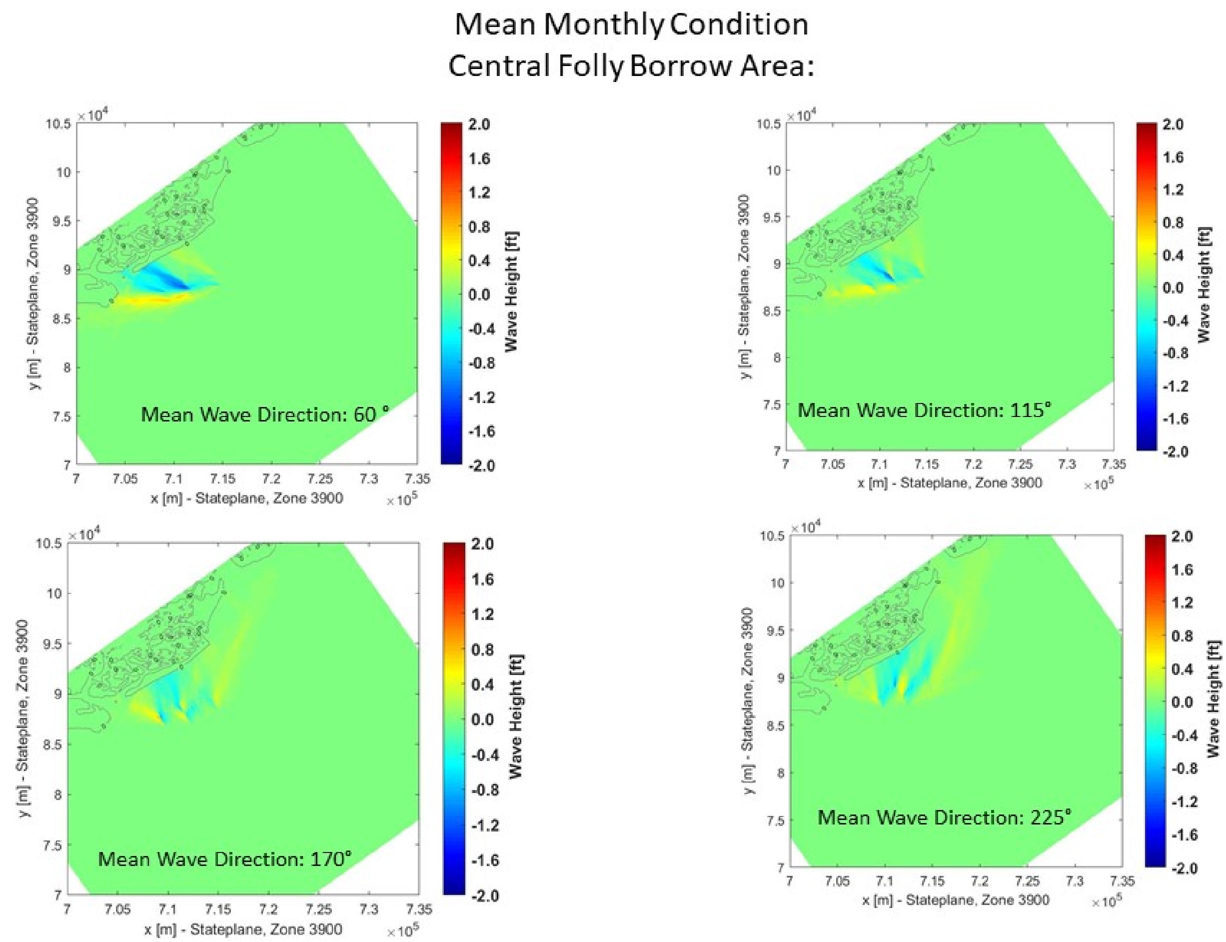

Figure 3: Mean monthly condition at the Central borrow area. Warm tones indicate increases in wave height when compared to the no borrow are simulations and cool tones represent decreases in wave height.

The save point locations provide similar results as shown in the above difference plot with most increases and decreases being ~0.5 ft. for all wave directions and borrow area sites. Under the 60° wave direction, the greatest decreases were observed by the Central borrow area site from points 9-12. Under the 115 ° wave direction, the Lighthouse borrow area showed decreases at save points 3-5 and Central showed decreases at points 7-10. Both Lighthouse and Central gave a slight increase at point 6. The 170° wave direction showed decreases from the Lighthouse borrow area at points 1-3 and the Central borrow area showed decreases at points 6-8, with increases at points 10. Finally, under the 225° wave direction, the Lighthouse borrow area showed increases at points 4 and 5 and decreases at points 1 and 2. While the Central borrow area, showed decreases at points 4-7 and an increase at point 9.

Max Monthly Condition: The max monthly condition, 8.5 ft. wave height and 9 sec. period, showed greater effects on the wave heights due to the presence of the borrow area sites when compared to the mean monthly condition. Overall, the locations of the increases and decreases were similar to what was observed under the mean monthly condition, but the magnitude and extent of the difference is greater. Under the max monthly condition, on average increases and decreases of ~2 ft. were observed due to the borrow area sites. The Central borrow area site showed the greatest effects on the wave heights, shown in Figure 4. The Central borrow area site showed decreases of ~4.0 ft. in the 60 ° wave direction, with increases of ~3.0 ft. in the perimeter, and increases and decreases of 1.0-2.0 ft. in the other wave directions. The Seaward borrow area showed the smallest effects on the wave heights with diffuse differences of less than 1.0 ft.

Max Monthly Condition
Central Folly Borrow Area:

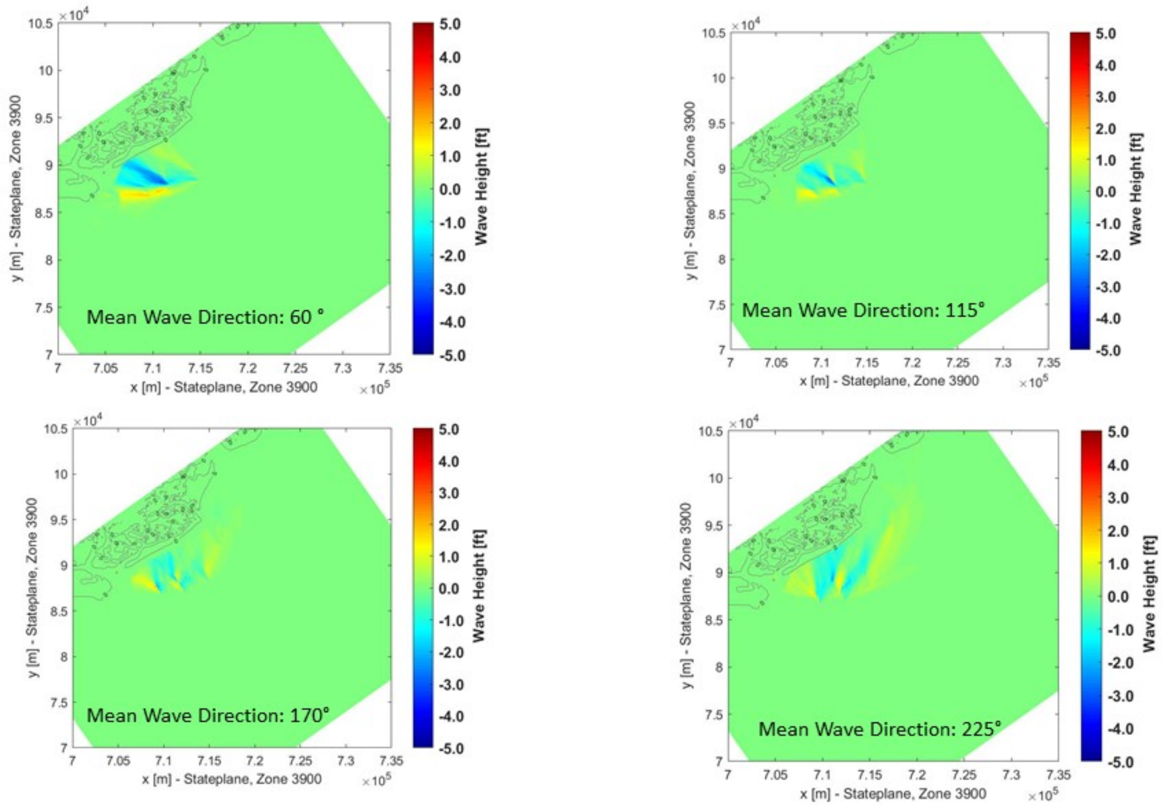

Figure 4: Max Monthly Condition at the Central borrow area site. Warm tones indicate increases in wave height when compared to the no borrow are simulations and cool tones represent decreases in wave height.

The save point locations show differences only under the most oblique wave angles (60° and 225°). Under the 60° wave direction, decreases at points 4 and 5 for the Lighthouse borrow area and decreases at points 9 and 10 for the Central borrow area occur. As well as, under the 225° wave direction, the Central borrow area shows decreases at points 4, 5, and 7 with increases at points 9 and 10.

Extreme Event Condition: The extreme event condition, 20.3 ft. wave height, 18 sec. period and 97° mean direction, showed the greatest effects due to the borrow area sites. However, for most of the borrow area sites, these effects were isolated at the borrow area and had very little effect on the coastline, as shown in Figure 5. Under the extreme condition, all of the borrow area sites show increases in the wave height of ~1.4 ft. or greater. However, the Central borrow area site shows the greatest increase of up to ~5.0 ft. and the Stono Inlet borrow area shows the widest distribution of wave height increases (~1.5 ft.). The deepening of these area compared to their surrounding allow the waves to propagate further inshore before breaking, which is most likely the cause for the observed increases under this condition.

Due to the isolation of the effects at the borrow area sites and their lack of propagation onshore, there were no differences observed in the save point location plots for wave height.

SUMMARY: The effects of the four borrow areas were investigated offshore of Folly Beach, SC using the STWAVE nearshore model. Nine identified conditions were selected to represent the mean monthly, max monthly and extreme event in the area, based on the 39-year record at the offshore WIS stations 63348 and 63350. The mean monthly condition showed the lowest impacts on wave heights due to the borrow areas with decreases of ~0.5 ft. in the borrow area and increases in ~0.5 ft. in the perimeters. The Seaward borrow area showed the least amount of effects under this condition and the Central borrow area showed the greatest effects. Under the max monthly condition, the borrow area sites showed increases and decreases in the wave heights of ~1.5 ft. with a decrease of up to ~4.0 ft. at the Central borrow area site. The Seaward borrow area site showed the least effects under this condition as well. The extreme event condition showed the greatest decreases and increases due to the borrow areas, but did not extend shoreward. The Central borrow area showed the greatest increases under the extreme event; while the Seaward borrow area continued to have the least effect on wave heights.

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Smith, J. M., A. R. Sherlock, and D. T. Resio. 2001. STWAVE: Steady-state spectral wave model, user's guide for STWAVE version 3.0, ERDC/CHL SR-01-01, US Army Engineer Research and Development Center, Vicksburg, MS, 80 pp.

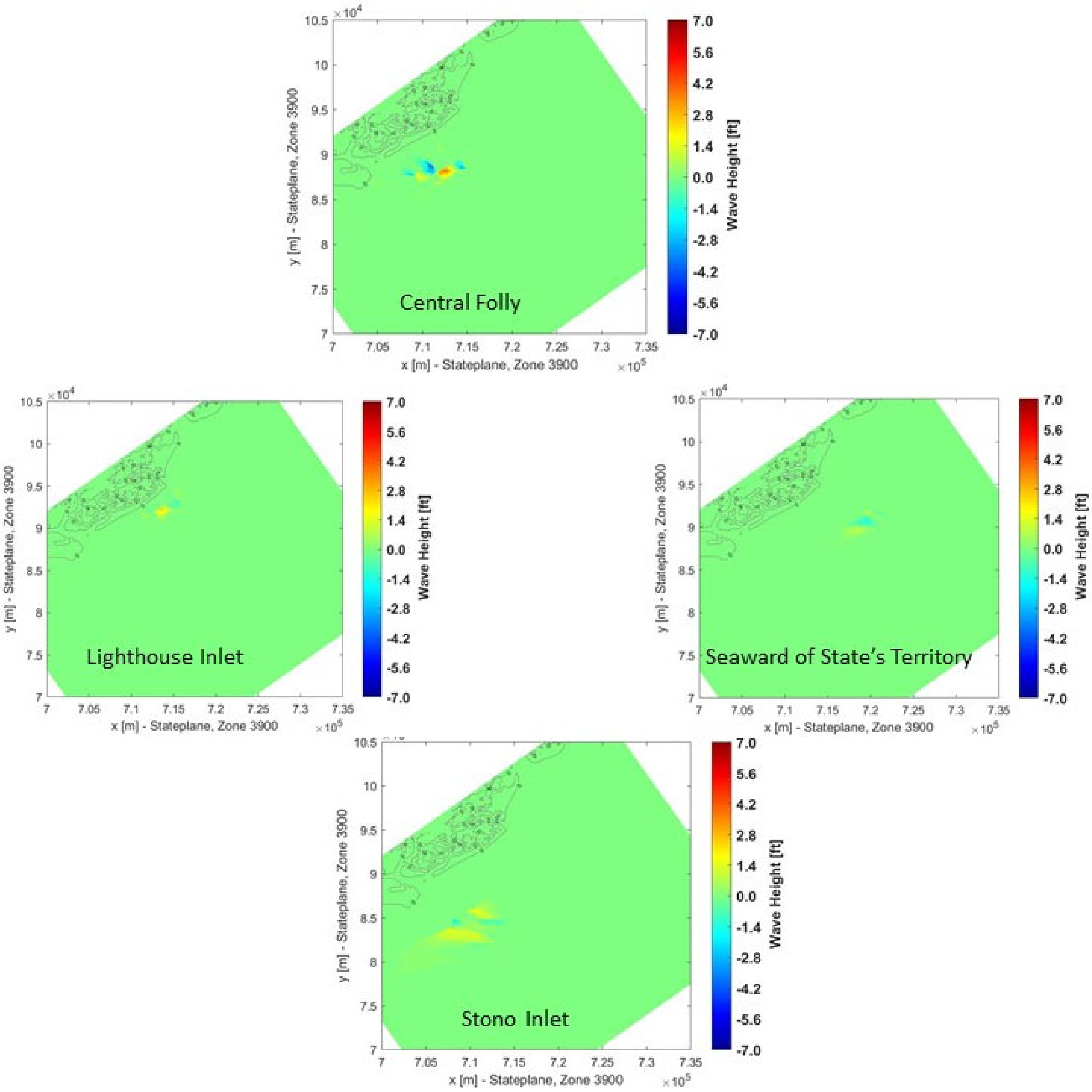
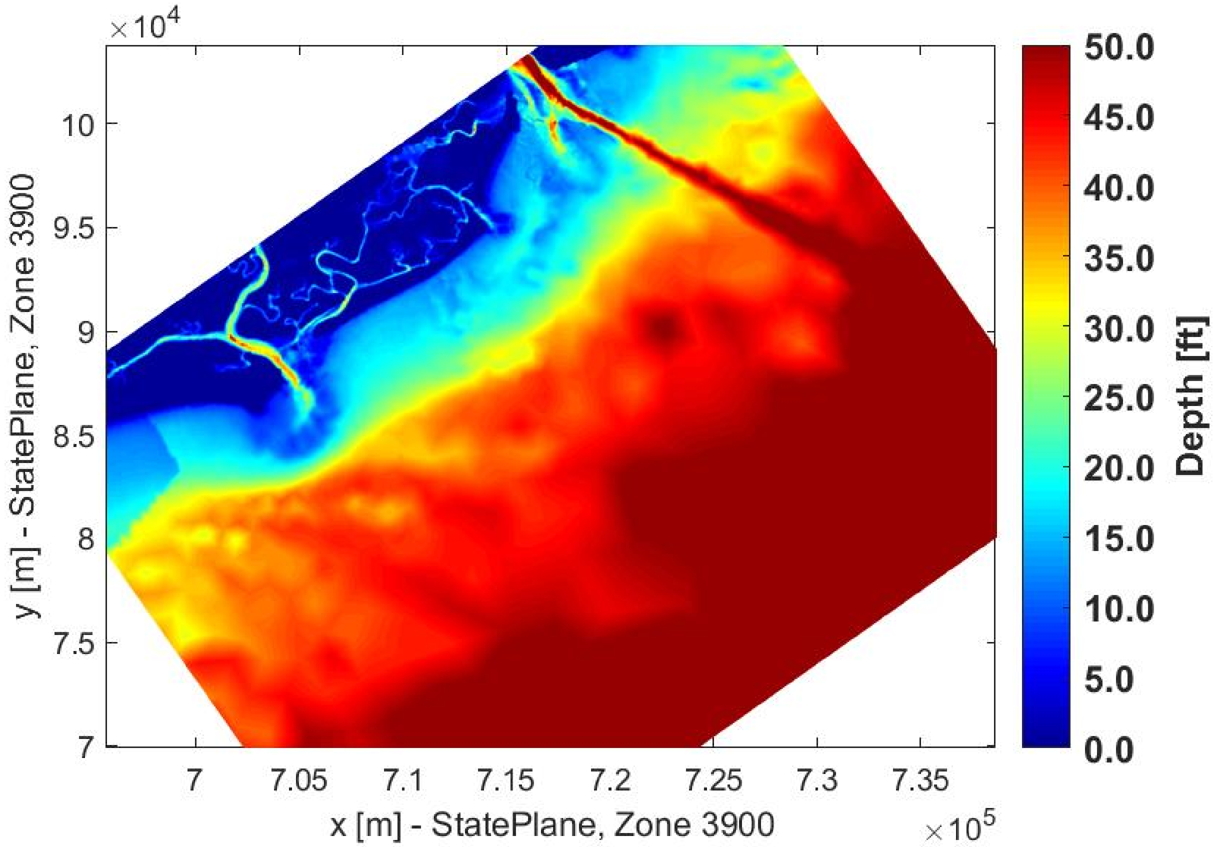
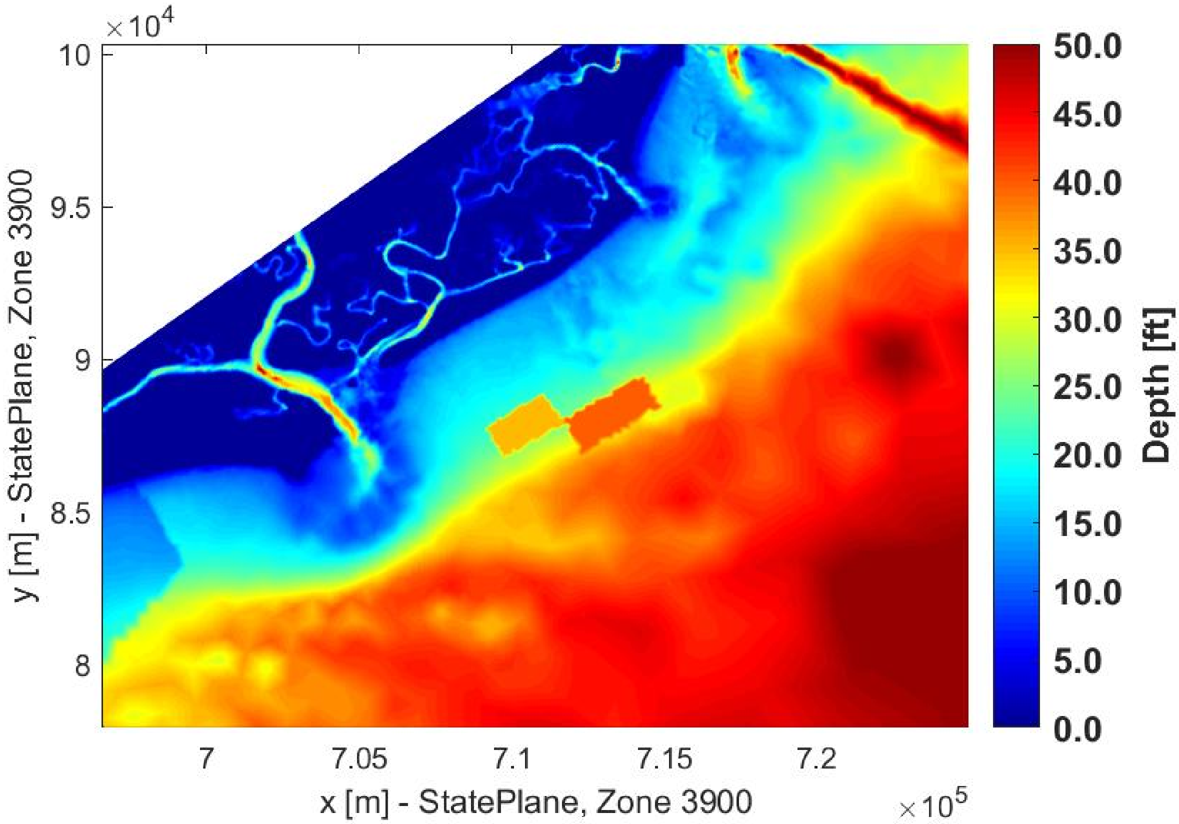


Figure 5: Extreme Event Condition at all four borrow areas. Warm tones indicate increases in wave height when compared to the no borrow are simulations and cool tones represent decreases in wave height.

