ST. LUCIE COUNTY, FLORIDA

COASTAL STORM RISK MANAGEMENT PROJECT

FINAL INTEGRATED FEASIBILITY STUDY AND ENVIRONMENTAL ASSESSMENT

APPENDIX A
Engineering

US Army Corps
of Engineers
Jacksonville District

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1 Background

St. Lucie County is located on the south-central east coast of Florida (Figure 1-1). The county is bounded to the north by Indian River County and to the south by Martin County. St. Lucie County has approximately 22 miles of sandy shoreline located on a coastal barrier island that varies in width from approximately 400 feet to 1.5 miles. The St. Lucie County shoreline is subject to erosion caused by both tropical and extra-tropical storms as well as other natural shoreline processes. The purpose of this study is to assess the feasibility of providing Federal Coastal Storm Risk Management (CSRM) measures to the southern portion of the St. Lucie County shoreline.

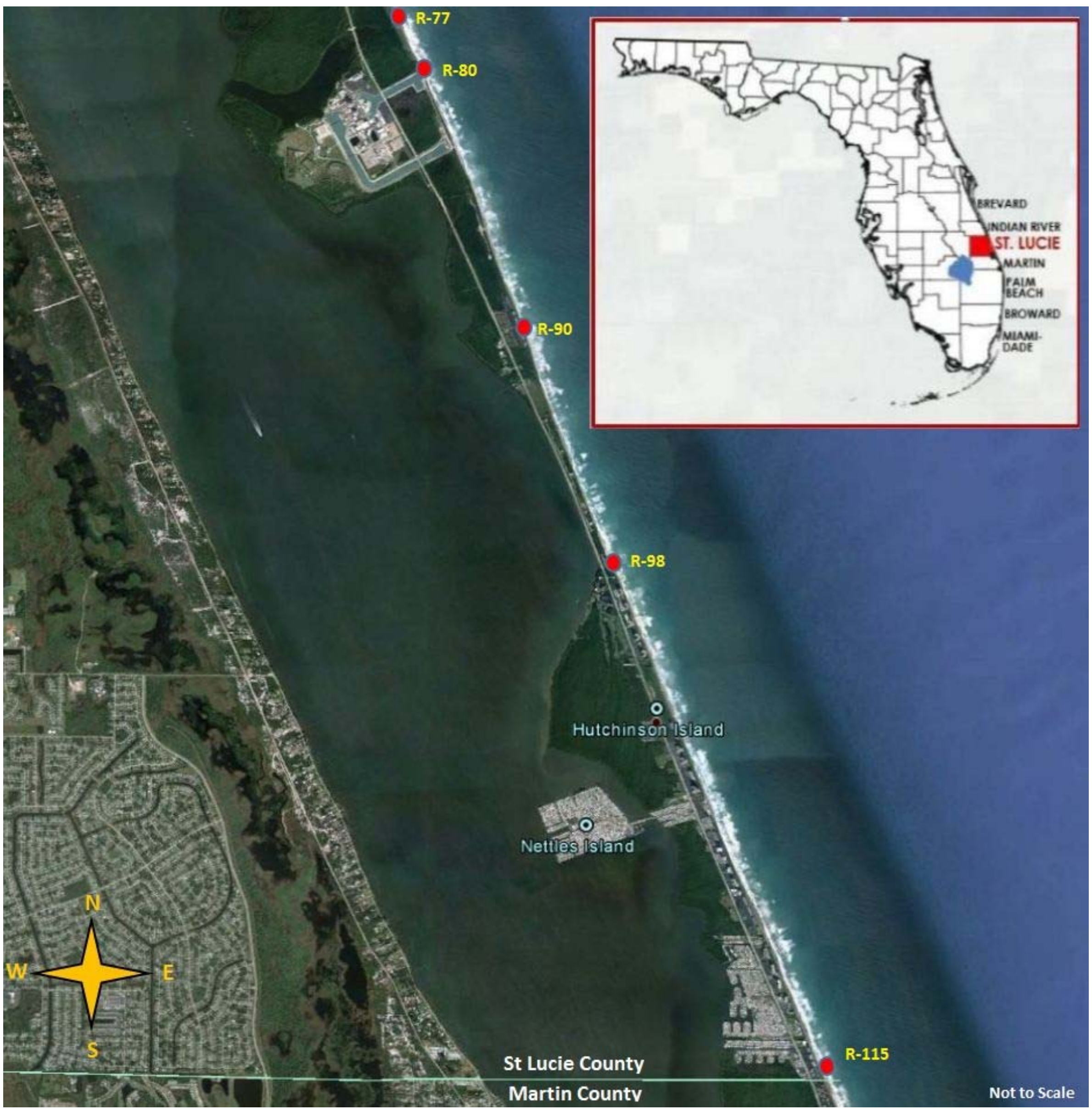

Figure 1-1. St. Lucie County Project Area

Four study reaches have been identified for St. Lucie County. The full study area extends from Florida Department of Environmental Protection (FDEP) Range Monuments R-77 to R-115 (Martin County Line) (Figure 1-1):

- North Hutchinson Island (NHI)– R-77 to R-80
- Power Plant Area (PP) – R-80 to R-90
- Narrows of Hutchinson Island (NH) – R-90 to R-98
- South Hutchinson Island (SHI) – R-98 to R-115

2 Problem Identification

In the past, beaches of St. Lucie County have generally experienced substantial erosion due to the combined effects of winds, waves, and tides. The objectives of this appendix include quantification of existing beach erosion problems in the southern portion of St. Lucie County and the design of corrective measures specific to that environment. Quantification efforts involve analysis of historical shoreline positions, estimation of longshore transport rates, and prediction of cross-shore losses of beach material due to storms. The results of those efforts serve as the basis for the design and analysis of various measures, which could be employed to reduce storm damage in the project area.