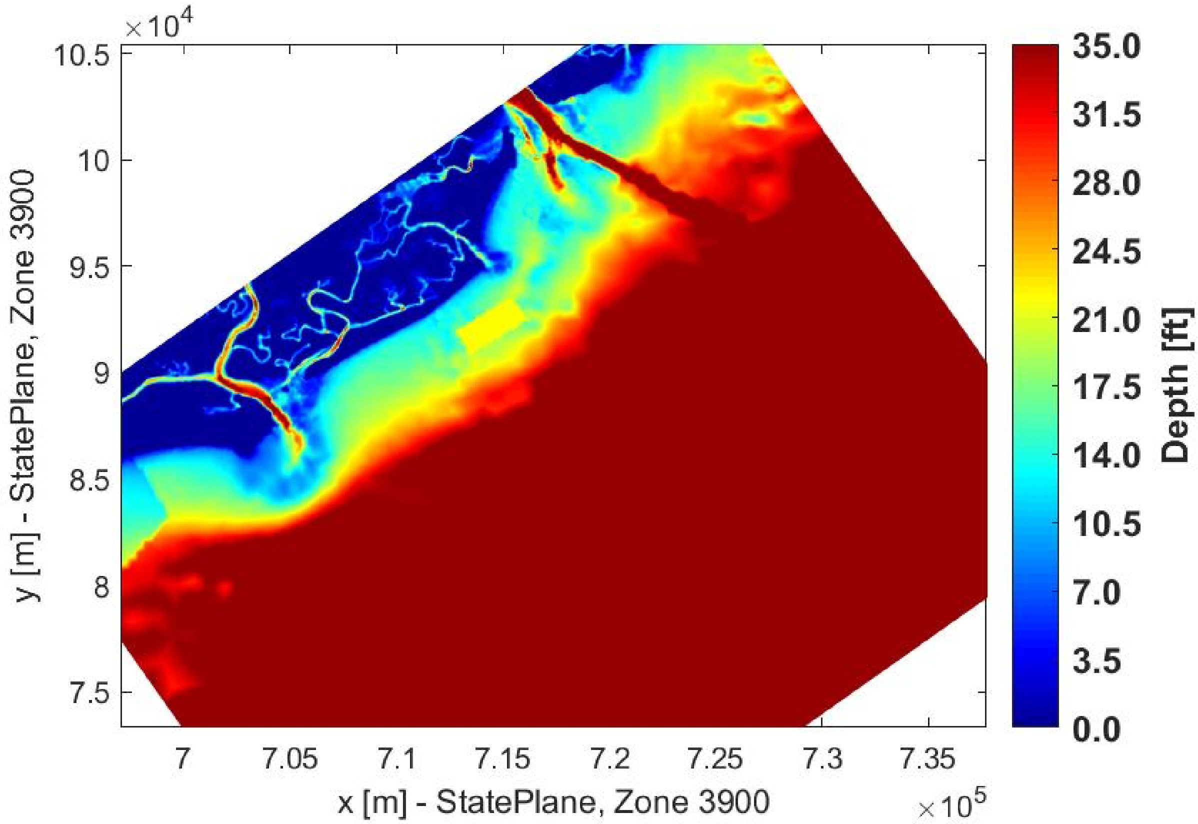
Appendix A— Depth Changes in Grid
Base Condition Bathymetry



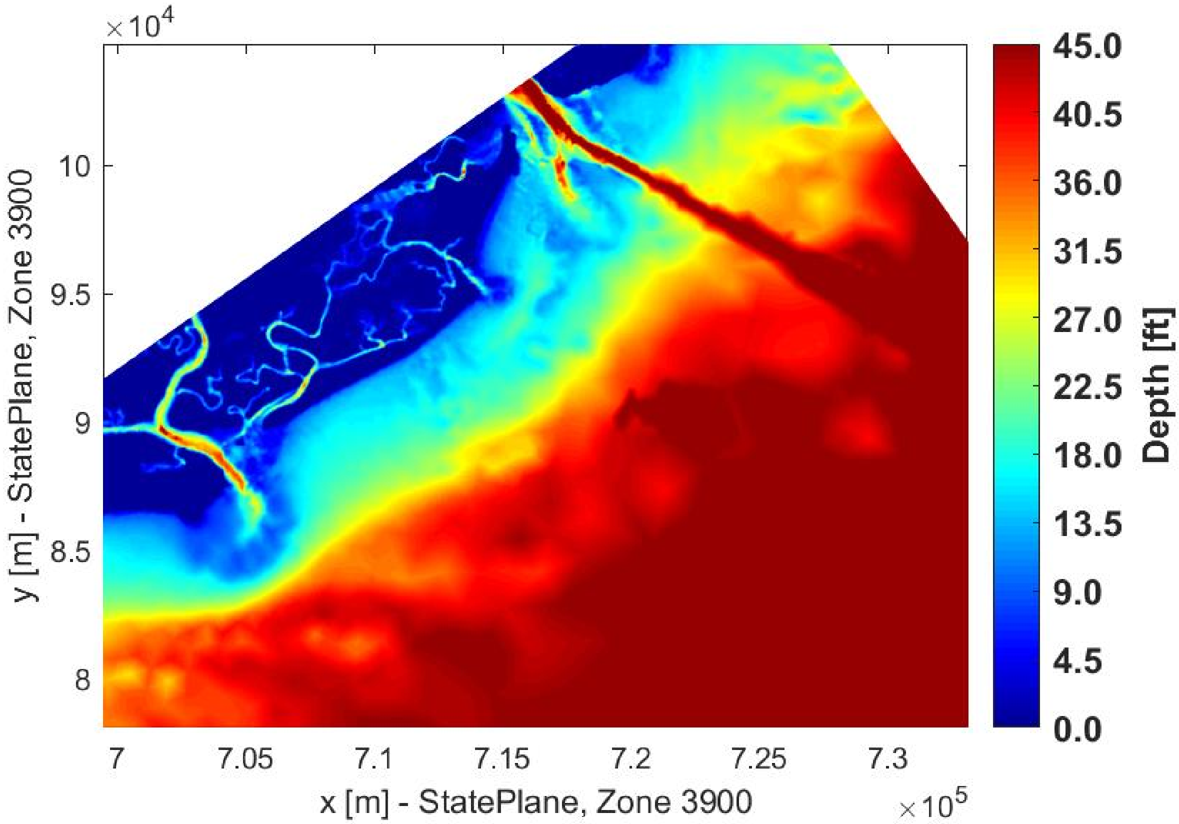
Central *Borrow Area modified Bathymetry*



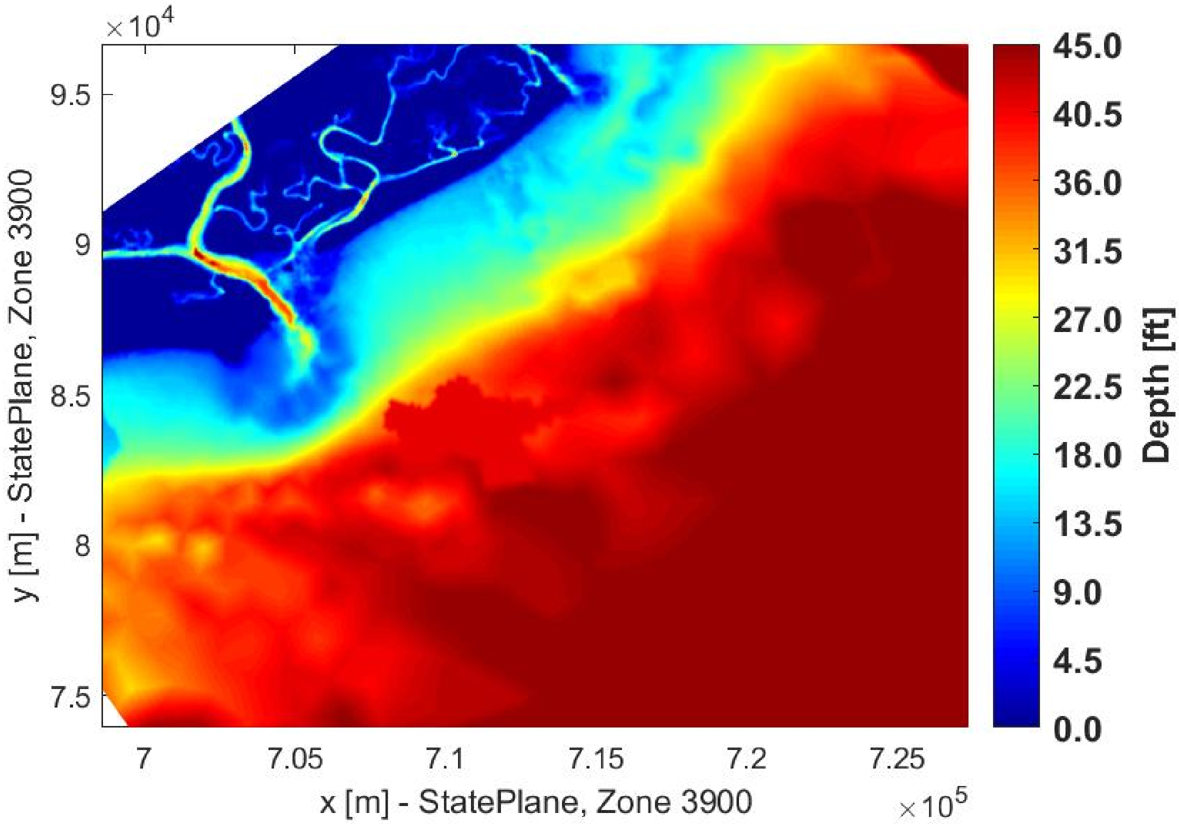
Lighthouse Borrow Area Modified Bathymetry



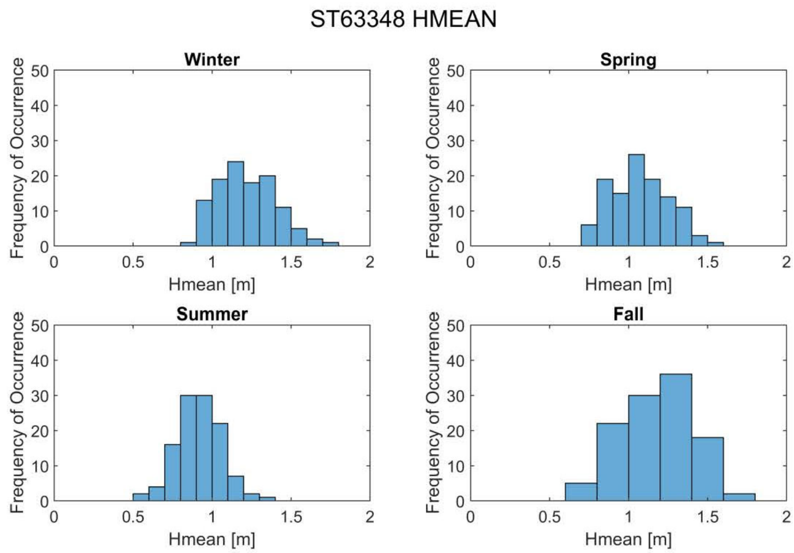
Seaward Borrow Area Modified Bathymetry

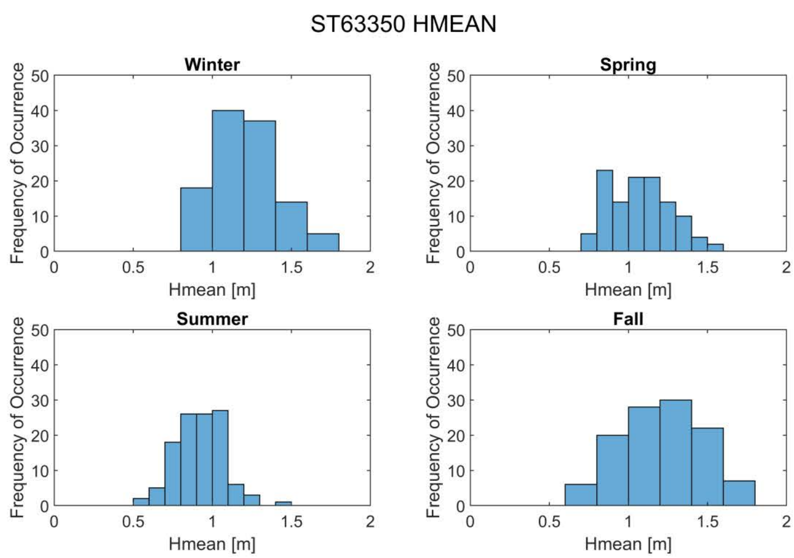


Stono Inlet Borrow Area Modified Bathymetry

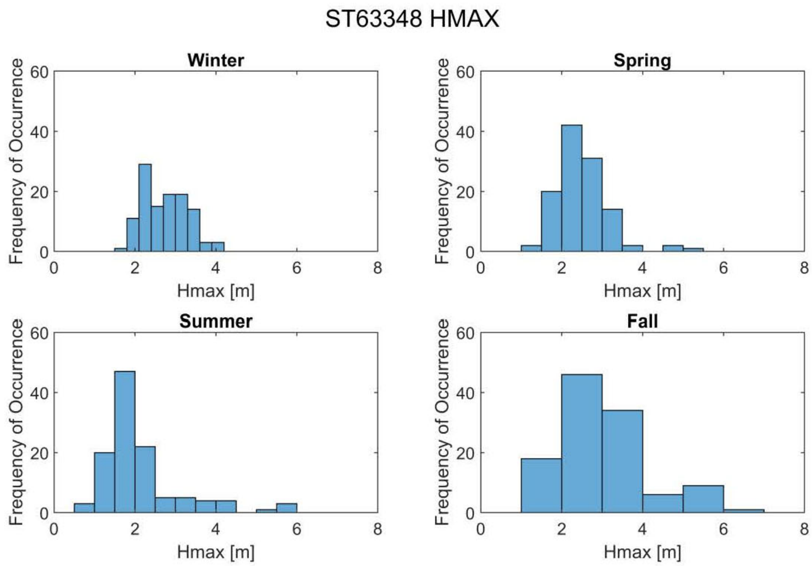


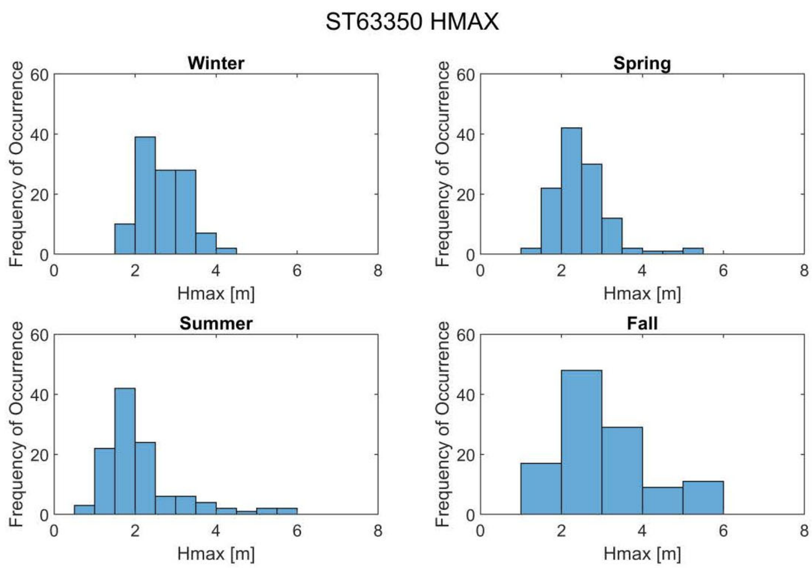
Appendix B—Seasonal Wave Height Statistics





The frequency of occurrence for the mean monthly wave conditions from 1980 to 2017





The frequency of occurrence for the max monthly wave conditions from 1980 to 2017

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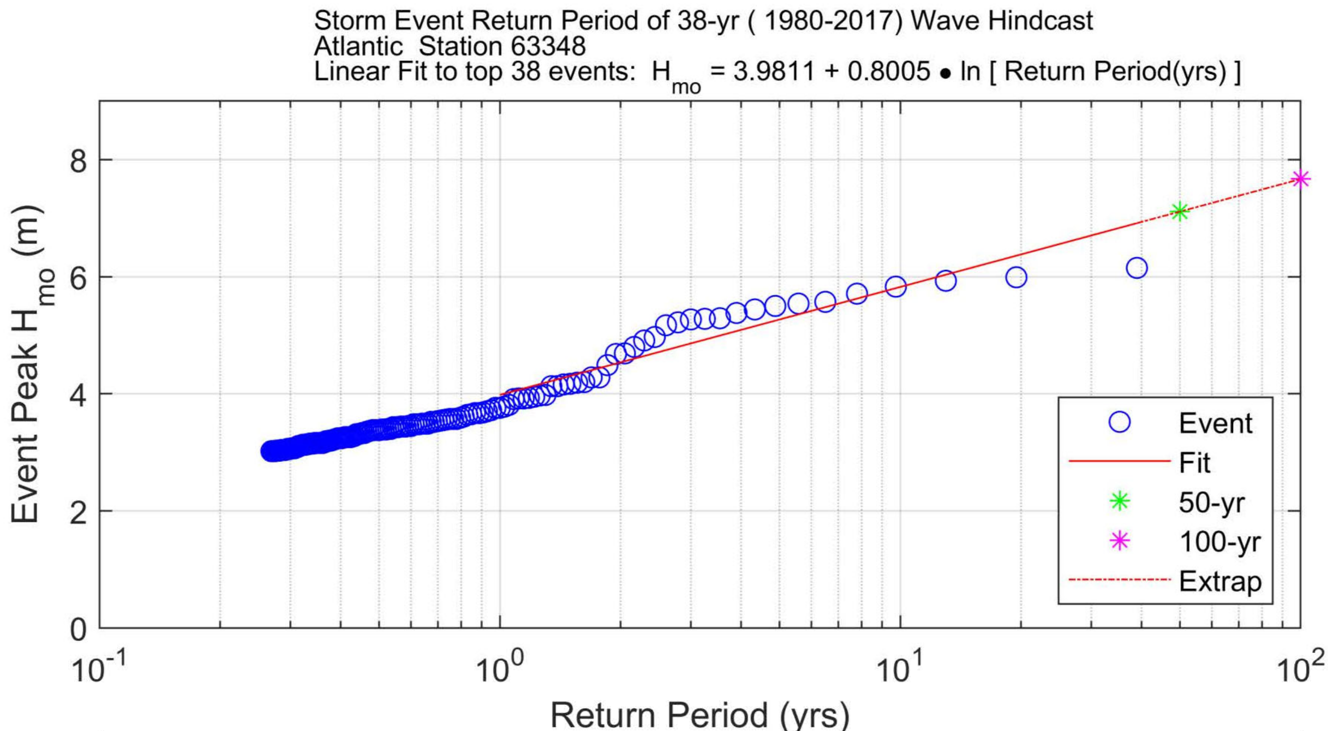
Appendix C—Extremal Analysis
Extremal Analysis WIS Station 63348

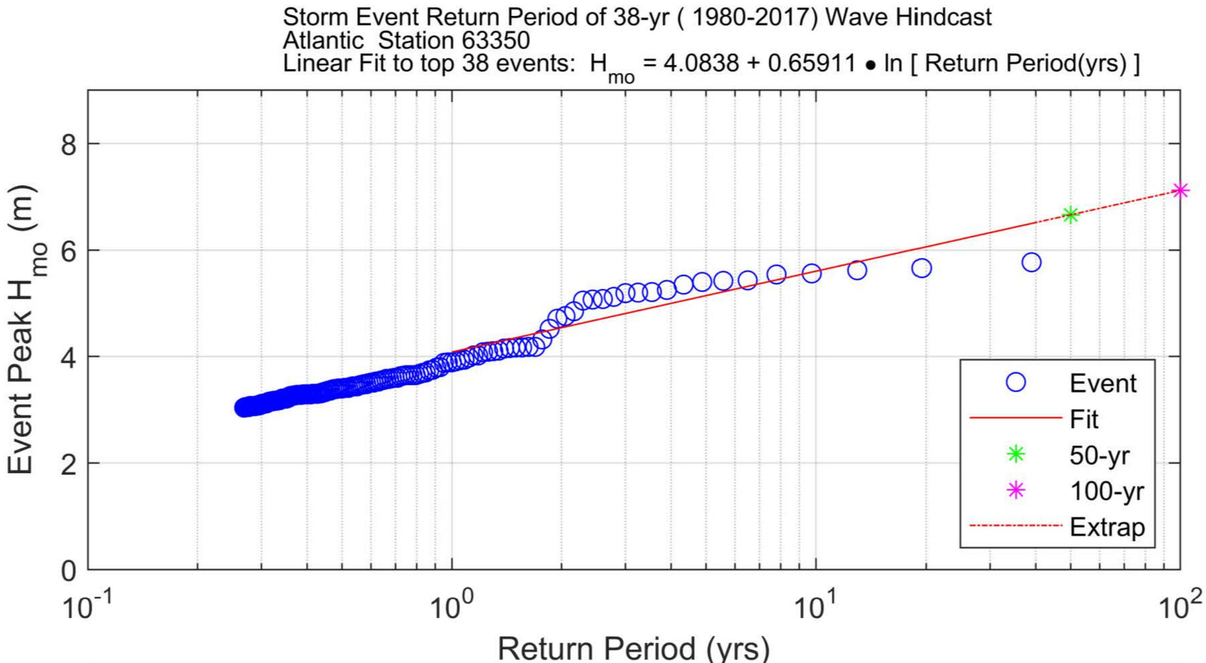


Top 10 events based on Peak H_{mo}

Event	Date/Time(UTC)	H_{mo}	T_{pp}	θ_{wave}	Event	Date/Time(UTC)	H_{mo}	T_{pp}	θ_{wave}
1	1989/09/22 02:00	6.15	18.25	97.0	6	1996/09/05 18:00	5.57	15.74	117.0
2	2008/09/06 00:00	5.99	15.69	128.0	7	1996/07/11 19:00	5.54	15.25	131.0
3	1999/09/15 19:00	5.93	16.09	130.0	8	1985/09/26 17:00	5.50	17.17	125.0
4	2011/08/26 19:00	5.83	16.18	130.0	9	2010/09/02 22:00	5.44	17.05	125.0
5	1998/08/26 08:00	5.71	16.48	119.0	10	2016/10/08 10:00	5.38	12.90	148.0

An event is defined as any period when H_{mo} > 3.00m θ_{wind} is direction that waves are arriving from

Extremal Analysis WIS Station 63350



Top 10 events based on Peak H_{mo}

Event	Date/Time(UTC)	H_{mo}	T_{pp}	θ_{wave}	Event	Date/Time(UTC)	H_{mo}	T_{pp}	θ_{wave}
1	1989/09/22 00:00	5.77	18.07	114.0	6	1985/09/26 17:00	5.43	17.19	129.0
2	2008/09/06 00:00	5.66	15.69	128.0	7	2010/09/02 23:00	5.42	17.04	127.0
3	1999/09/15 18:00	5.62	16.06	131.0	8	1996/09/05 18:00	5.40	15.77	122.0
4	1998/08/26 09:00	5.56	16.75	122.0	9	1996/07/11 20:00	5.35	15.28	132.0
5	2011/08/26 19:00	5.54	16.15	133.0	10	2012/10/27 14:00	5.25	14.93	122.0

An event is defined as any period when H_{mo} > 3.00m θ_{wind} is direction that waves are arriving from

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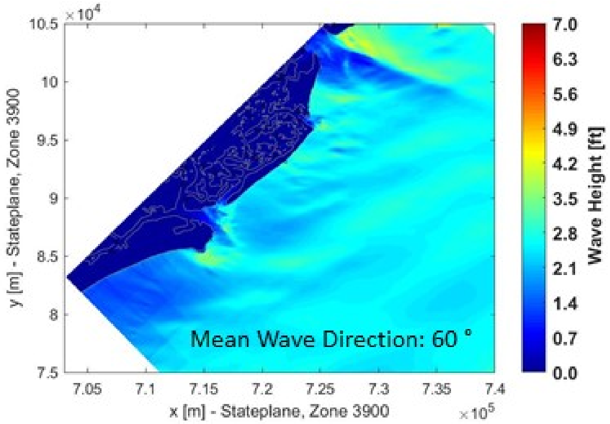
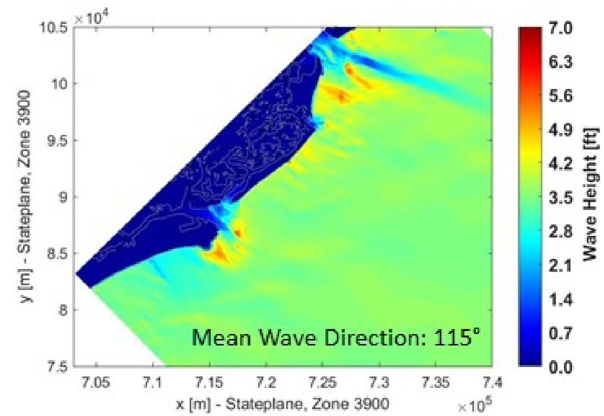
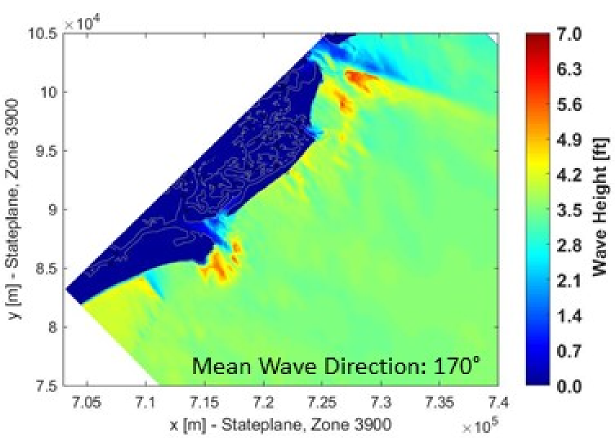
Appendix D—Spectral Wave Height Plots

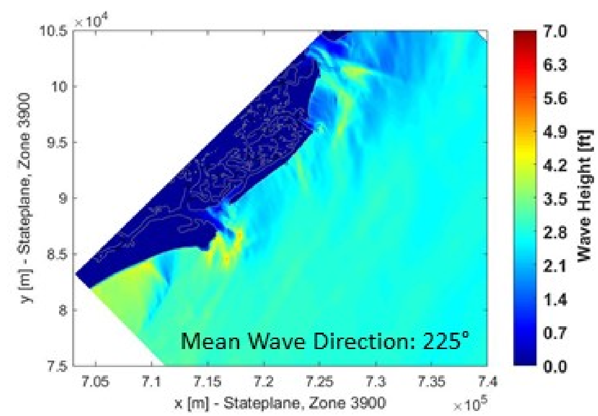
Mean Monthly Condition

Base:

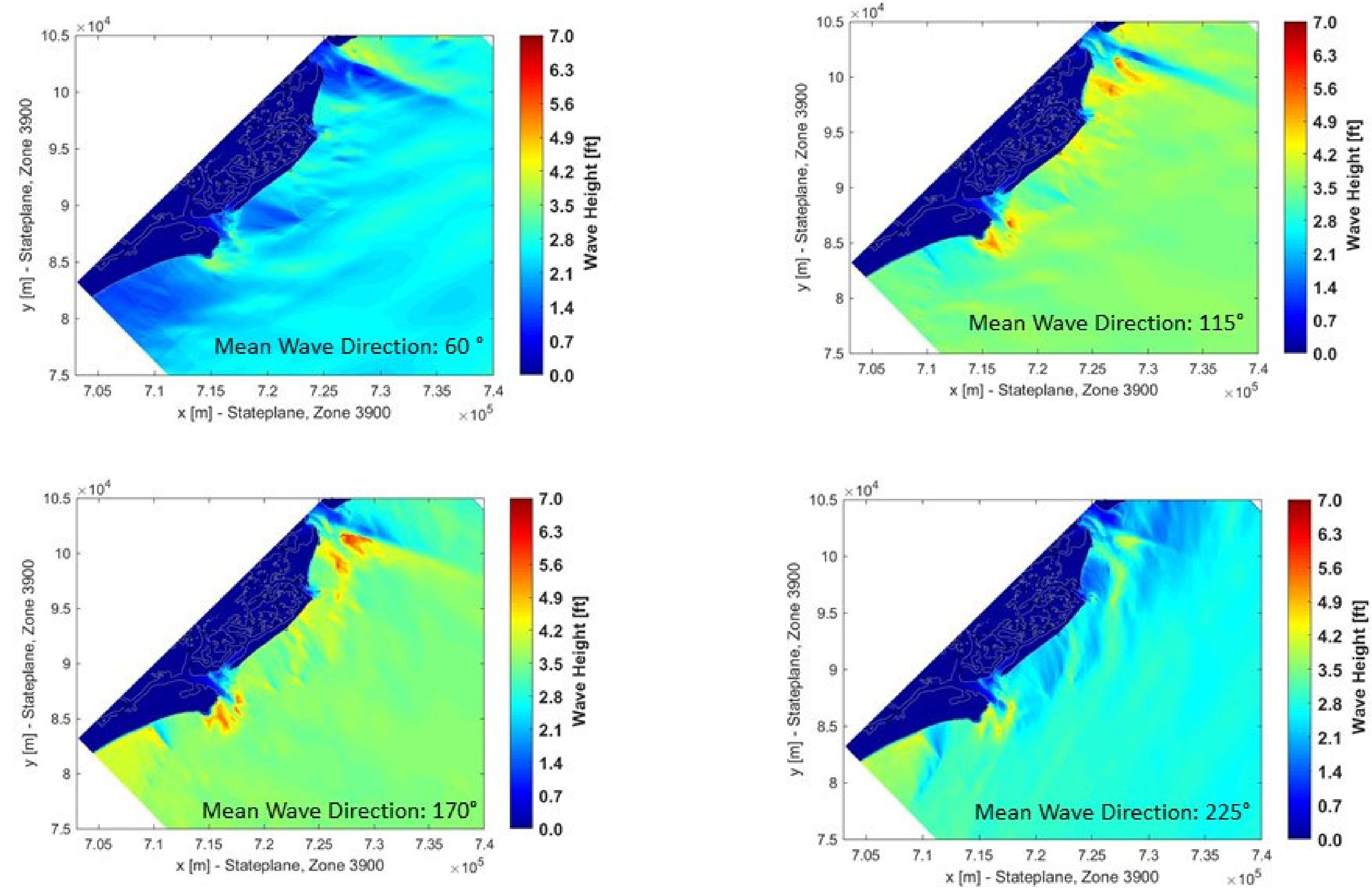




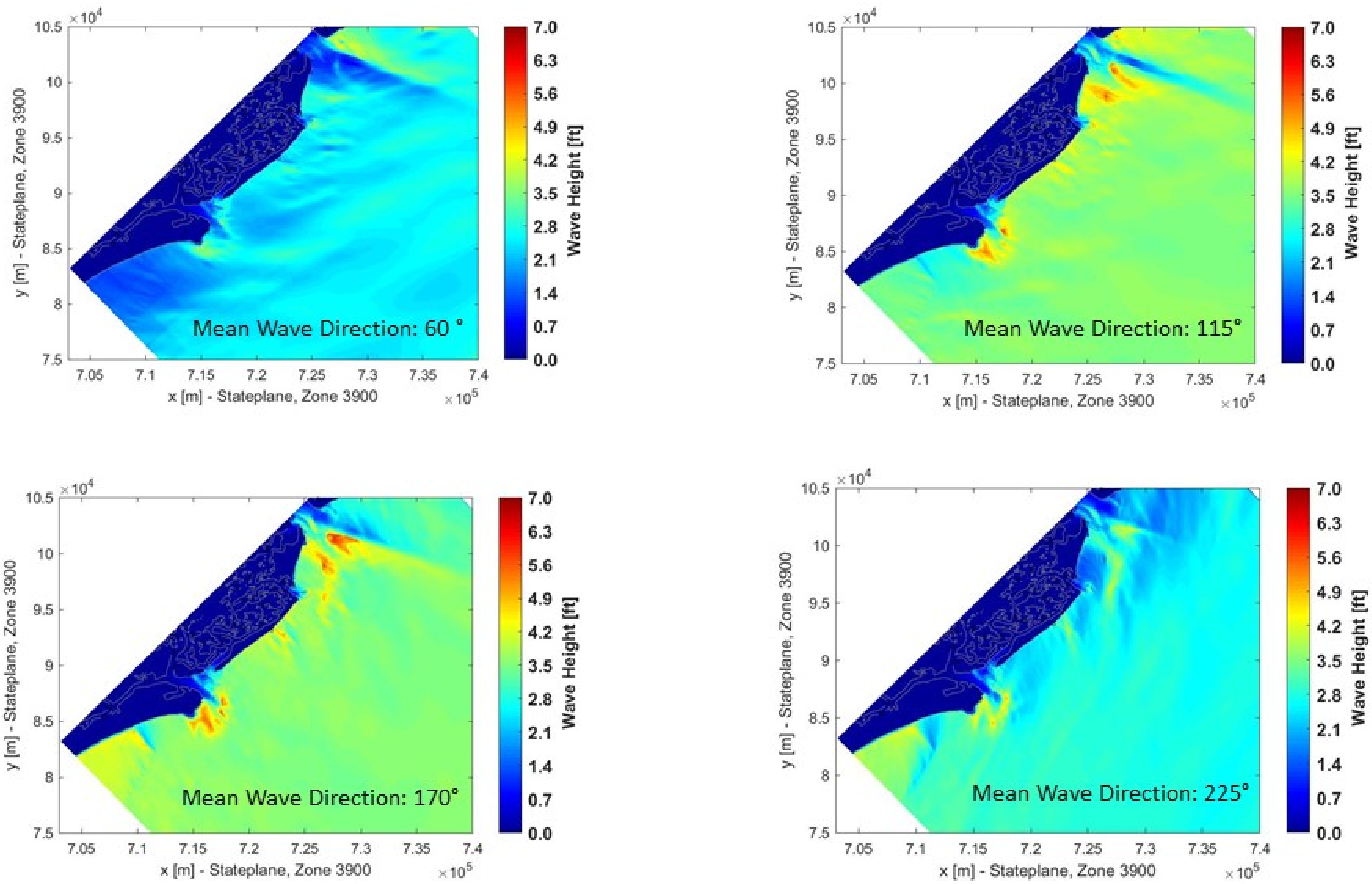




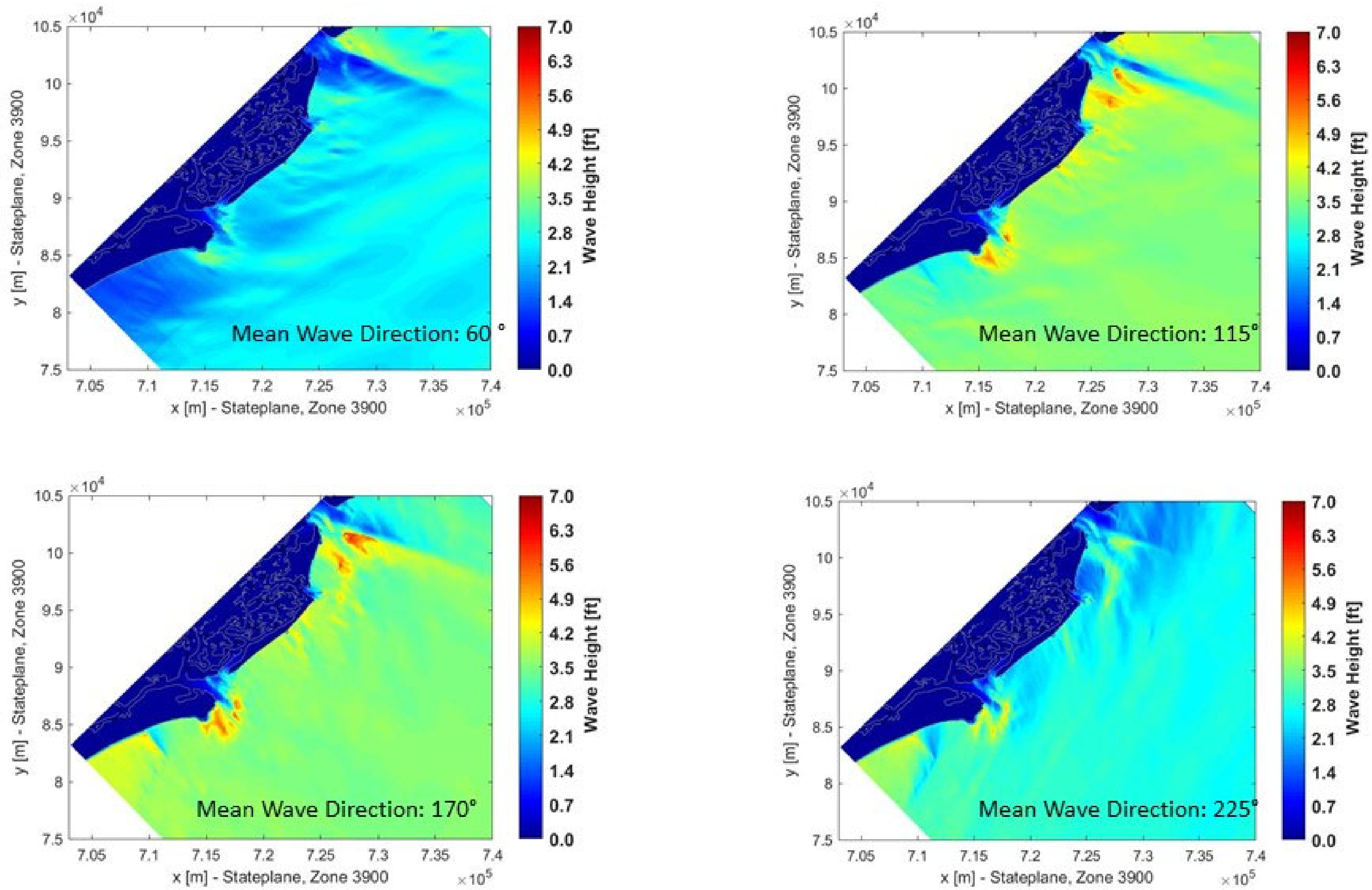
Mean Monthly Condition
Central Folly Borrow Area:



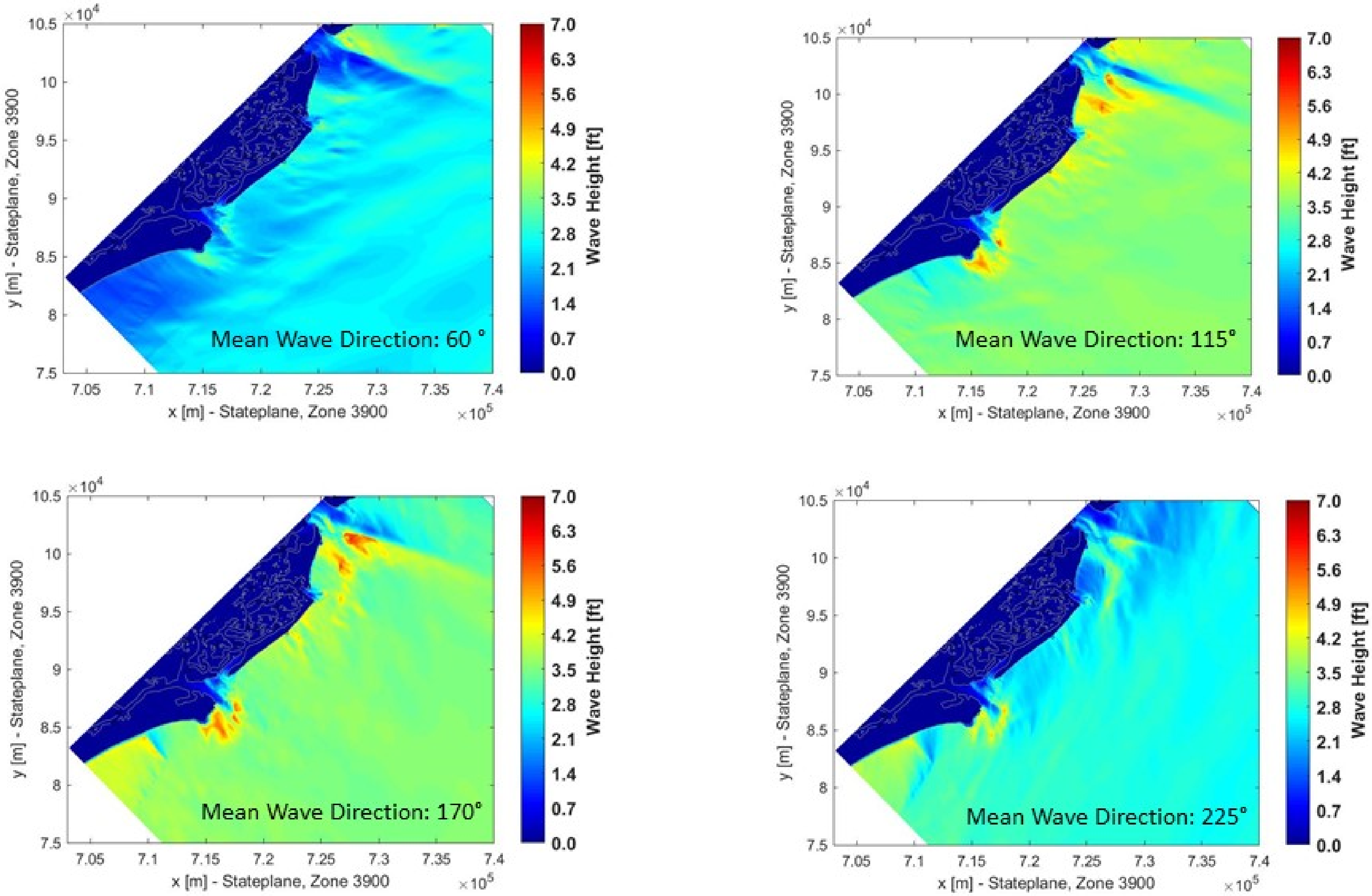
Mean Monthly Condition
Lighthouse Inlet Borrow Area:



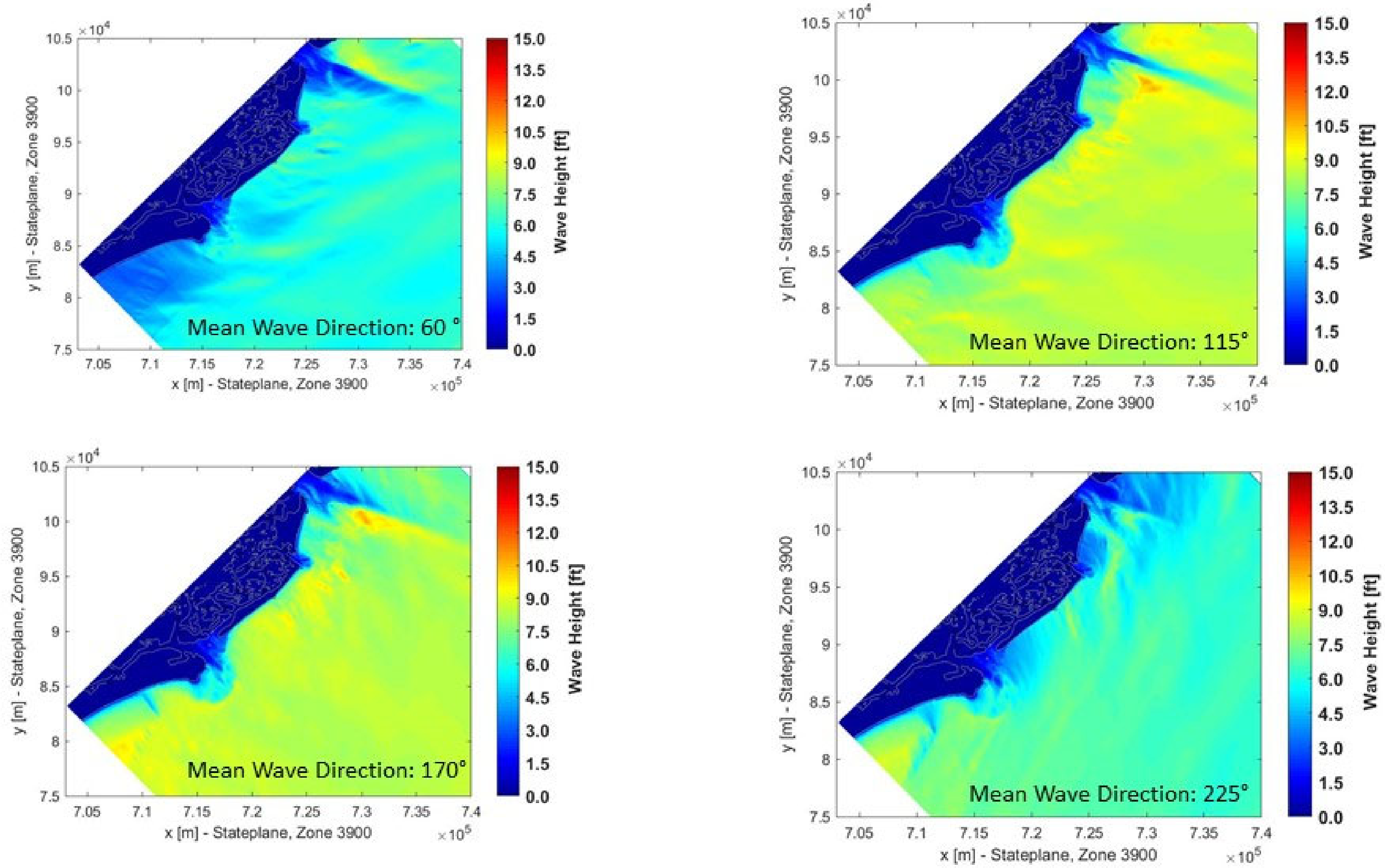
Mean Monthly Condition
Seaward of State's Territory Borrow Area:



Mean Monthly Condition
Stono Inlet Borrow Area:



Max Monthly Condition
Base:



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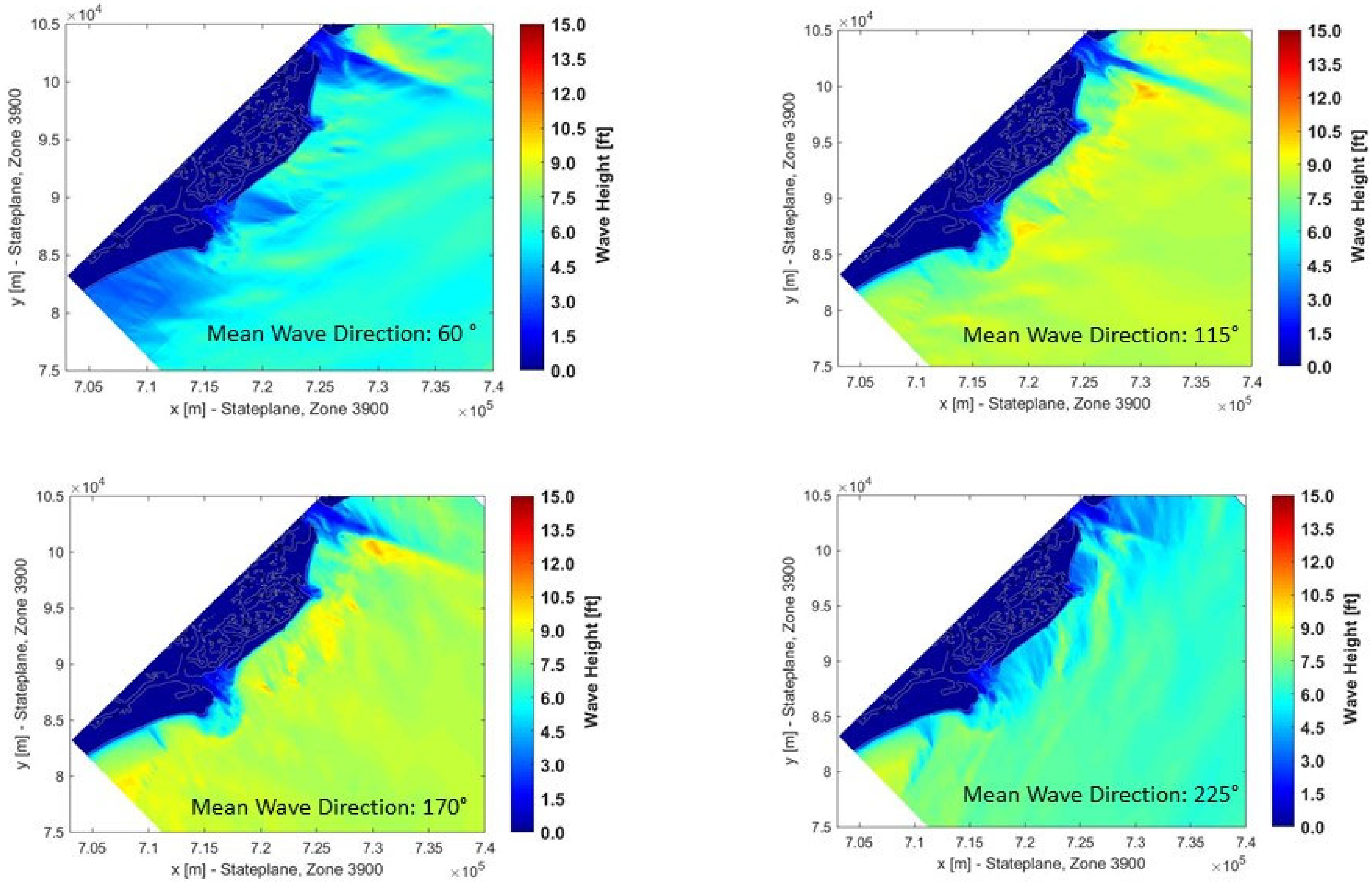
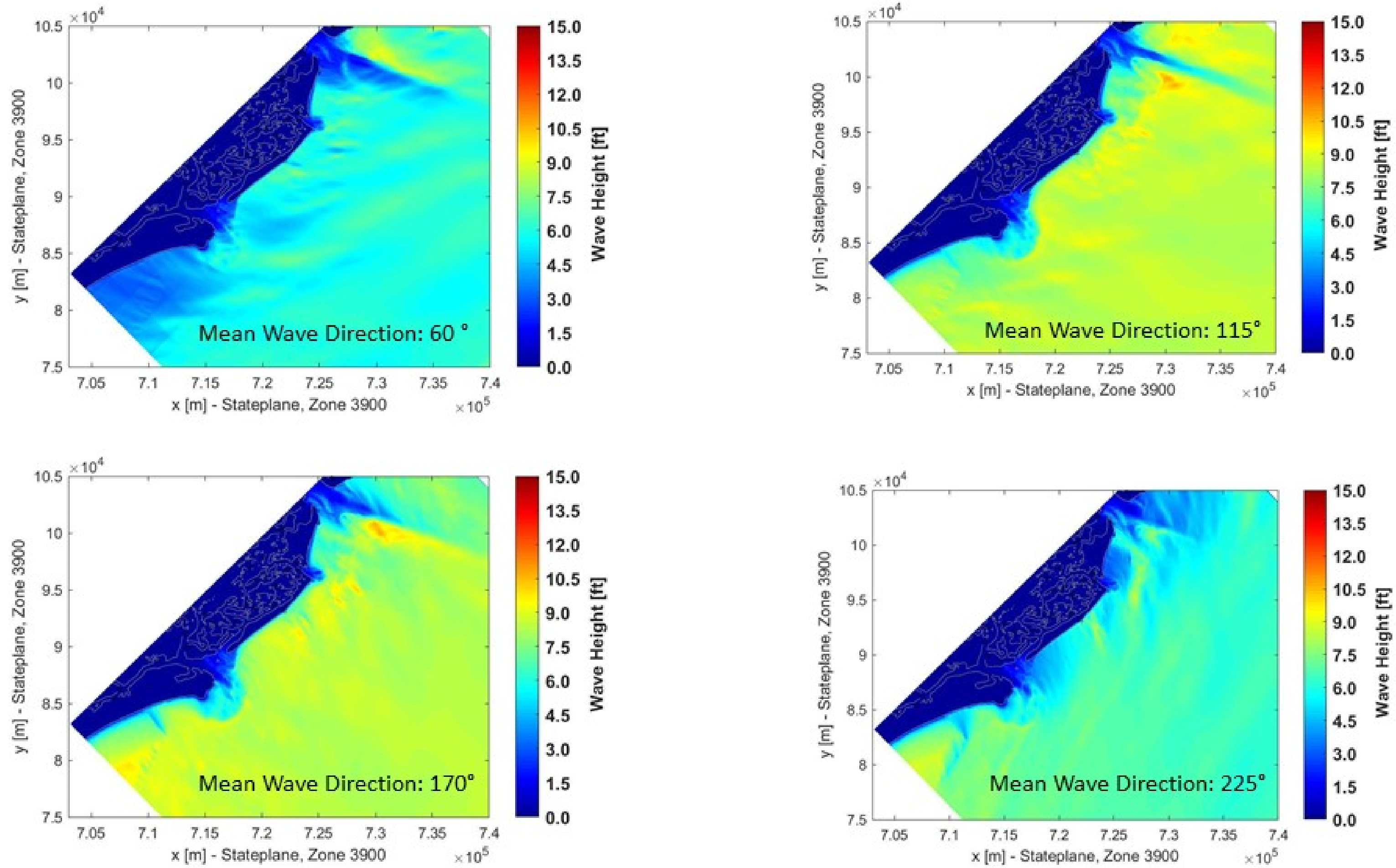
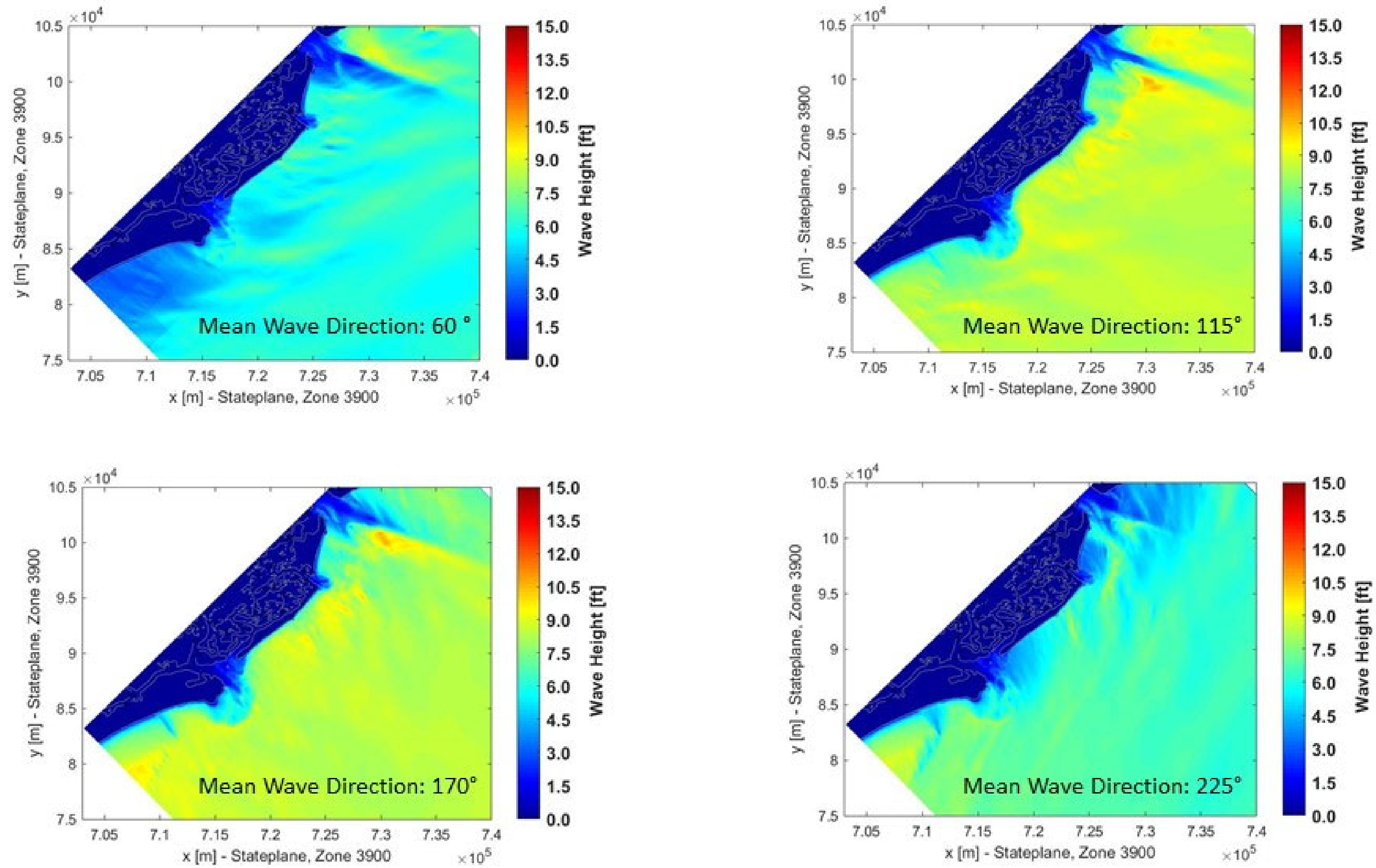
Central Folly Borrow Area:



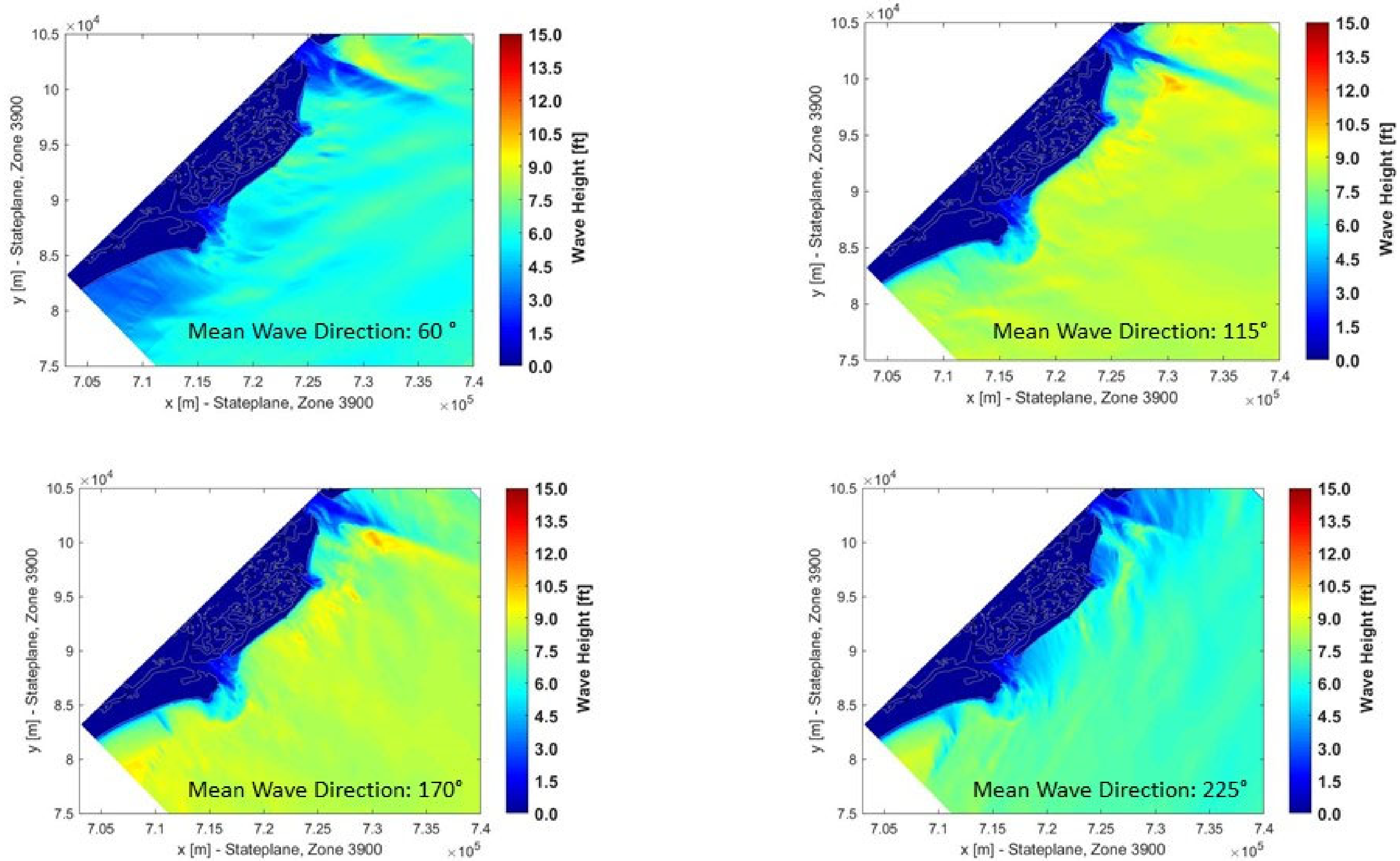
Max Monthly Condition
Lighthouse Inlet Borrow Area:



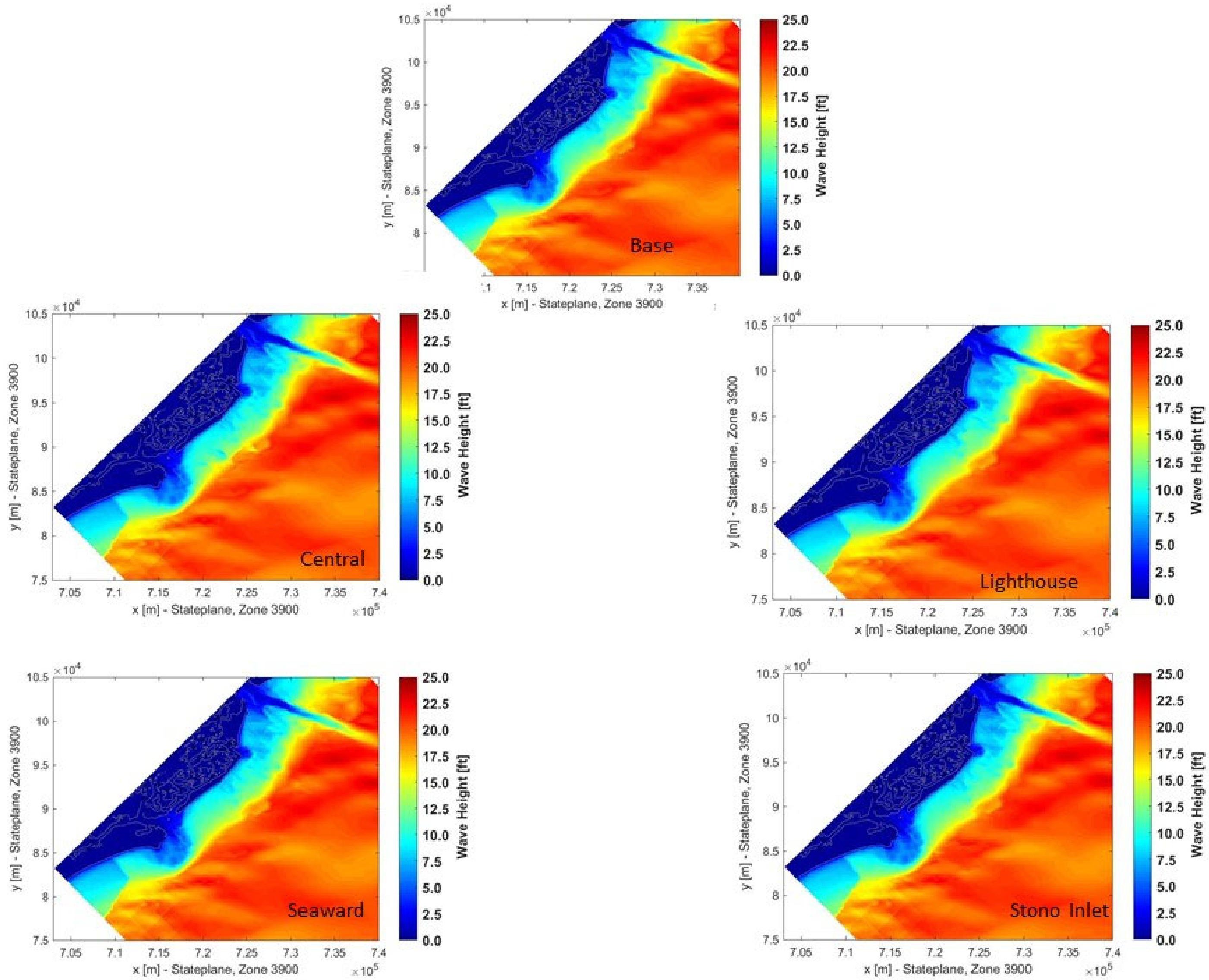
Max Monthly Condition
Seaward of State's Territory Borrow Area:



Max Monthly Condition
Stono Inlet Borrow Area:

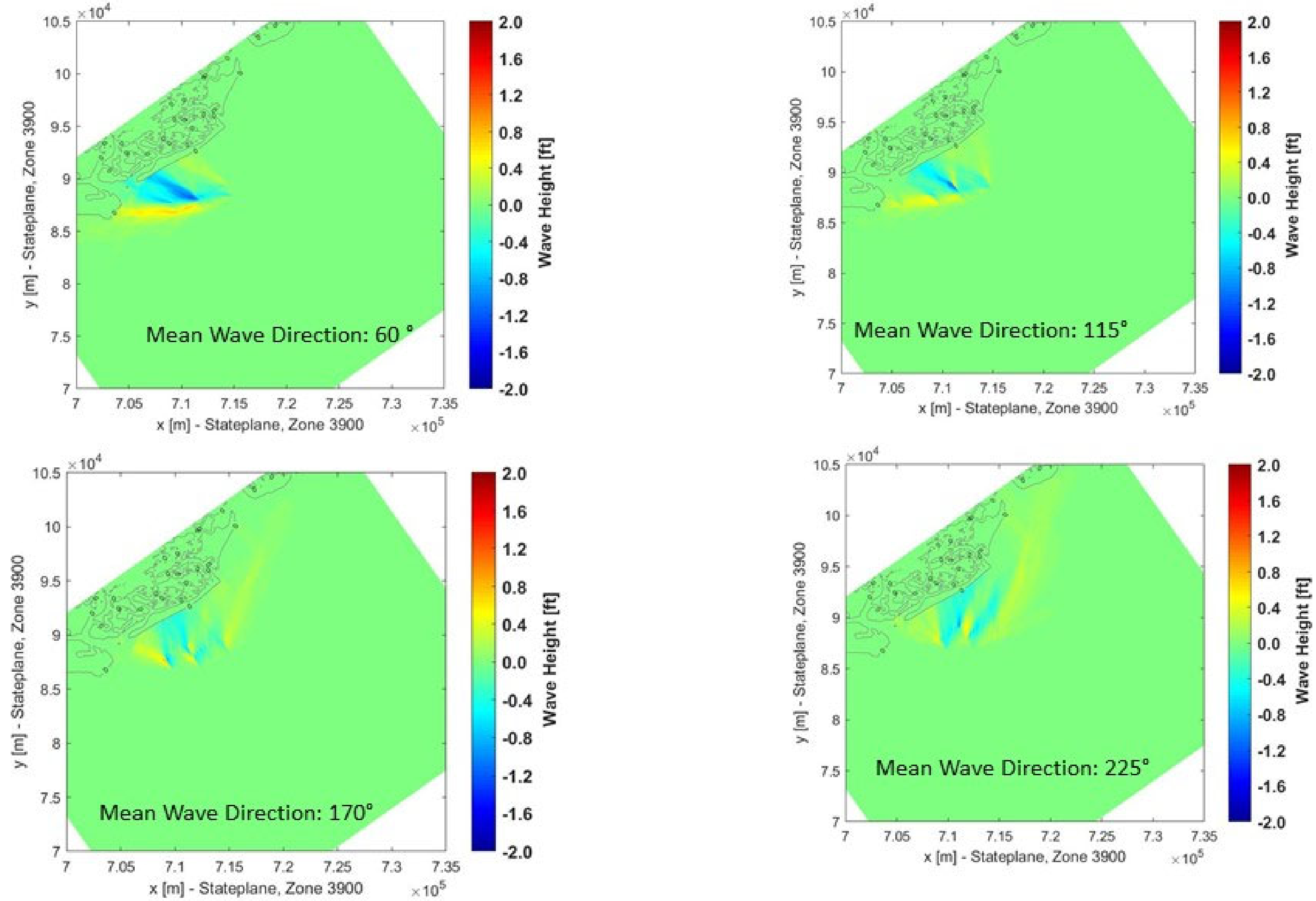


Extreme Event Condition:

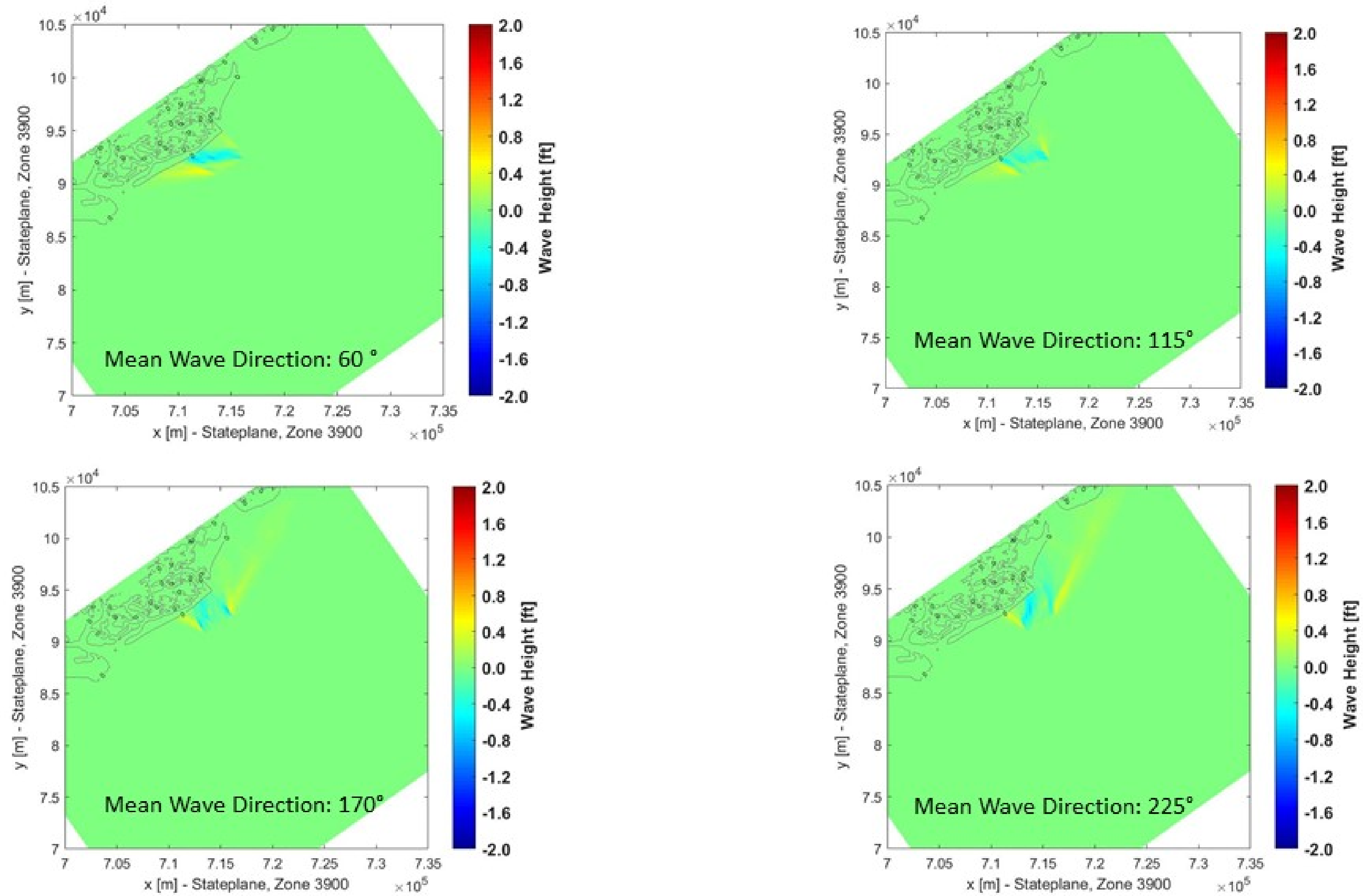


Appendix E—Difference Wave Height Plots

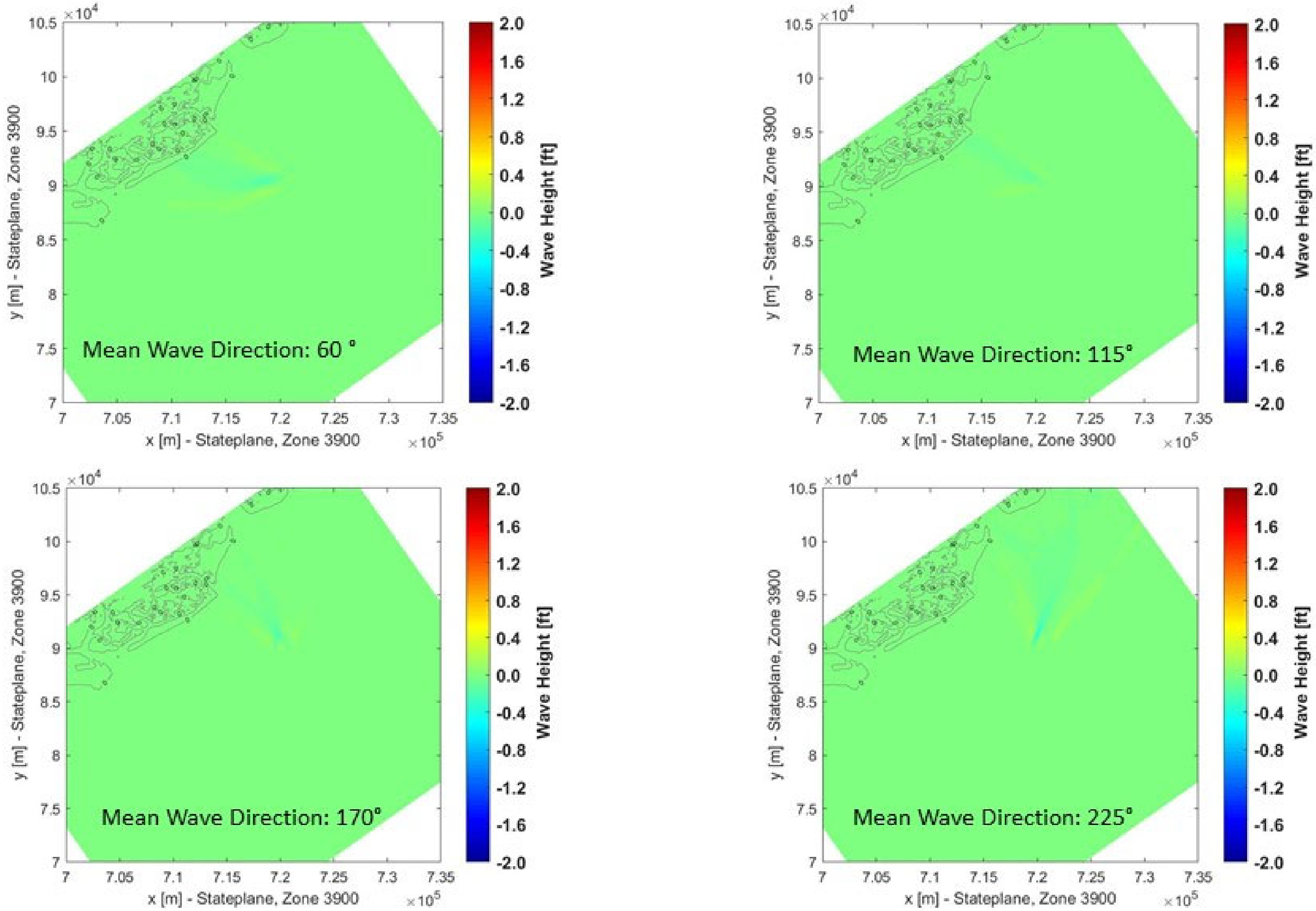
Mean Monthly Condition
Central Folly Borrow Area:



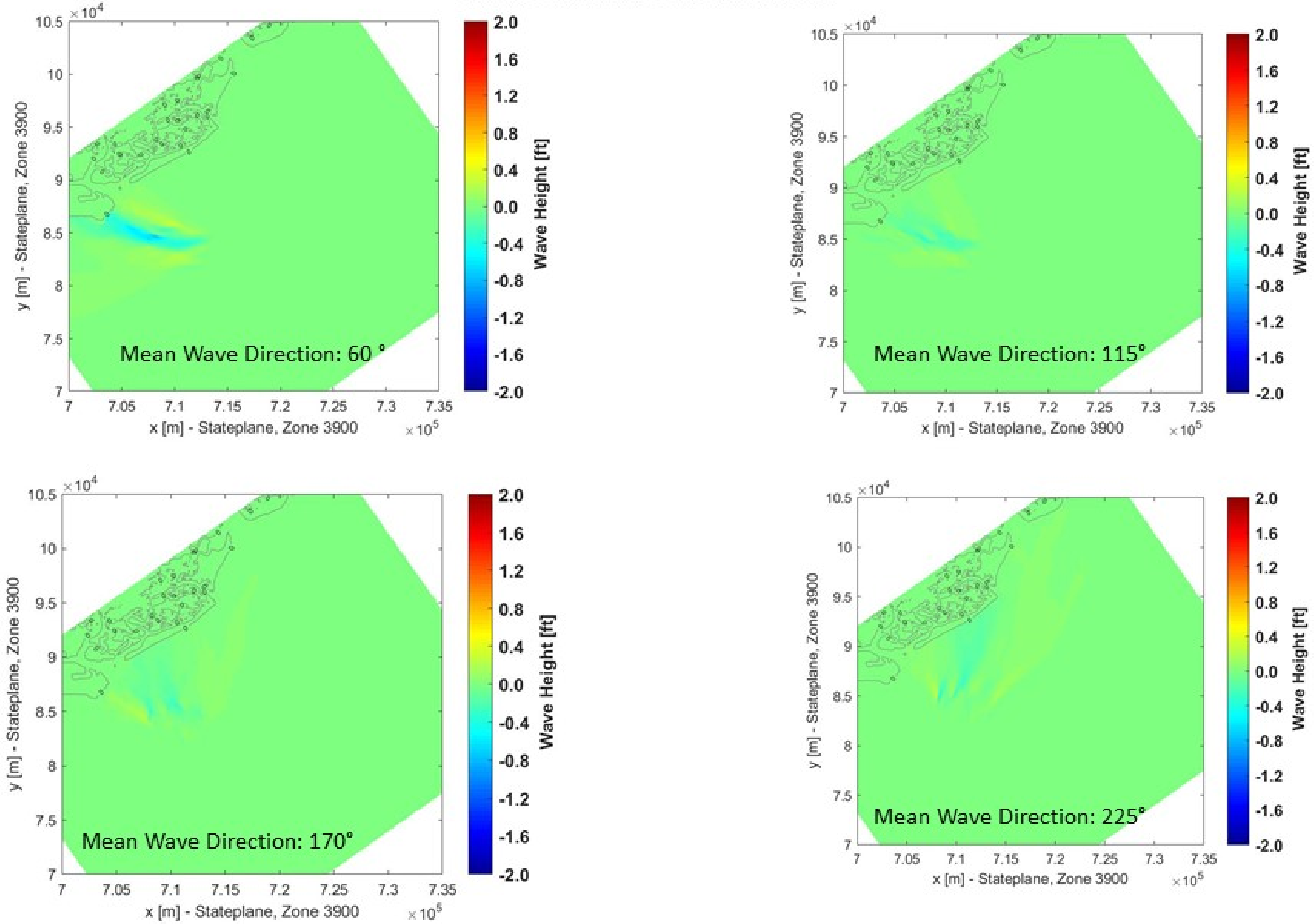
Mean Monthly Condition
Lighthouse Inlet Borrow Area:



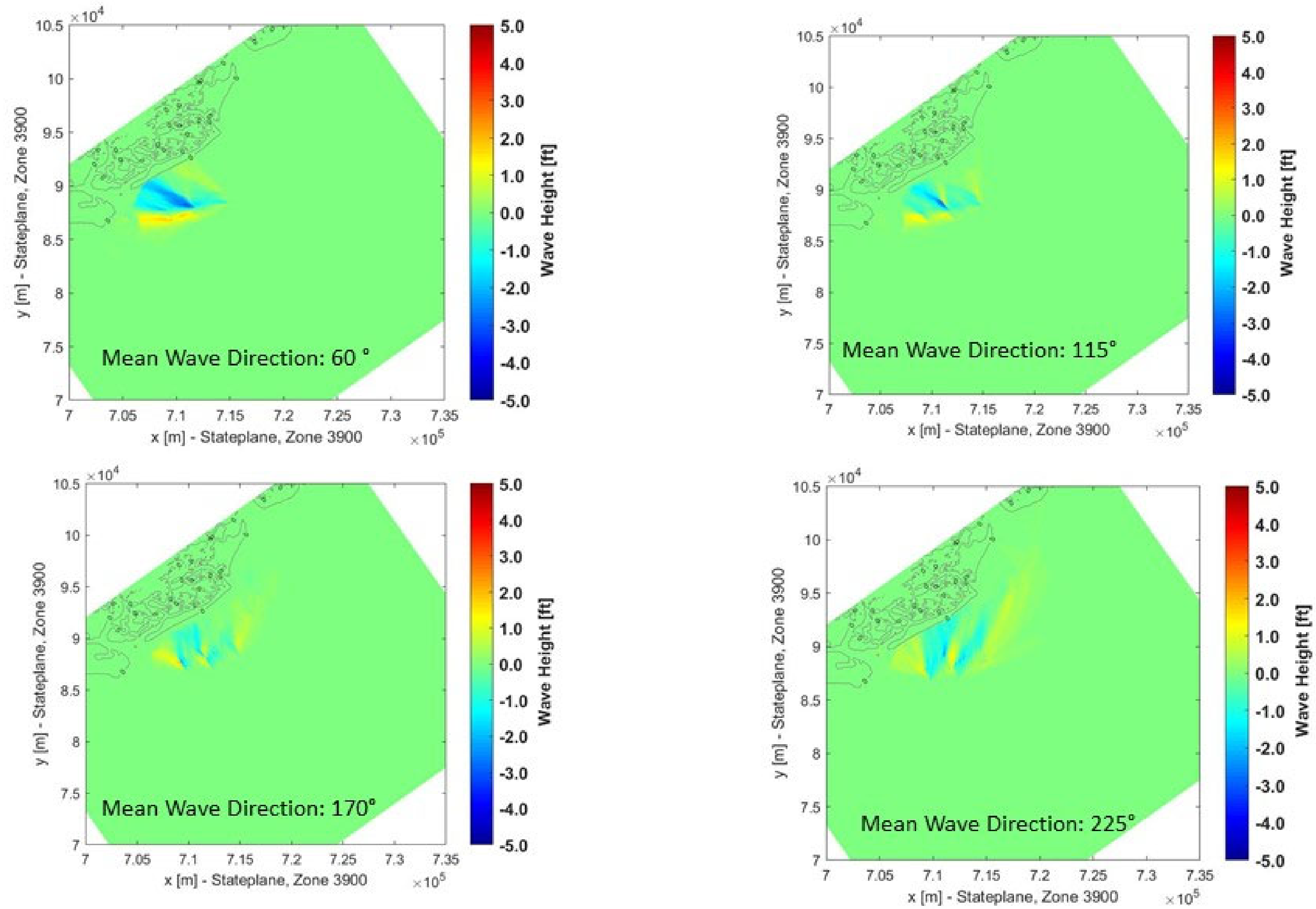
Mean Monthly Condition
Seaward of State's Territory Borrow Area:



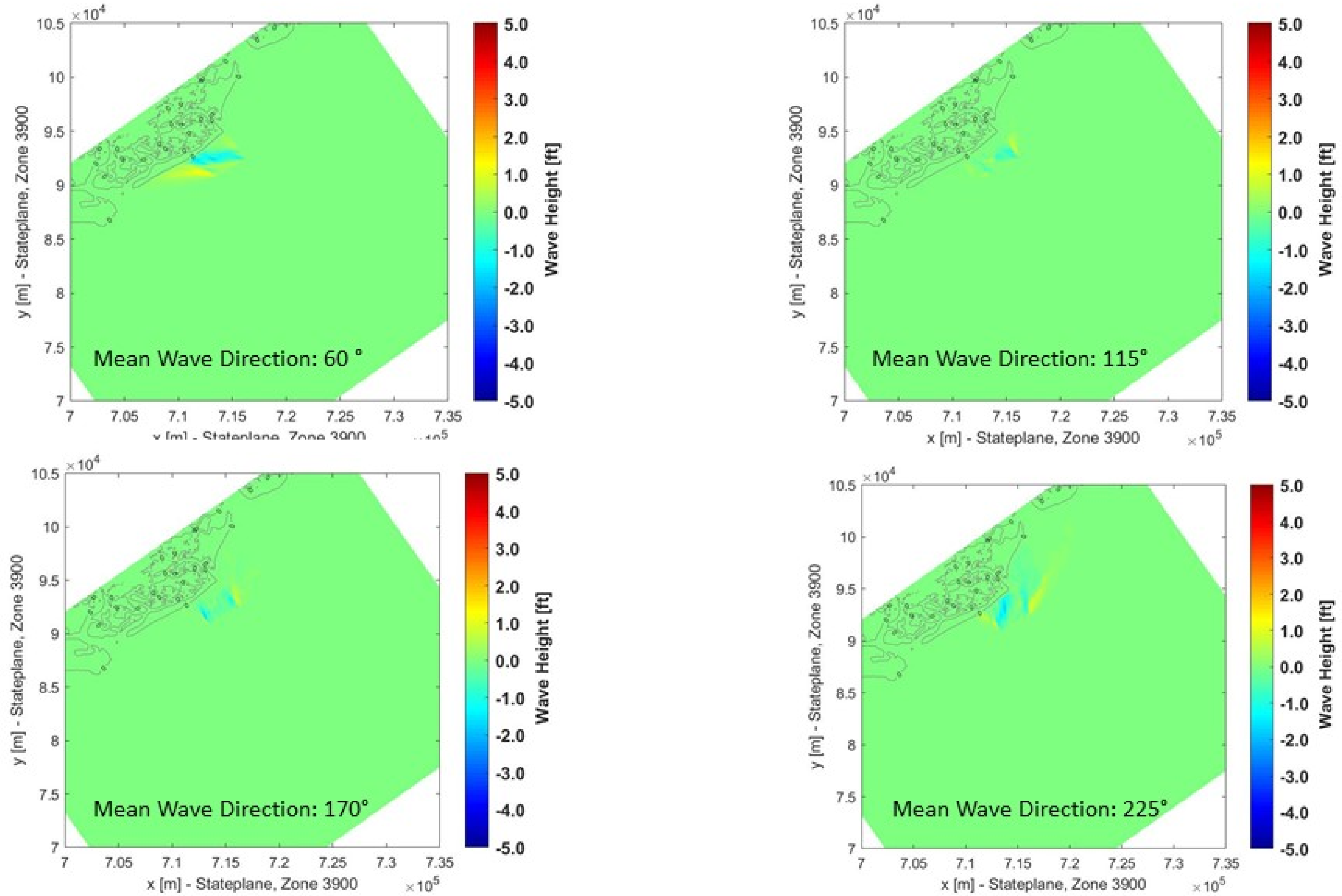
Mean Monthly Condition
Stono Inlet Borrow Area:



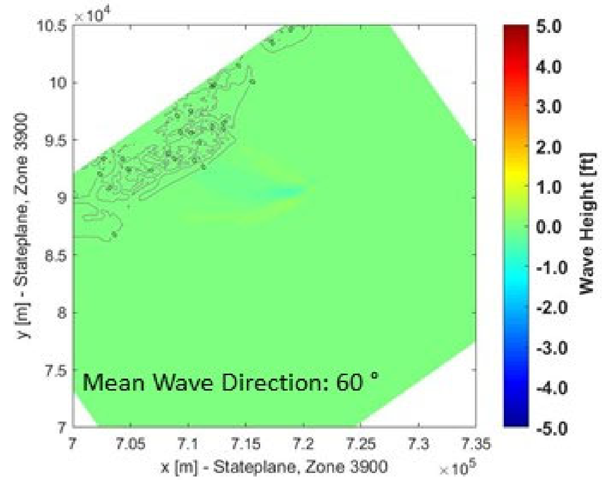
Max Monthly Condition
Central Folly Borrow Area:

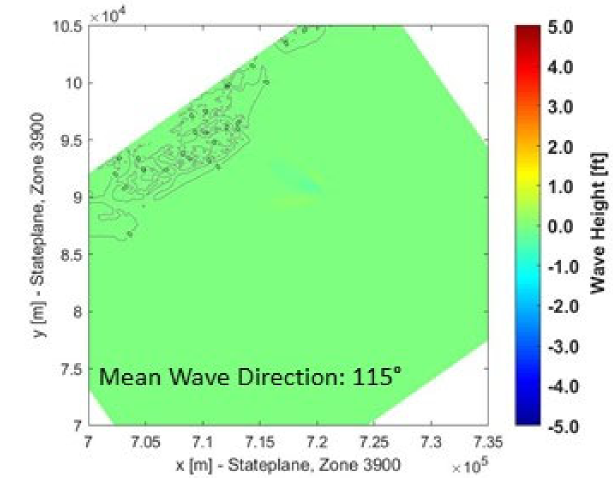


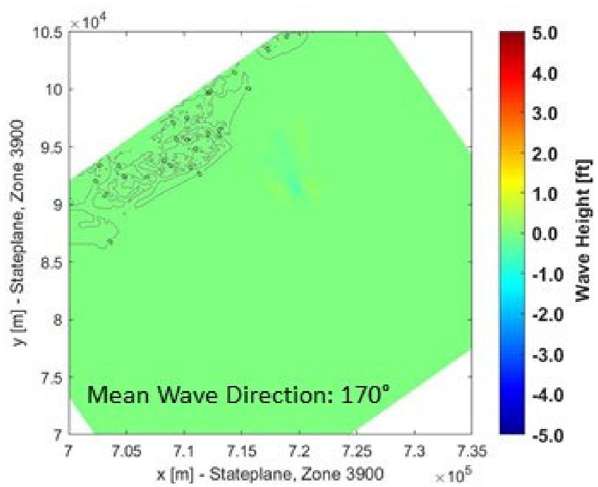
Max Monthly Condition
Lighthouse Inlet Borrow Area:

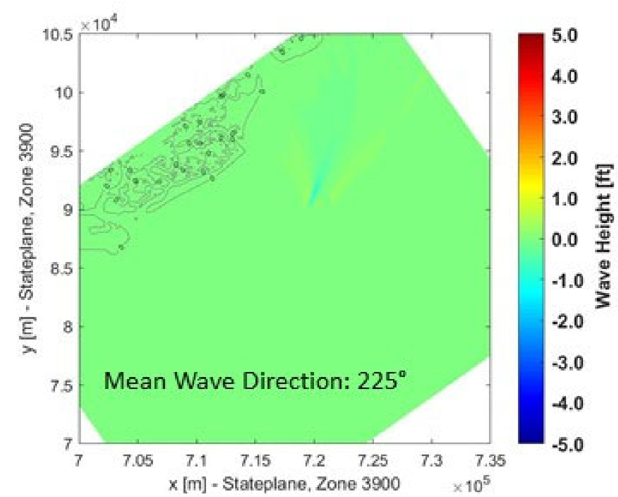


Max Monthly Condition
Seaward of State's Territory Borrow Area:

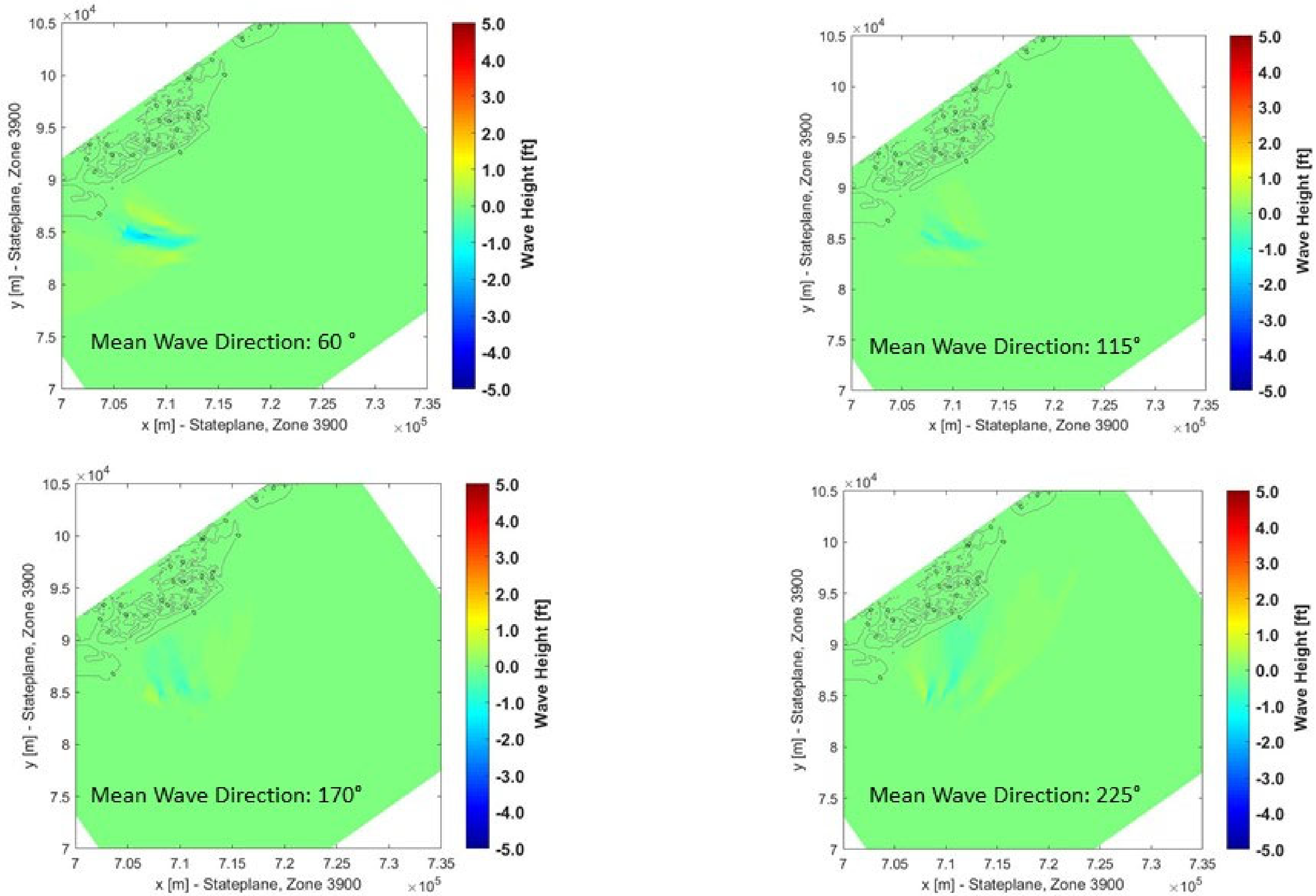




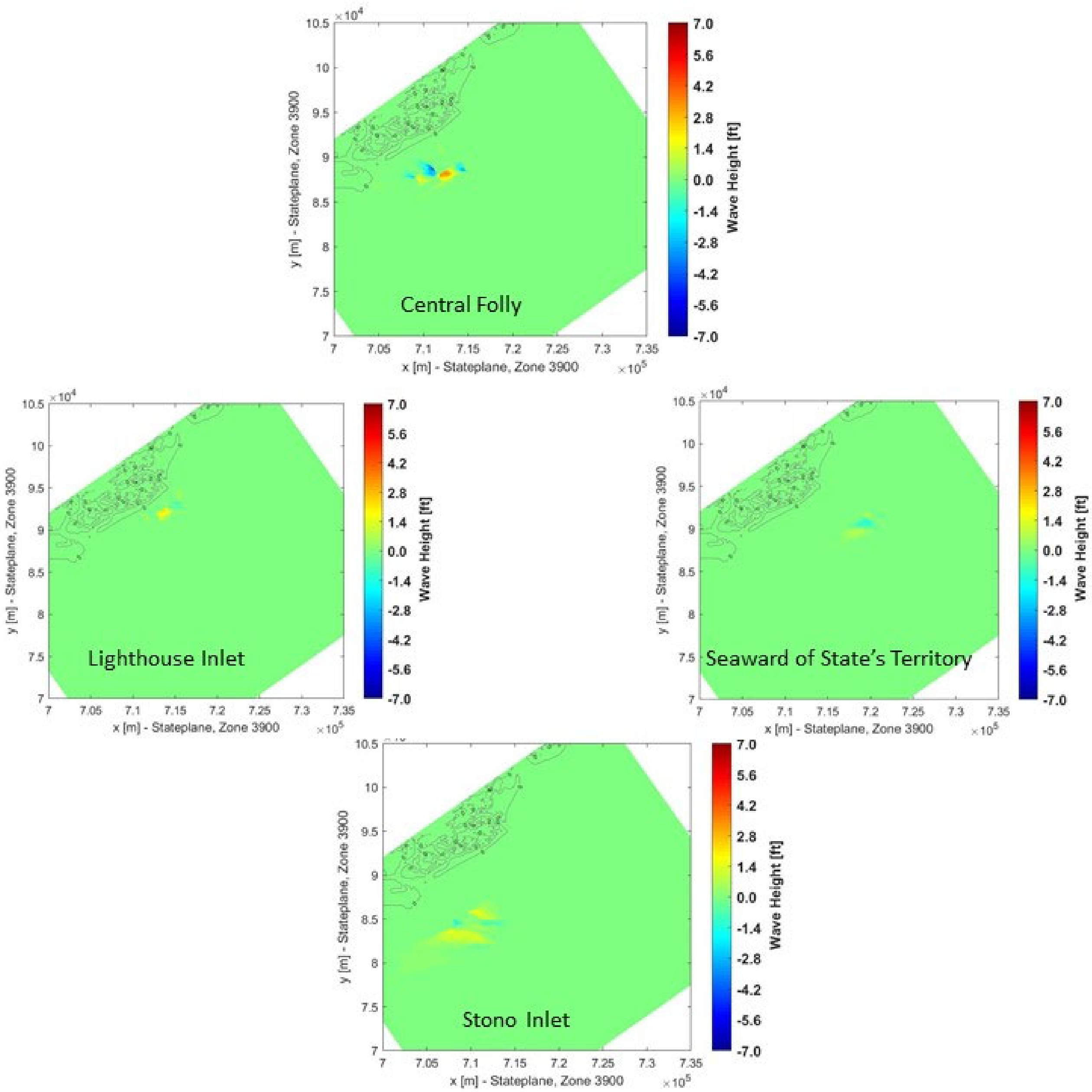




Max Monthly Condition
Stono Inlet Borrow Area:

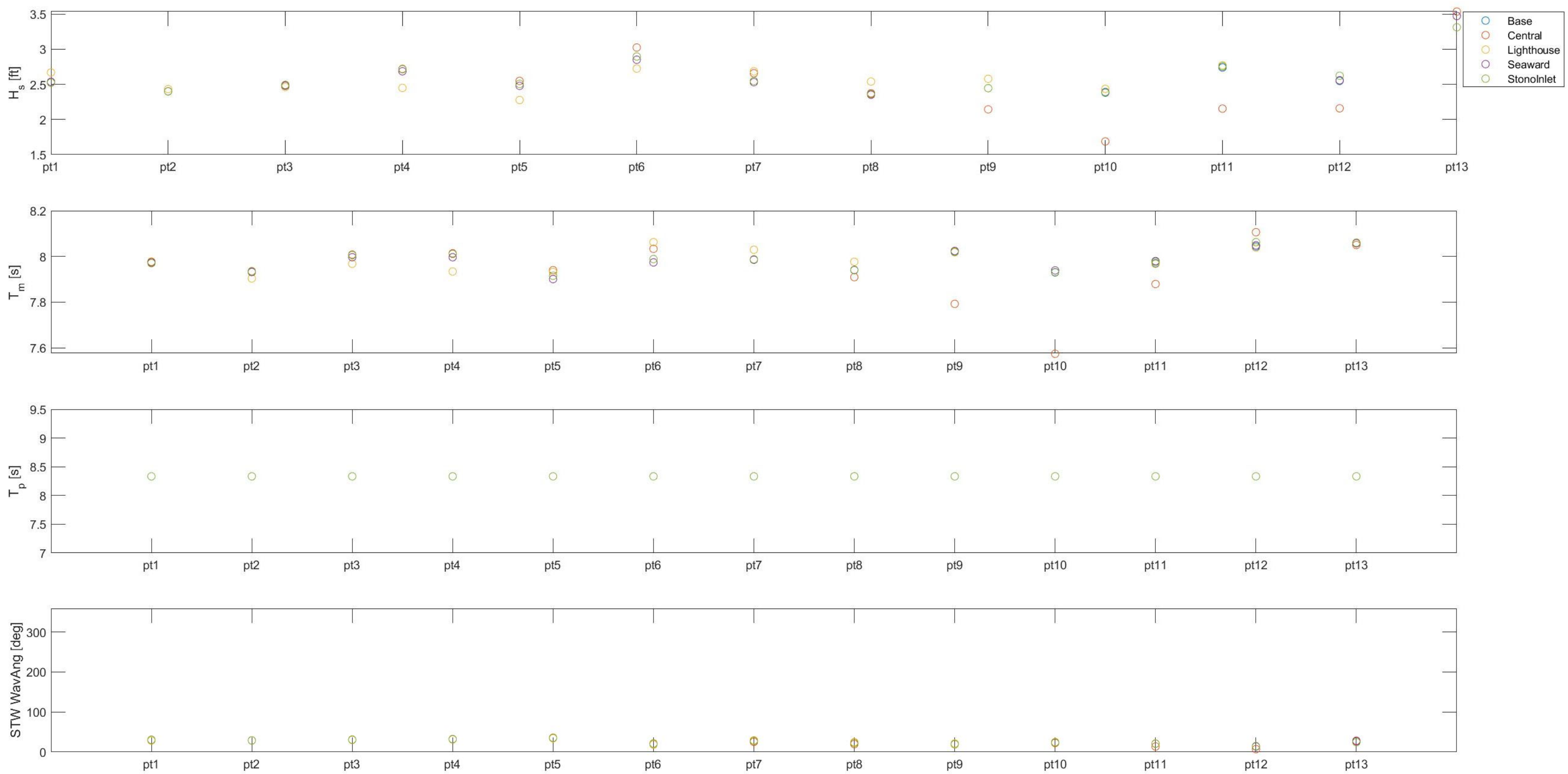


Extreme Event Condition

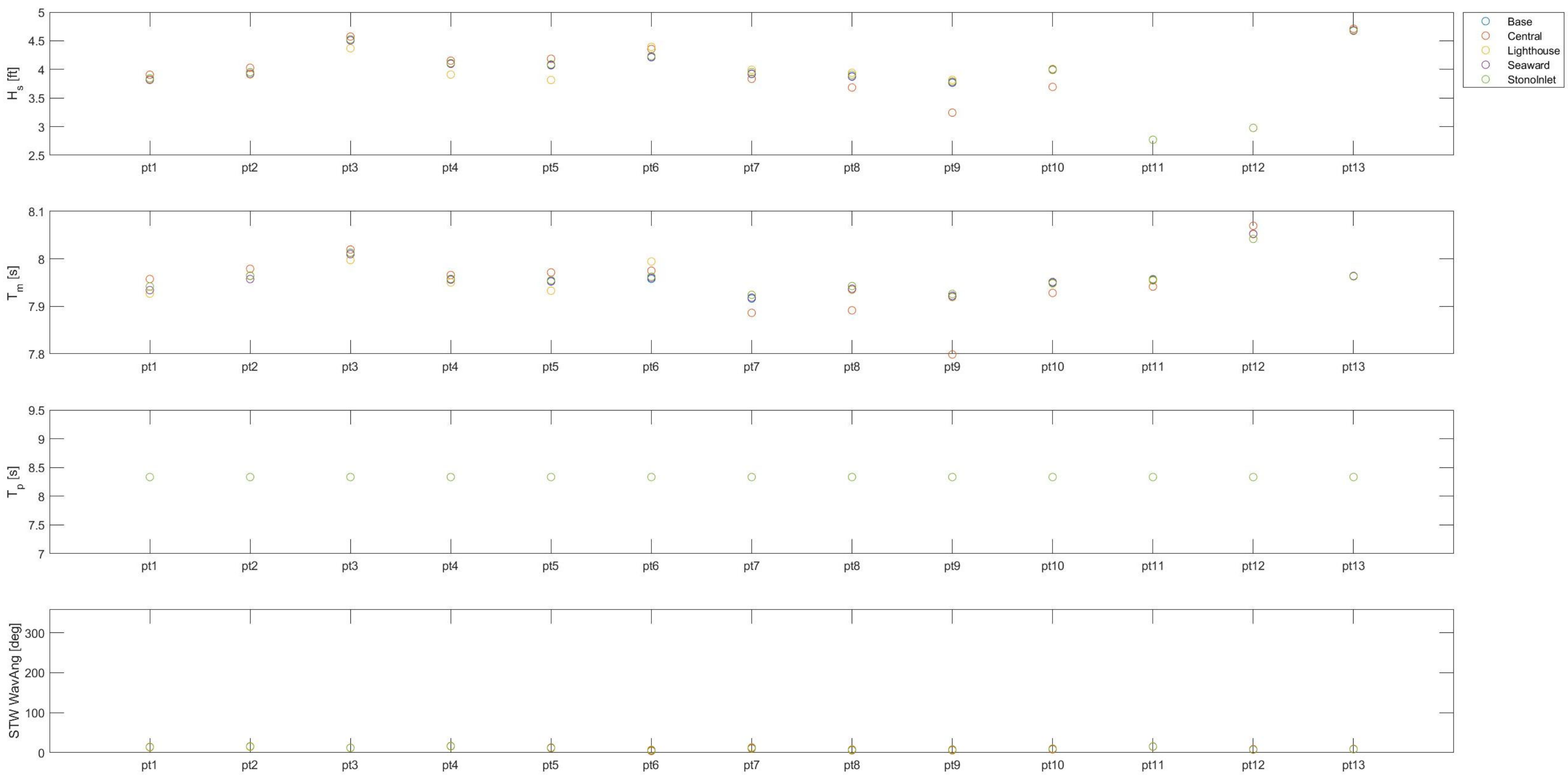


Appendix F—Save Point plots

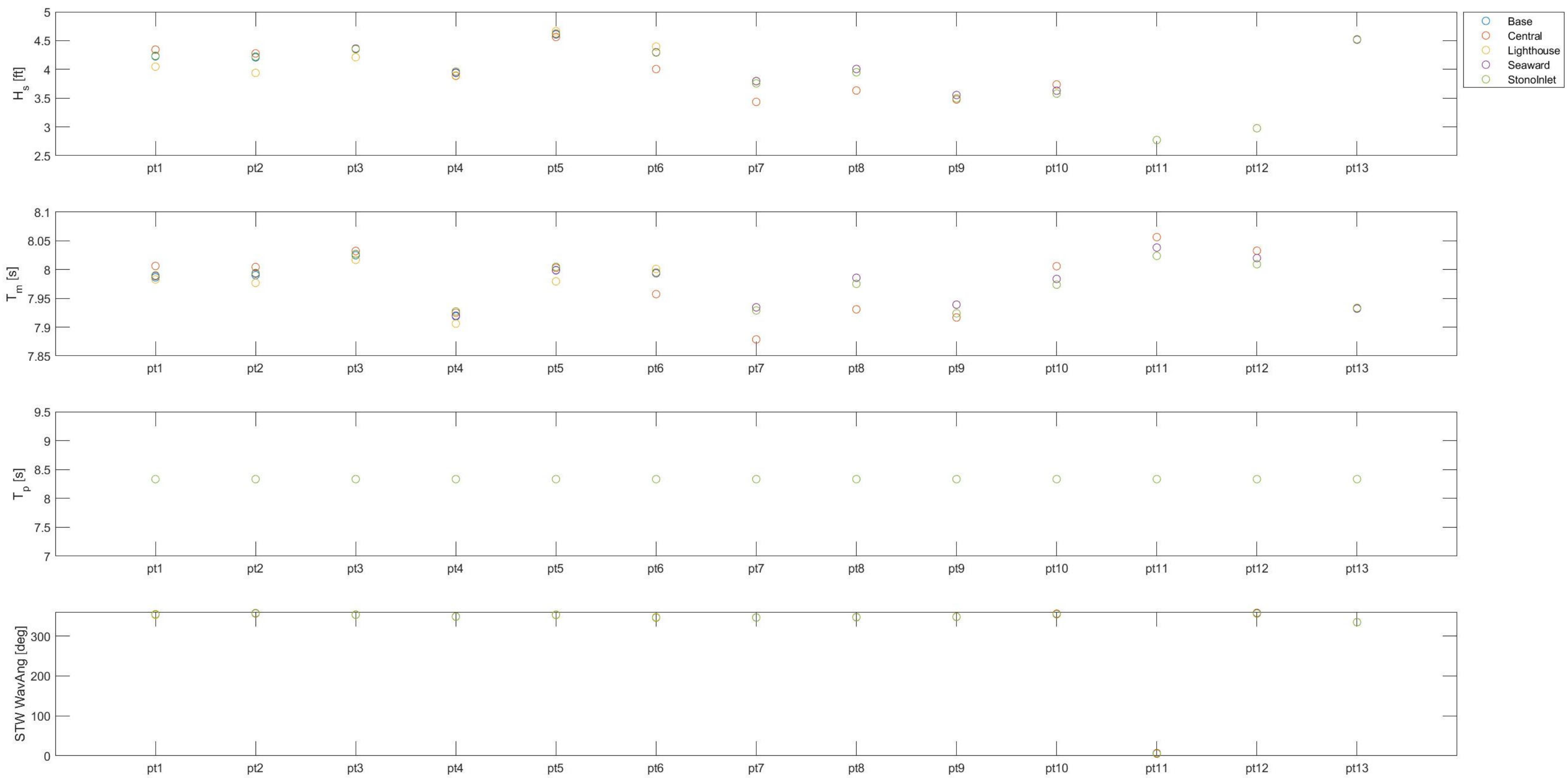
Mean Monthly- 60° Wave Direction



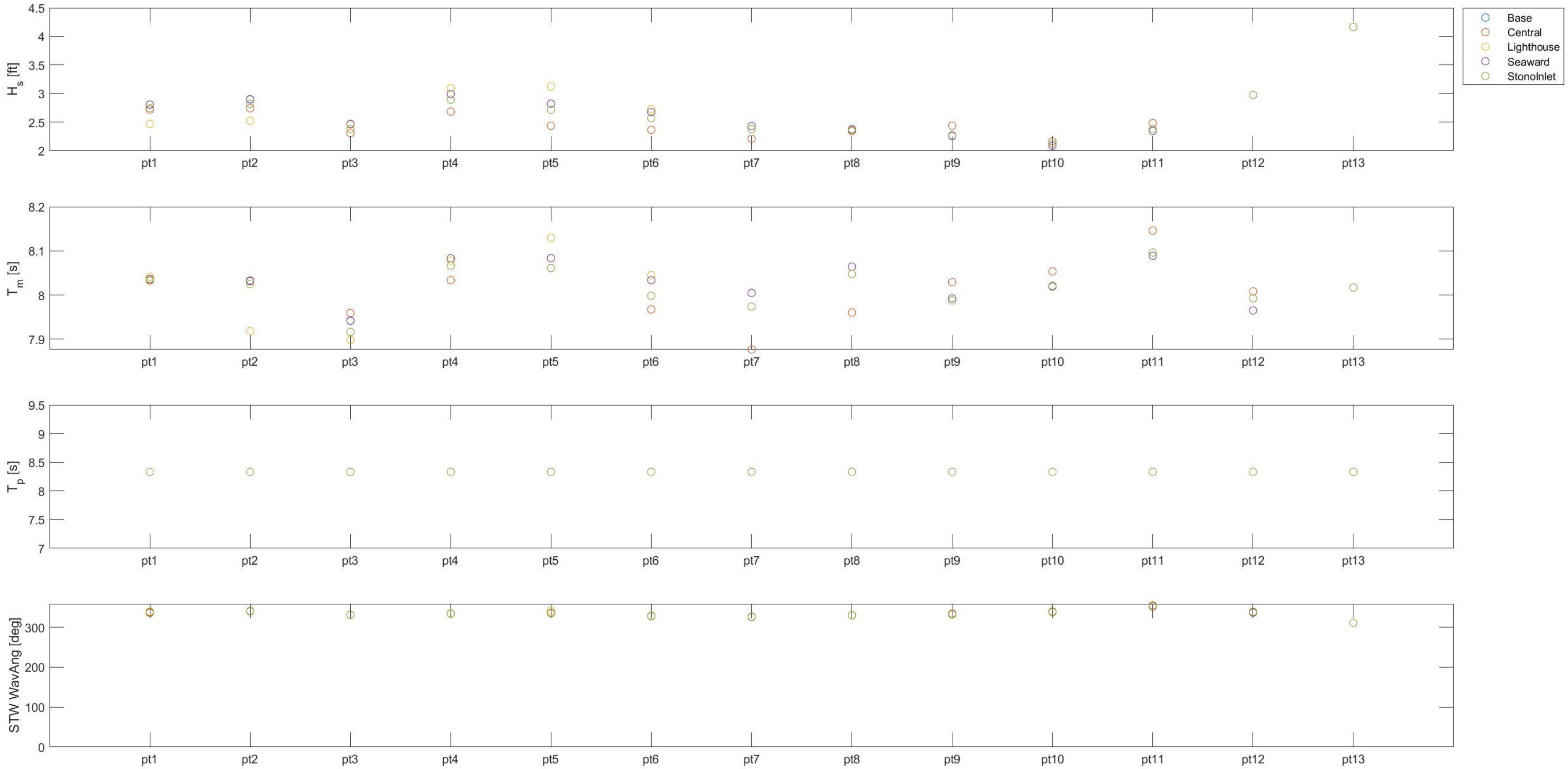
Mean Monthly- 115° Wave Direction



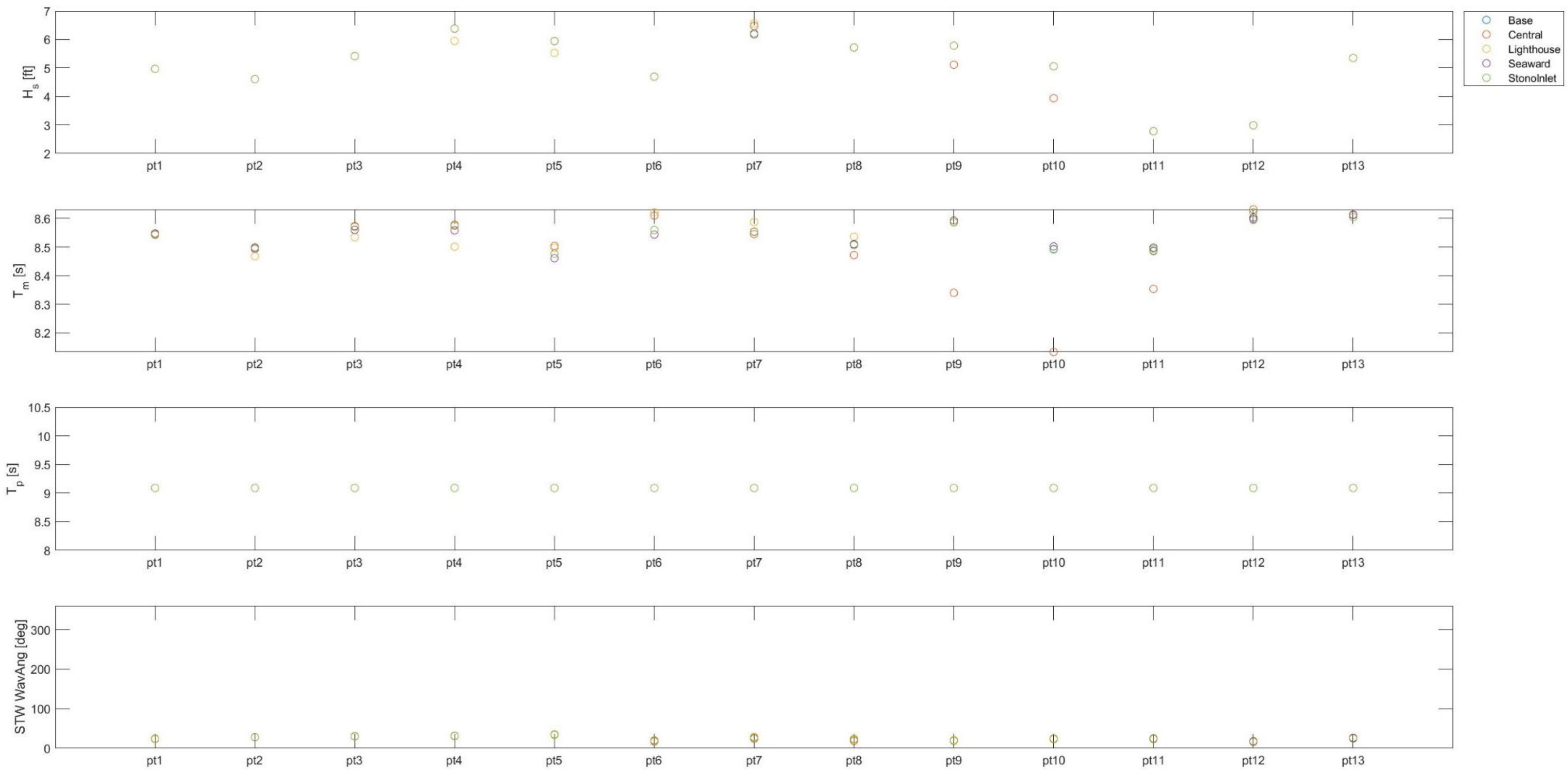
Mean Monthly- 170° Wave Direction



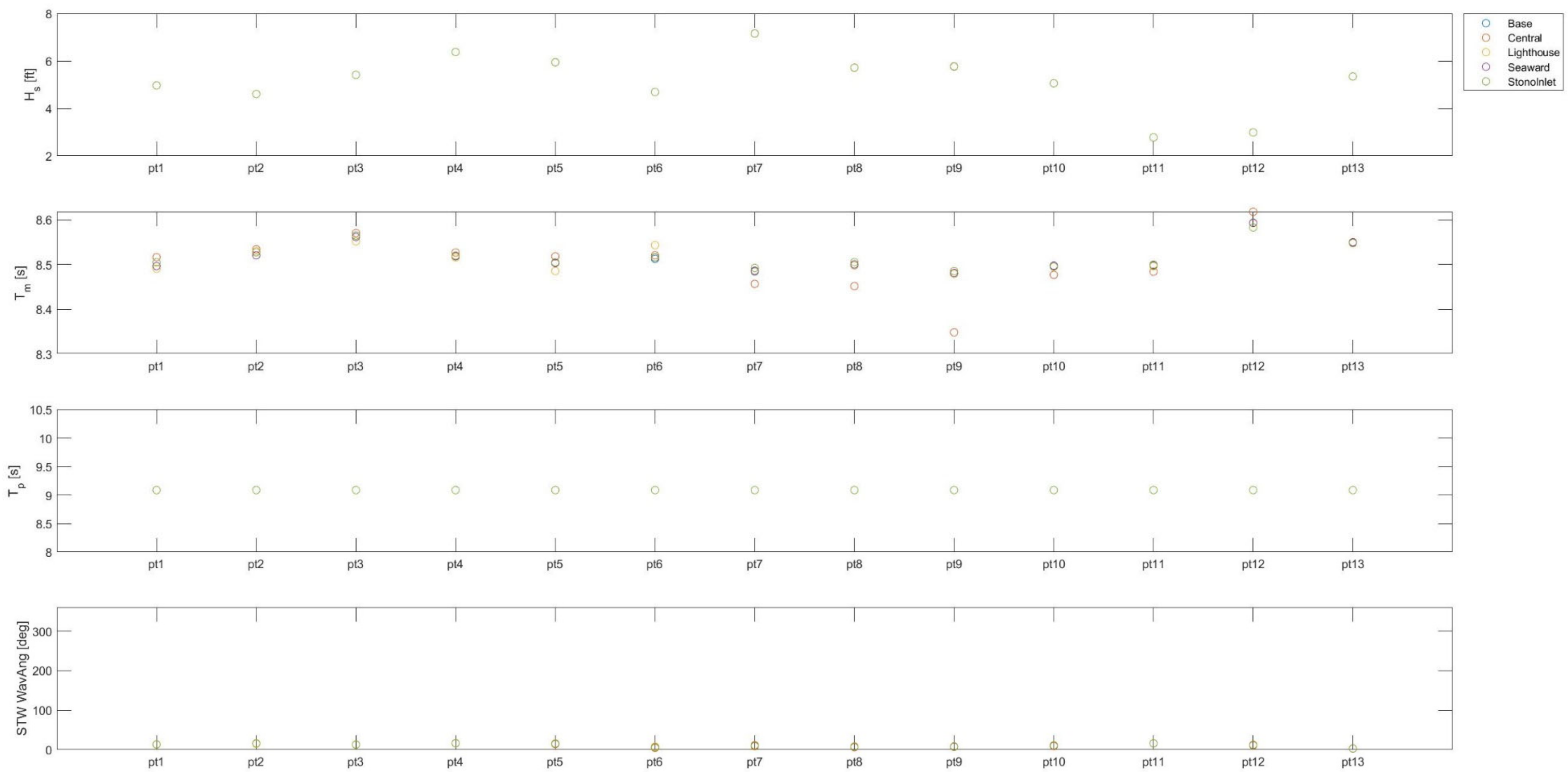
Mean Monthly- 225° Wave Direction



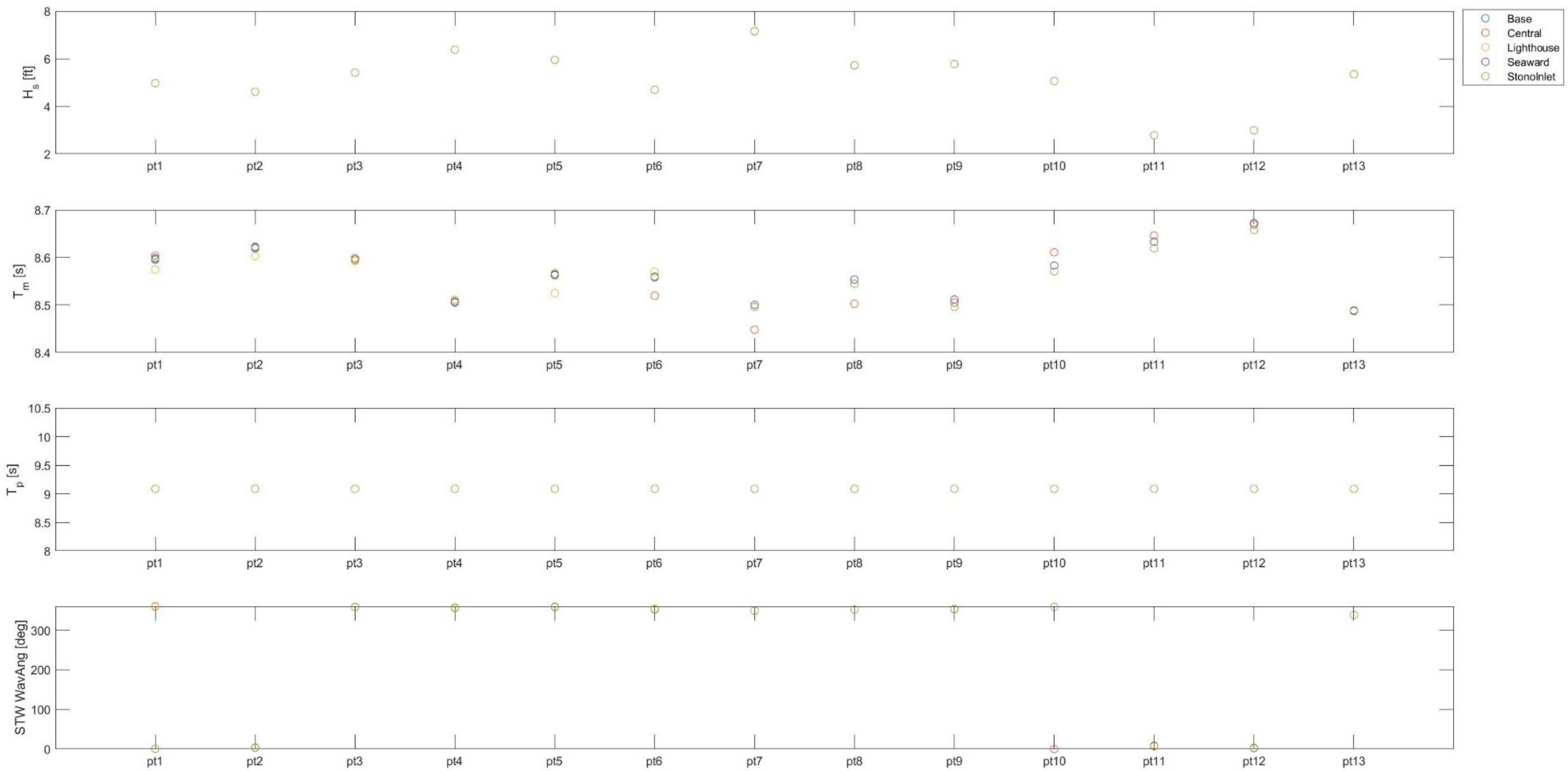
Max Monthly- 60° Wave Direction



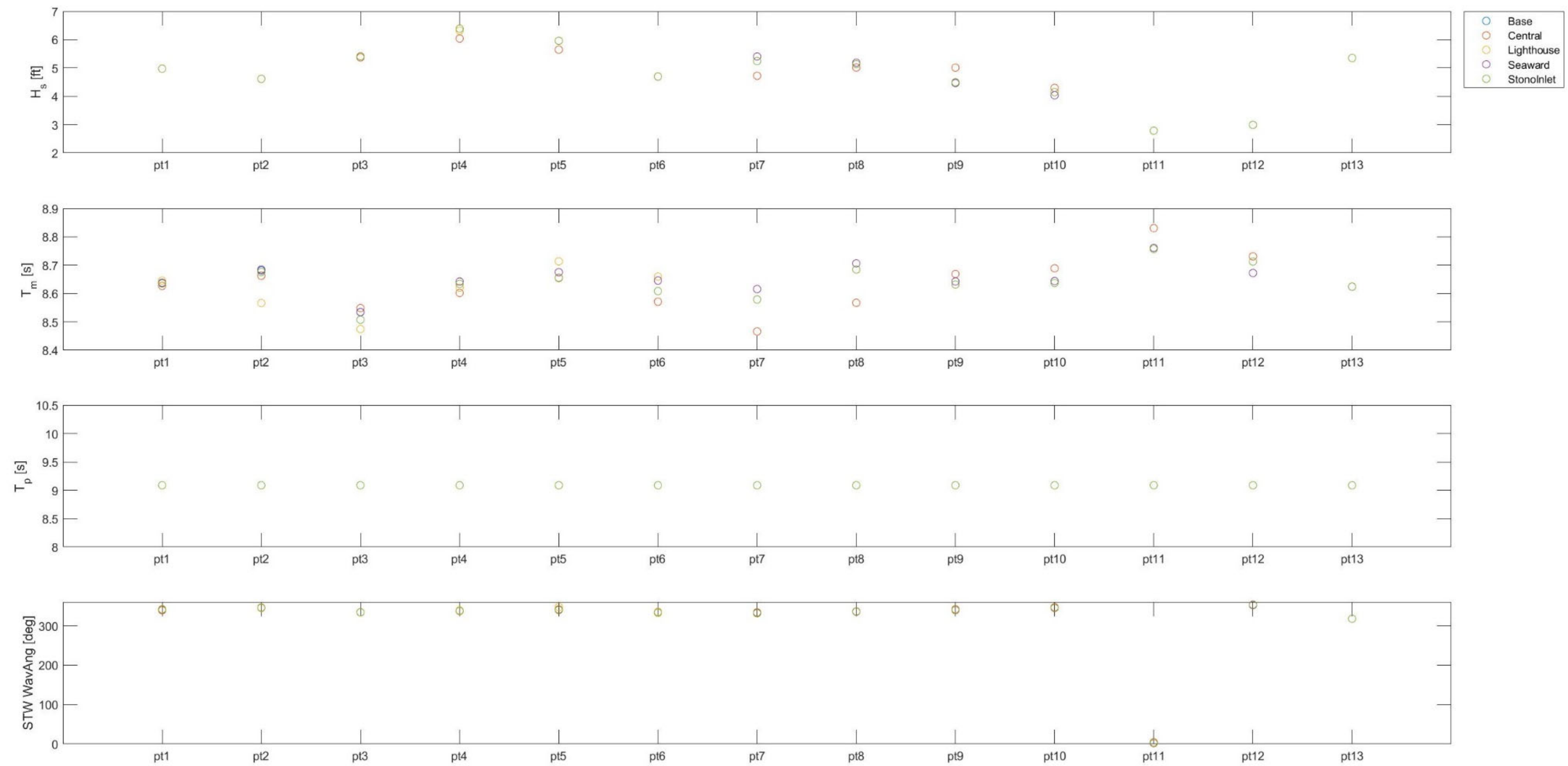
Max Monthly- 115° Wave Direction



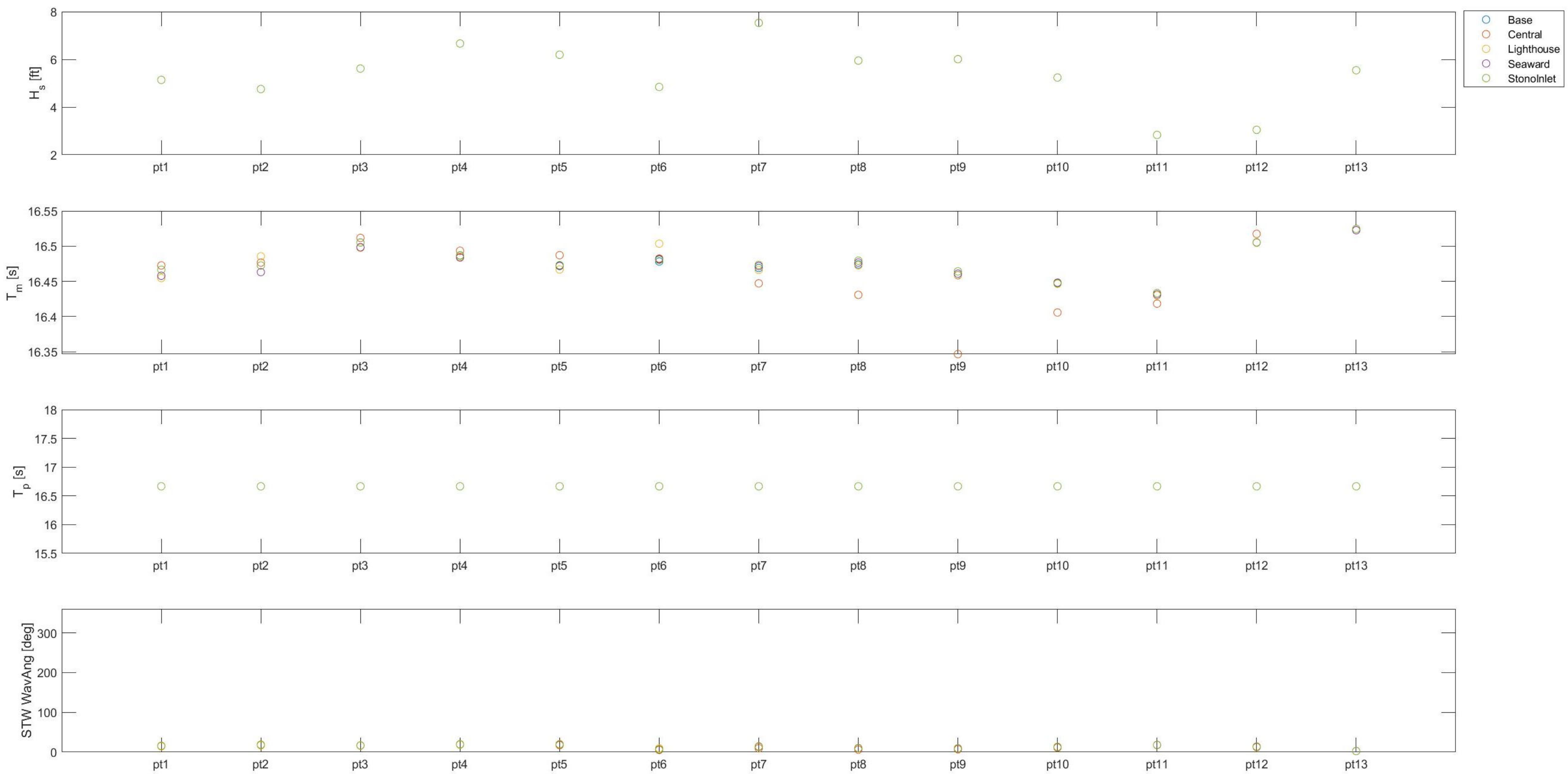
Max Monthly- 170° Wave Direction



Max Monthly- 225° Wave Direction



Extreme Even- 97° Wave Direction



Sub-Appendix D:

Folly Beach

Folly River Borrow Area Analysis

Folly River Borrow Area Refilling Rate.

A Folly River borrow area refilling rate was calculated for the May 2013 dredging.

Folly River surveys were collected in Q2 2014, Q4 2015, Q2 2017, and Q2 2018 on behalf of Charleston County Parks and Recreation Department (CCPRC). It is assumed that Q2 surveys were conducted in May and Q4 surveys were conducted in November. Material used in the 2103 Folly Beach nourishment is known to have been dredged from Folly River and was dredged in May of 2013, however no immediate post dredging survey was found so it is assumed that the 415,000 cy of material placed on the beach was removed immediately prior to the 2014 survey data in this analysis. The terminal groin was completed in June 2013 so this refilling rate is assumed to be appropriate for post groin construction refilling rates.

Using SMS 13.0.8, the borrow area was defined with 25 foot spaced points which was used to generate a Triangulated Irregular Network (TIN). Each of the surveys conducted was interpolated onto the TIN using inverse distance weighting creating a bottom surface depth. Figures 1-4 show the interpolated bottom surface depth TIN for surveys conducted from 2014 to 2018. In each image the full borrow area is shown in a magenta line, with the thicker black line overtop indicating the perimeter of the calculated TIN.