3 Natural Forces

3.1 Winds

Local winds in the project area are the primary means of generating the small-amplitude, short period waves which are the primary mechanisms of daily (non-storm related) sand transport along the south-central Florida shoreline. St. Lucie County lies near 27 degrees north latitude, at the northern boundary of the tropical trade wind zone. Winds in this region vary seasonally with prevailing winds from the northeast though the southeast. While winds from the east and southeast dominate during the winter, spring, and summer months, the greatest velocities originate from the east-northeast quadrant during the fall months (September through November).

Wind data offshore of the project area are available from the U.S. Army Corps of Engineers (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 and produces a 33-year record extending from 1980 through 2012, consisting of a time-series of wind and wave climate at 3-hour intervals for stations located along the east and west coasts of the US, as well as the Gulf of Mexico and Great Lakes. Model output includes significant wave height, peak and mean wave period, peak and mean wave direction, wind speed, and wind direction.

There are 523 WIS stations along the Atlantic Coast. WIS Station 452 (labeled 63452), located approximately 18 miles northeast of the study area (Figure 3-1) in 216 feet of water, is representative of offshore deep water wind and wave conditions for the project area. Table 3-1 provides a summary of WIS wind data and contains average wind speeds and frequency of occurrence, broken down into eight 45 degree angle-bands. This table indicates that winds are predominantly from the east and southeast. A wind rose presented in Figure 3-2 provides a further breakdown of winds in the project area.

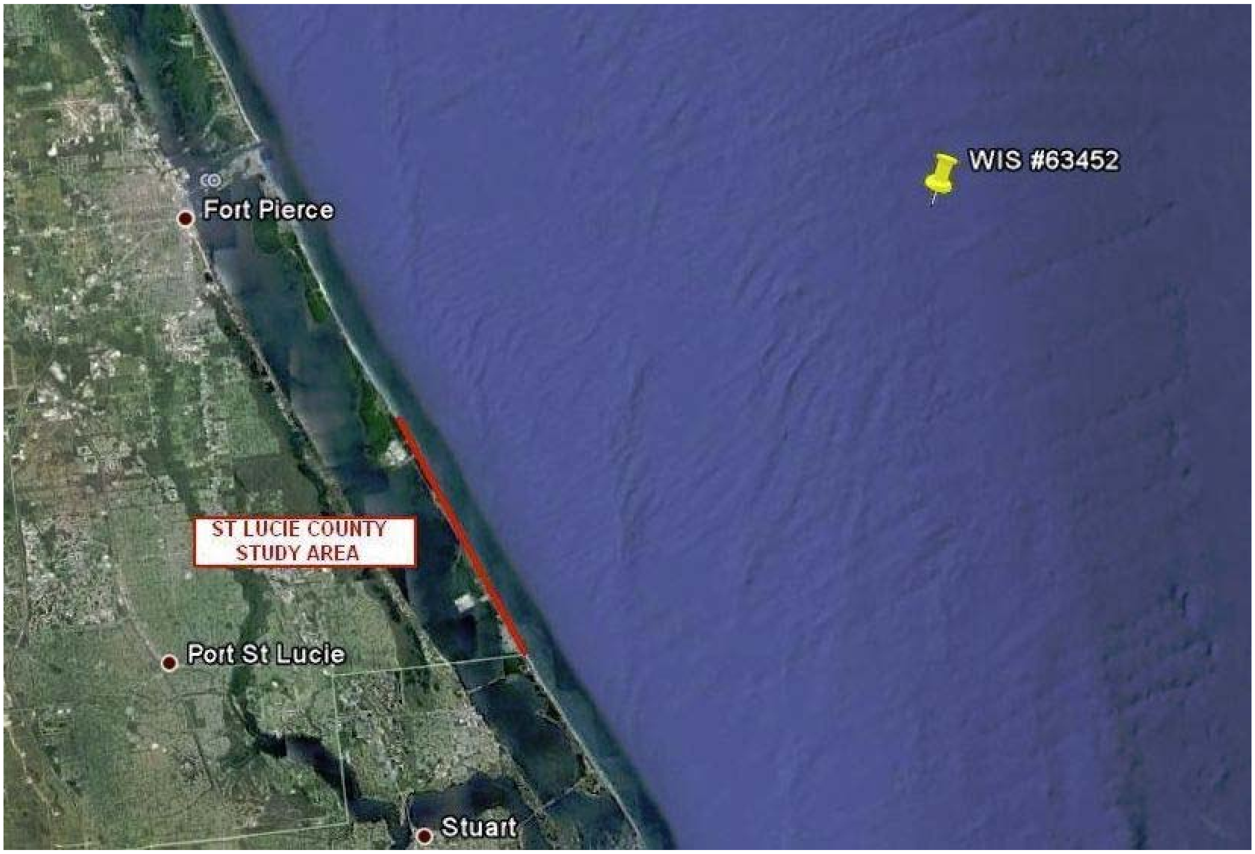

Figure 3-1. WIS Station #63452

Table 3-1. Average Wind Conditions

Wind Direction (from)	WIS Station #63452 (1980 – 2012)	
	Percentage Occurrence (%)	Average Wind Speed (mph)
North	9	14.8
Northeast	14	14.3
East	22	13.2
Southeast	19	11.9
South	14	12.1
Southwest	8	12.2
West	6	14.1
Northwest	8	16.1

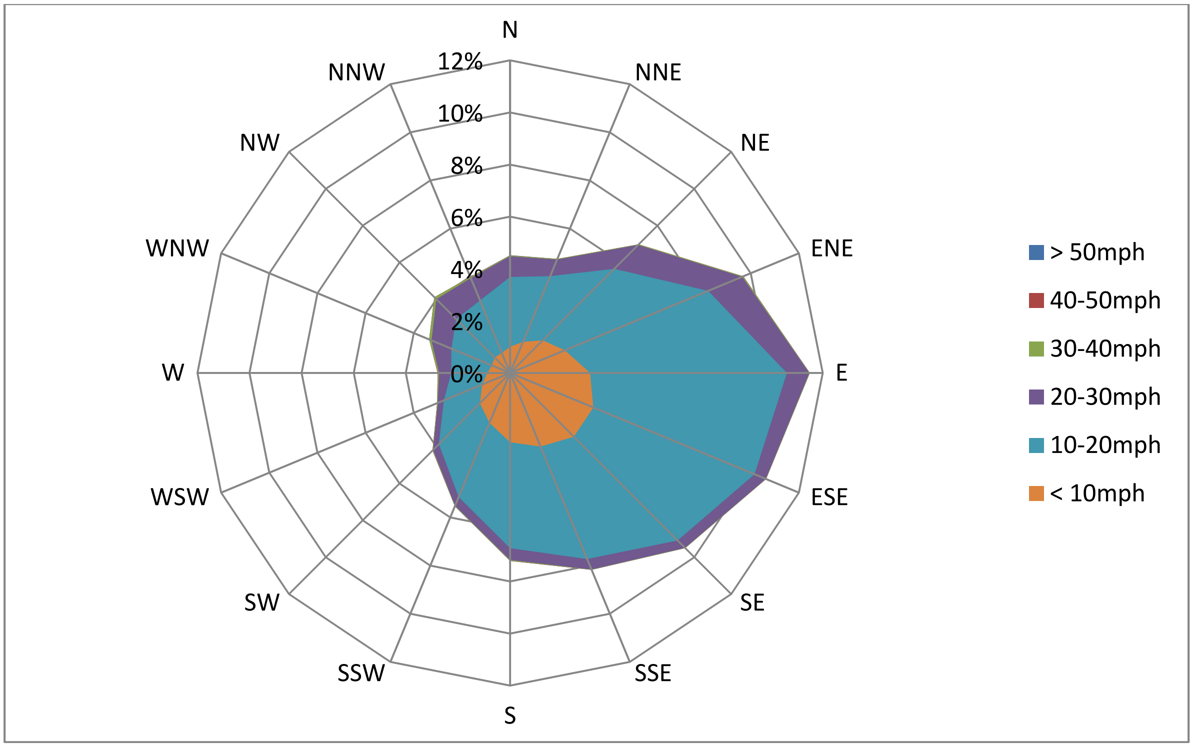

Figure 3-2. Wind Rose – WIS Station 63452

Due to the variability of wind conditions in South Florida through the year, a further breakdown of data provides a summary of seasonal conditions (Table 3-2).

In the fall and winter, frontal weather patterns driven by cold Arctic air masses can extend as far as South Florida. These fronts typically generate winds in the left-forward quadrant that rotate onto land from the northeast. This "Northeaster" behavior is responsible for the increased intensity of wind speed seen in the east and northeast sector winds during fall and winter months. Northeasters may result in wave conditions that can cause extensive beach erosion and shorefront damage.

Spring (March through May) is dominated by winds from the east. In the summer months (June through August) winds shift from east to predominantly southeast. This is partially due to trade winds and tropical weather systems traveling east to west in the lower latitudes. Additionally, daily breezes onshore and offshore result from differential heating of land and water masses. These diurnal winds typically blow perpendicular to the shoreline and have less magnitude than trade winds and Northeasters. Daily breezes can also account for the general shift to east/southeast winds during the summer months when Northeasters no longer dominate.

During the summer and fall months, tropical cyclones may develop into tropical storms and hurricanes, which can generate devastating winds, waves, and storm surge when the storm passes over or near the project area. These intense seasonal events will be discussed in greater detail in Section 3.4 (Storm Effects).

Table 3-2. Seasonal Wind Conditions

Month	WIS Station #63452 (1980 – 1999)	
	Average Wind Speed (mph)	Predominant Direction (from)
January	15.3	E
February	15.1	E
March	15.1	E
April	13.8	E
May	12.1	E
June	10.8	S
July	10.4	SE
August	10.4	SE
September	11.6	NE
October	14.1	NE
November	15.5	NE
December	15.3	E

3.2 Waves

The dissipation of energy as waves enter the nearshore zone and break is the principal driver for sediment transport. Wave height, period and direction, in combination with tides and storm surge, are the most important factors influencing the behavior of the project beach and dune system.