Figure 1: May 2014 bathymetric survey data with interpolated bottom surface TIN overlay.

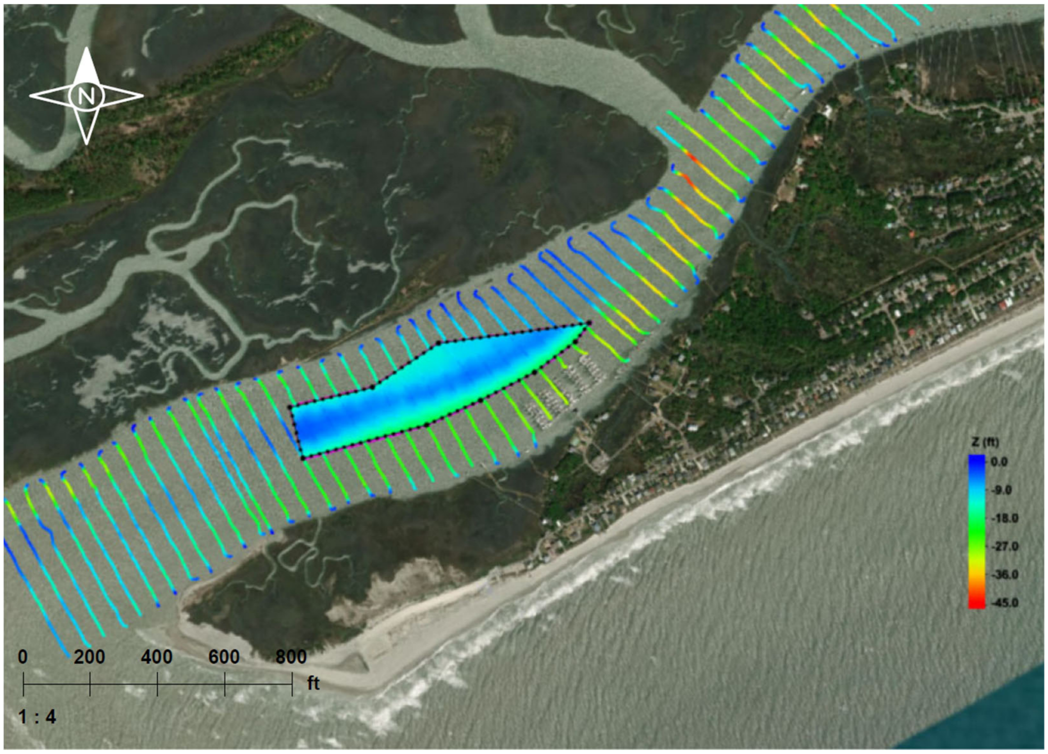


Figure 2: May 2015 bathymetric survey data with interpolated bottom surface TIN overlay.

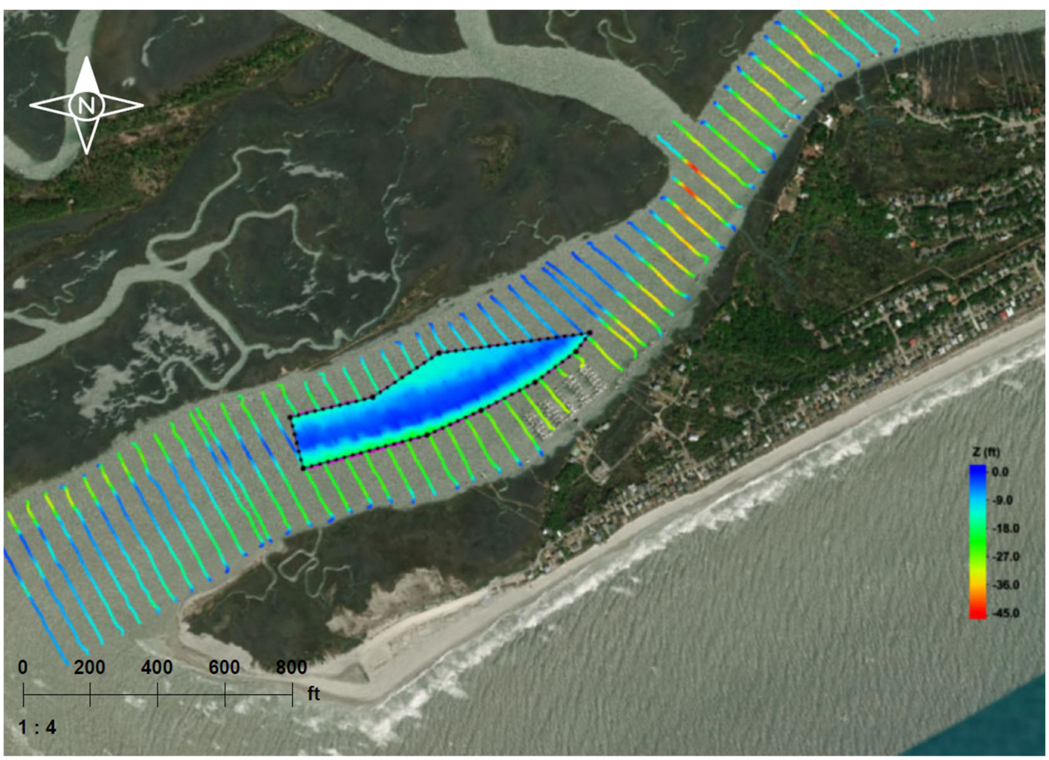


Figure 3: November 2017 bathymetric survey data with interpolated bottom surface TIN overlay.

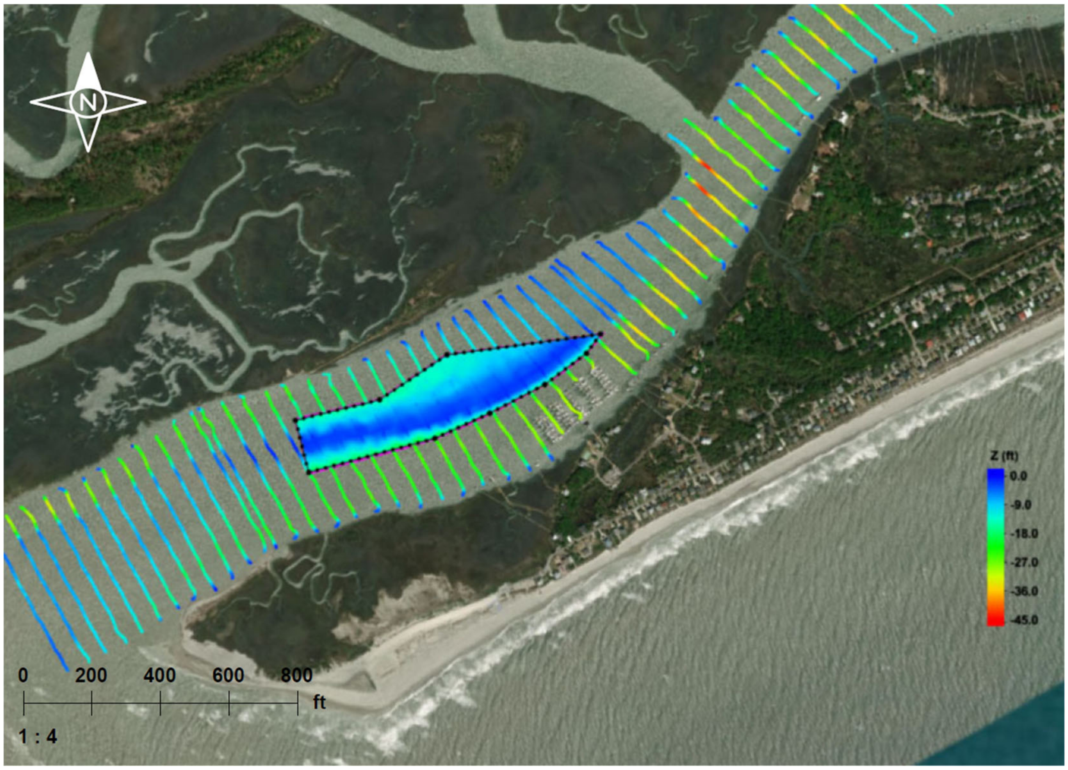


Figure 4: May 2018 bathymetric survey data with interpolated bottom surface TIN overlay.

Changes in the bottom surface elevation were compared from survey to survey to calculate volume change. Positive changes in water volume equate to sediment lost while negative changes in water volume equate to sediment gained. For each period between surveys the sediment volume deposited, sediment volume lost, net sediment volume change, and percent of original sediment loss replaced were calculated, shown in Table 1. Over the four year period the average refilling rate of this portion of the borrow area, assuming all material was taken from this area, was calculated to be 12.25%.

Table 1: Volume change analysis measuring sediment deposition within the inshore Folly River borrow area following dredging activities in May 2013.

	Time Periods Between Bathymetric Surveys				
	2014	2014-2015	2015-2017	2017-2018	Totals
Δt [yr]		1	2.5	0.5	4
Volume Deposited [cy]		116,698	106,538	51,350	274,586
Volume Lost [cy]		-16,478	-18,720	-35,959	-71,157
Net ΔV Calculated [cy]	-415,000**	100,220	87,818	15,391	203,429
% loss replaced		24.15%	21.16%	3.71%	49.02%

** Represents estimated volume of sediment removed based on sediment placed on the beach.

Volume of Sediment Still Missing [cy]:	211,571
Average % Original Loss Replaced/Year:	12.25%
Estimated Total Years to Replace:	8.2

Sub-Appendix E:

Stono Inlet, Folly River and Nearshore Folly Beach Hydrodynamic Analysis

study ongoing