The St. Lucie County study area is exposed to open-ocean swells originating from north-northeast to just north of due east. Open-ocean swells originating from south of due east are blocked by two large shoals north and west of the Bahamas known as the Little Bahama Bank and the Great Bahama Bank, respectively (Figure 3-3). Water depths across the Bahama Banks average about 30 feet, so longer-period swells are reduced or eliminated by bottom friction or the presence of land masses as they traverse the Bank. The minimum fetch between the western edge of the Banks and the St. Lucie County study area is about 65 miles, which allows ample distance for the generation of shorter-period wind waves in the deep waters of the Florida Straits. During severe storm events such as hurricanes and tropical storms, high wind velocities can generate large, damaging waves over the relatively short distance between the Bahamas and Florida.

The project area experiences daily (non-storm related) sediment transport due to typical seasonal wave conditions. This results in variable, generally low level, rates of erosion and accretion dependent on incident wave direction and intensity. Prolonged periods of daily erosion can lead to the undermining of structures and roads over time. However, the main cause of damage to the St. Lucie County shoreline and upland development are the large storm waves which are produced primarily by tropical disturbances, including hurricanes, and by fall/winter "northeasters". St. Lucie County is located in an area of considerable hurricane activity, and hurricane impacts occur on a relatively frequent basis (see Section 3.4 - Storm Effects).

The study area is exposed to the open ocean toward the northeast. This orientation makes the coastline vulnerable to wave attack from distant storms as well seasonal conditions. Most hurricanes and tropical storms traversing northward through the Atlantic within several hundred miles of the east coast will produce large swells which are capable of causing erosion along the St. Lucie County shoreline.

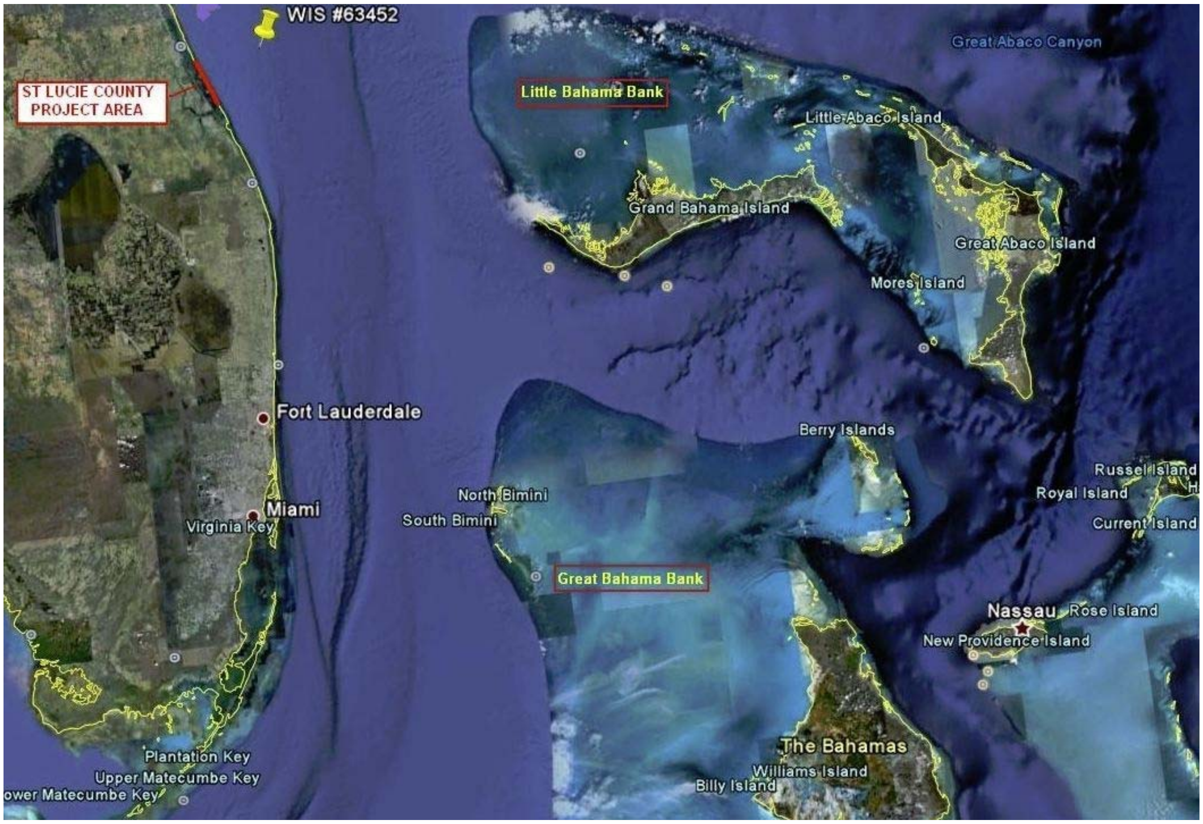

Figure 3-3. Little and Great Bahama Banks

Wave data for this report were also obtained from WIS hindcast at Station #63452. Table 3-3 summarizes the percentage of occurrence and average wave height of waves by direction for this dataset. Not surprisingly, the dominant wave direction is from the northeast and east. This reflects the blockage of open-ocean swell from the southeast quadrant. Higher average wave heights indicate the influence of northeastern activity during the winter months. This can be seen in greater detail in the wave rose presented in Figure 3-4.

Table 3-3. Average Deep Water Waves (1980 to 2012)

Wind Direction (from)	WIS Station #63452 (1980-2012)	
	Percentage Occurrence (%)	Average Wave Height (feet)
North	8	4.3
Northeast	43	4.3
East	38	2.9
Southeast	9	2.7
South	1	3.1
Southwest	0.3	2.8
West	0.2	3.1
Northwest	1	3.9

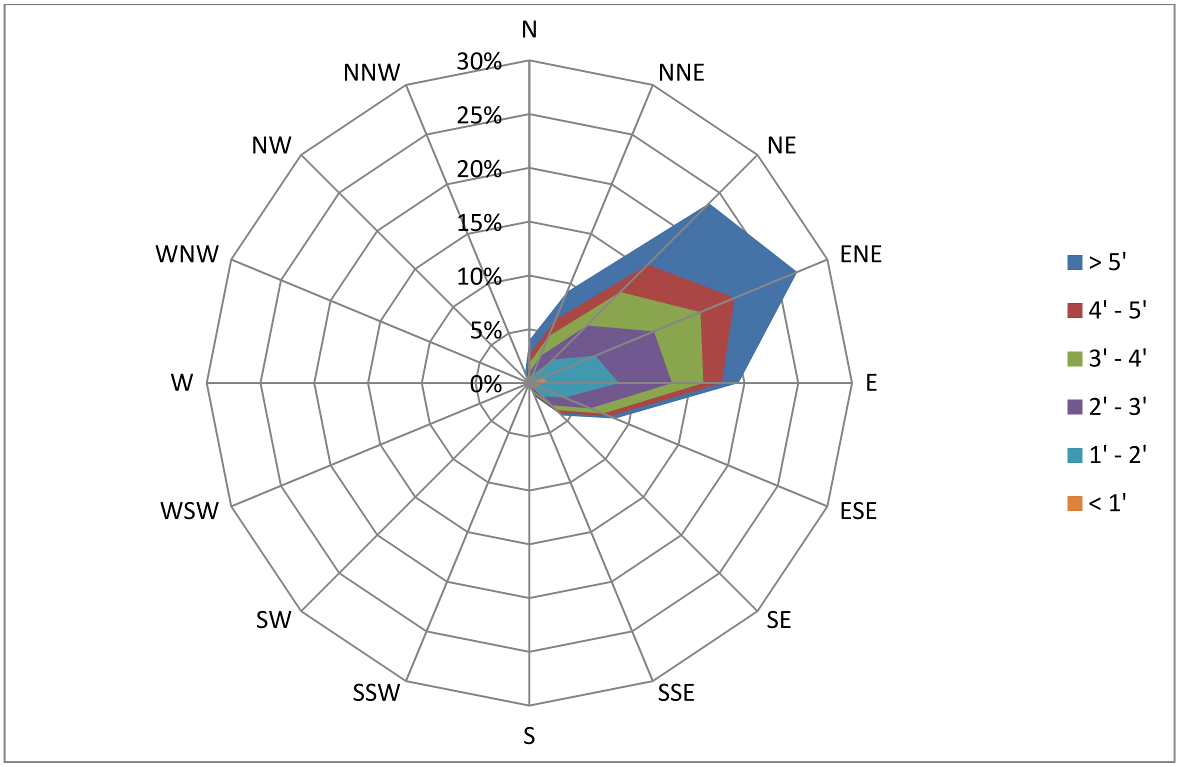

Figure 3-4. Wave Rose – WIS Station 63452

Similar to wind conditions, wave conditions in South Florida also experience seasonal variability. The seasonal breakdown of wave heights provided in Table 3-4 shows that fall and winter months have a marked increase in wave height due to Northeaster activity. The intensity and direction of these winter wave conditions are reflected in the dominant southward sediment transport and seasonal erosional patterns in the project area. Summer months, on the contrary, experience milder conditions, with smaller wave heights. Although again, waves are dominant from the northeast quadrant.

Table 3-4. Seasonal Wave Conditions

Month	WIS Station #63452 (1980-2012)	
	Average Wave Height (feet)	Predominant Direction (from)
January	4.21	NE
February	4.22	NE
March	4.37	NE
April	3.71	NE
May	3.13	NE
June	2.11	E
July	1.82	E
August	2.15	E
September	3.40	NE
October	4.69	NE
November	5.02	NE
December	4.49	NE

Wave periods have the same seasonality as wave heights. Table 3-5 provides a seasonal breakdown of percent occurrence by wave period. From this table, it can be seen that short period, locally-generated wind waves are common throughout the year. The yellow highlighted values show the dominant wave period for each month. None of these dominant periods are greater than 6.0 seconds. It can also be seen that in the summer months the shortest period waves occur more frequently. During the winter months a shifting towards more frequent higher-energy, longer-period storm swells occur. Note that the percentage of waves with period greater than 12.0 seconds increases from a low of 0.5% in July to a high of 7.2% in December.

Table 3-5. Wave Period – Percent Occurrence – WIS Station 63452

Wave Period	Percent Occurrence by Wave Period Band											
(Sec)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
< 4.0	11.9	12.9	11.6	17.0	21.3	34.8	53.1	41.9	16.8	5.2	8.2	10.4
4.0 - 4.9	30.5	26.9	28.3	28.1	28.6	22.2	18.4	18.3	21.9	18.3	22.6	25.4
5.0 - 5.9	28.5	33.3	30.4	27.9	23.5	18.8	9.5	16.7	23.9	34.5	31.7	33.6
6.0 - 6.9	6.5	6.1	6.8	5.4	3.3	4.8	2.6	4.7	6.2	8.9	8.8	5.9
7.0 - 7.9	3.9	2.9	3.8	2.9	2.3	3.9	3.9	5.3	3.9	6.4	4.9	2.9
8.0 - 8.9	2.6	2.2	2.4	2.2	3.7	3.0	4.2	2.8	4.0	5.2	4.9	2.4
9.0 - 9.9	3.5	4.2	3.0	3.7	5.1	4.8	3.7	2.3	5.2	6.4	5.4	3.8
10.0 - 10.9	3.3	4.1	3.7	3.6	4.7	4.3	2.6	2.6	4.5	6.0	4.3	5.1
11.0 - 11.9	3.3	4.0	4.2	4.2	4.5	2.8	1.6	2.3	6.4	3.8	3.6	3.4
> 12.0	6.1	3.4	5.9	5.0	3.1	0.9	0.5	3.1	7.2	5.5	5.7	7.2

3.3 Tides and Currents

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

Tides in the St. Lucie County area are semidiurnal: two high tides and two low tides per tidal day (24 hours 50 minutes). Two measures of tidal range are commonly used: the mean tide range is defined as the difference between Mean High Water (MHW) and Mean Low Water (MLW), and represents an average range during the entire lunar cycle (27.3 days). The range of tidal elevations between successive high and low tides is typically greater at any location during periods of a new or full moon. The spring tide range is the average semidiurnal range which occurs semimonthly when the moon is new or full.

Tide ranges are relatively low along the St. Lucie County region of Florida's east coast. The nearest tide station to the study area is NOAA Tide Station #8722212, located at the Ft. Pierce Inlet south jetty, about 12 miles north of the center of the study area. Table 3-6 presents the tidal datums computed from this station, referenced to MHW and North American Vertical Datum 1998 (NAVD88). The mean tide range at this station is found to be 2.56 feet and the spring tide range is 3.59 feet (based on 2010 averages).

Table 3-6. Tidal Datums

Tidal Datum	Elevation (feet relative to:)	
	MHW	NAVD88
Mean Higher-High Water (MHHW)	0.22	0.28
Mean High Water (MHW)	0.00	0.06
North American Vertical Datum 1998 (NAVD88)	-0.06	0.00
Mean Diurnal Tide Level (DTL)	-1.27	-1.21
Mean Tide Level (MTL)	-1.28	-1.22
Mean Sea Level (MSL)	-1.24	-1.18
Mean Low Water (MLW)	-2.56	-2.50
Mean Lower-Low Water (MLLW)	-2.76	-2.70

The primary ocean current in the project area is the Florida Gulf Stream. With the exception of intermittent local reversals, it flows northward. The average annual current velocity is approximately 28 miles per day, varying from an average monthly low of 17 miles per day in November to an average monthly high of approximately 37 miles per day in July. The Gulf Streams lies approximately 25 miles offshore of the project area.

The near-shore currents in the project vicinity are not directly influenced by the Gulf Stream, but may be influenced indirectly via interaction with incident waves. Littoral currents affect the supply and distribution of sediment on the sandy beaches of St. Lucie County. Longshore currents, induced by oblique wave energy, generally determine the long-term direction and magnitude of littoral transport. Cross-shore currents may have a more short term impact, but can result in both temporary and permanent erosion. The magnitude of these currents is determined by the wave characteristics, angle of waves from offshore, local tides, configuration of the beach and the nearshore profile. For St. Lucie County beaches, the net sediment transport is from north to south.

Influence of Ft. Pierce Inlet and St. Lucie Inlet ebb and flood currents on local currents is negligible. In both cases the distance between the inlet and the project area (8 miles and 7 miles, respectively) places the project outside the influence of inlet tidal fluctuations.

3.4 Storm Effects

The beaches of St. Lucie County are influenced by tropical systems during the summer and fall and by Northeasters during the winter and spring. Although hurricanes typically generate larger waves and storm surge, Northeasters often have a greater impact on the shoreline because of longer storm duration and greater frequency of occurrence.

Periodic and unpredictable hurricanes and coastal storms, with their energetic breaking waves and elevated water levels, can change the width and elevation of beaches and accelerate erosion. 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. After storms pass, gentle waves usually return sediment from the sand bars to the beach, which is restored gradually to its pre-storm configuration. While the beach profile typically recovers from storm energy impacts 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. This may cause a permanent increase in the rate of shoreline recession.

St. Lucie County is located in an area of considerable hurricane activity, resulting in relatively frequent hurricane impacts. Figure 3-5 shows historic tracks of hurricanes and tropical storms from 1851 to 2010, as recorded by the National Hurricane Center (NHC) and available from the National Oceanic and Atmospheric Administration. The circle in the center of this figure indicates a 50 mile radius from the center of the study area. Based on NHC records, 55 hurricanes and tropical storms have passed within this 50-mile radius over the 159-year period of record. Statistically, an average of one storm every 2.8 years.

The 50-mile radius was chosen for display purposes in Figure 3-5 because any tropical disturbance passing within this distance, even a weak tropical storm, would be likely to produce some damage along the shoreline. Stronger storms are capable of producing significant damage to the coastline from far greater distances. For example, Hurricane Andrew made landfall in southern Dade County in 1992 as a Category 5 storm. This storm produced significant coastal erosion along St. Lucie County, over 120 miles north of the storm track.

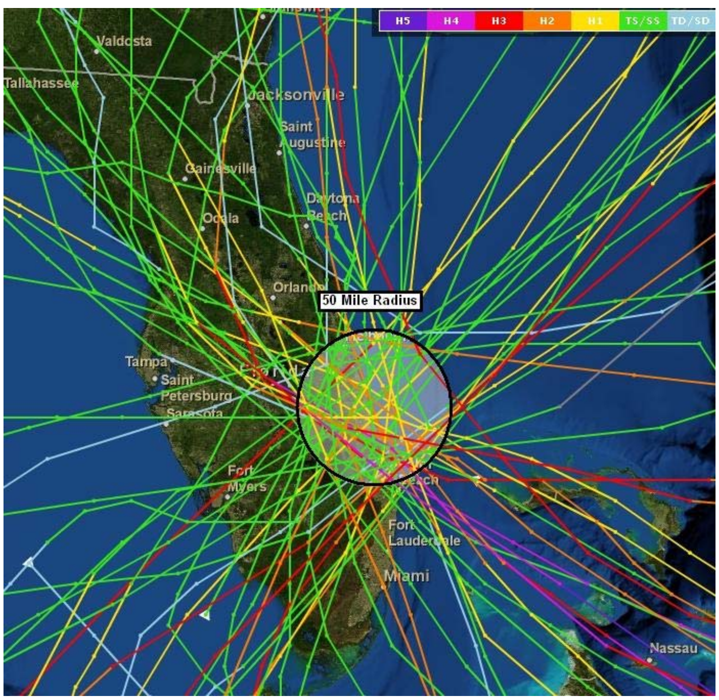

Figure 3-5. Historic storm tracks – Hurricanes and Tropical Storms (1851 – 2010)

In recent years, a number of named storms have significantly impacted the project area, including hurricanes Mitch (1998), Irene (1999), and Tropical Depression #4 (2000). However, the most severe storm events in recent years are due to the multiple storms of the 2004 and 2005 hurricane seasons. In August 2004 the study area was impacted by Hurricane Charley, followed by Hurricanes Frances, Jeanne, Ivan, and a strong Northeaster in September 2004. Of these storms, hurricanes Frances and Jeanne were considered to be 100-year storm events, and caused considerable erosion along this coastline. Hurricanes Frances and Jeanne made landfall only three weeks apart and within 2 miles of each other.

This season marked the first time that Florida (or any individual state) has been impacted by four hurricanes in one tropical season since weather records began in 1851. In 2005 the St. Lucie County area was again impacted, by Hurricanes Dennis (July), Katrina (August), Ophelia (September), Rita (September), and Wilma (October).

Damages to coastal projects from these combinations of storms in 2004 and 2005 included substantial erosion and damage from wind, wave, and water action beyond that which would ordinarily be expected by an individual storm. This is due, in part, to the fact that protective beach fill initially moved offshore by a storm did not have ample time to return onshore before the beach was impacted by the next storm. The large size of these hurricanes also contributed to damage levels along the St. Lucie County coastline as several storms inflicted damages far from their landfall points.
Since the study area is exposed to the open ocean toward the northeast, the coastline is vulnerable to wave attack from distant storms as well. Most hurricanes and tropical storms traversing northward through the Atlantic within several hundred miles of the east coast are capable of producing large swells which are capable of causing erosion along the St. Lucie County shoreline.

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. The combination of extremely high wind velocities coupled with low barometric pressures (such as those experienced in tropical storms, hurricanes, and very strong Northeasters) can produce very 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 a complete assessment of shoreline response and coastal storm risk. An increase in water depth may increase the potential for coastal flooding and allow larger waves to attack the shore.

The St. Lucie County CSRM study area is a low, flat barrier island that is particularly susceptible to overtopping from storm surges. Topographic surveys show that much of the island is less than 5 ft-NAVD88 in elevation. Maximum elevations of 10-15 ft-NAVD88 occur, but are almost exclusively along the oceanfront dune line. A series of hurricane storm-surge maps have been produced by the Florida Division of Emergency Management of all of Florida's coastal counties, and the map for St. Lucie County is shown in Figure 3-6. An examination of this map shows that virtually the entire study area would be inundated during even a Category 1 hurricane, and even the highest regions along the dune line would be flooded during a Category 3 storm. In the event of a hurricane, only three evacuation routes from the barrier island exist: the Highway (Hwy) A1A bridge near the south end of the barrier island (3 miles north of St. Lucie Inlet), the Hwy 732 bridge near the south end of the study area, and the Hwy A1A bridge at Ft. Pierce Inlet, at the north end of the barrier island. The only continuous road extending along the length of the barrier island is Hwy A1A, which is located landward of the dune line, generally at an elevation of 5 ft-NAVD88 or less.

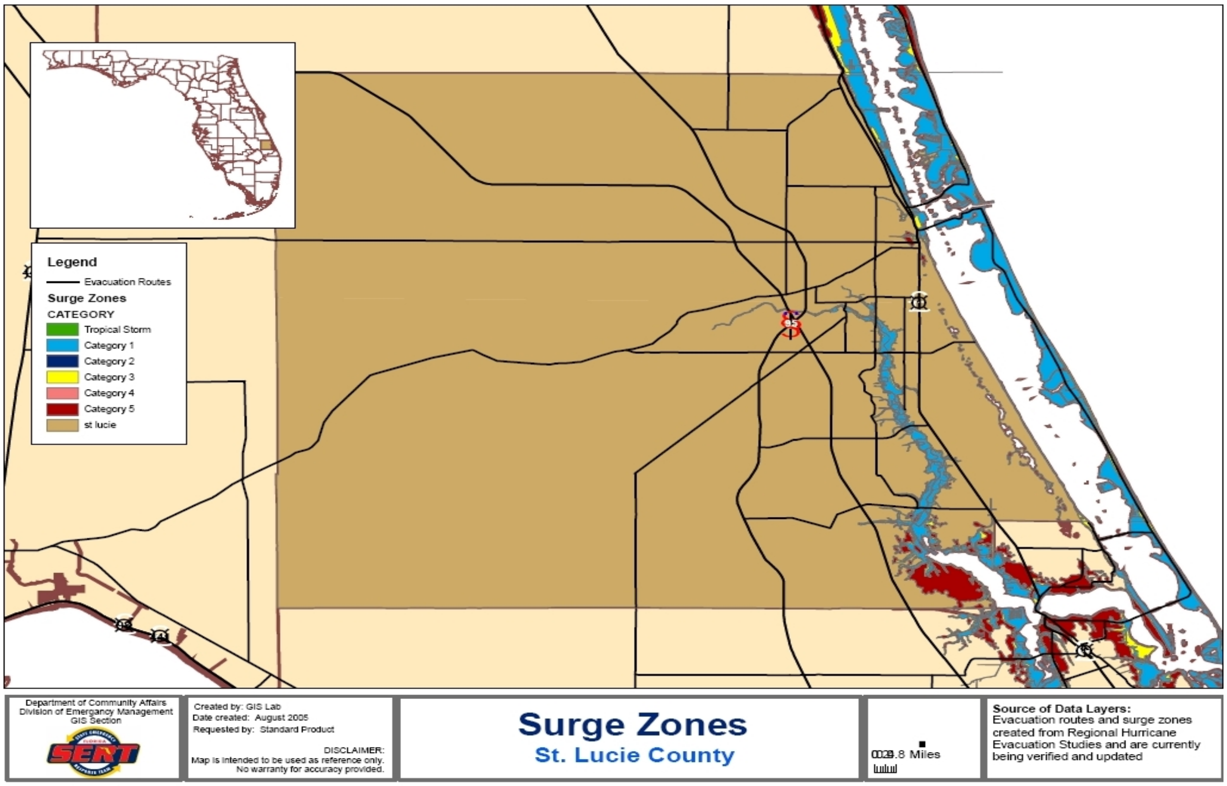

Figure 3-6. Storm Surge Zones, St. Lucie County (Florida Division of Emergency Management).

3.5 Sea Level Change

3.5.1 Relative Sea Level Change

Relative sea level (RSL) refers to local elevation of the sea with respect to land, including the lowering or rising of land through geologic processes such as subsidence and glacial rebound. It is anticipated that sea level will continue to rise over the life of the project, possibly at higher rates than presently measured. To incorporate the direct and indirect physical effects of projected future sea level change on design, construction, operation, and maintenance of coastal projects, the U.S. Army Corps of Engineers (USACE) has provided guidance in the form an Engineering Regulation, ER 1110-2-8162 (USACE, 2013).

ER 110-2-8162 provides both a methodology and a procedure for determining a range of sea level change 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 Baseline (or "Low") estimate representing the minimum expected sea level change, an Intermediate estimate (NRC Curve I), and a High estimate (NRC Curve III) representing the maximum expected sea level change. All three scenarios are based on the following eustatic sea level change equation:

$$E(t) = 0.0017t + bt^2$$

Where E(t) is the eustatic sea level change (in meters); t represents years, starting in 1992 (the midpoint of the current National Tidal Datum Epoch of 1983-2001), and b is a constant equal to 2.71E-5 (NRC Curve I), 7.00E-5 (NRC Curve II), and 1.13E-4 (NRC Curve III). This equation assumes a global mean sea level change rate of +1.7mm/year.

In order to estimate the eustatic sea level change over the life of the project, the eustatic sea level change equation is modified as follows:

$$E(t_2) - E(t_1) = 0.0017(t_2 - t_1) + b(t_2{}^2 - t_1{}^2)$$

Where t_1 is the time between the project's construction date and 1986 and t_2 is the time between the end of the project life and 1992. In order to estimate the required Baseline, Intermediate, and High Relative Sea Level (RSL) changes over the life of the project, the eustatic sea level change equation is further modified to include site specific sea level change as follows:

$$RSL(t_2) - RSL(t_1) = (e+M)\ (t_2 - t_1) + b(t_2^2 - t_1^2)$$

Where $RSL(t_1)$ and $RSL(t_2)$ are the total RSL at times t_1 and t_2, and the quantity ($e + M$) is the local sea level change in mm/year. Local sea level change accounts for the eustatic change (0.0017mm/year) as well as uplift or subsidence and is generally available from the nearest tide gage with a tidal record of at least 40 years. The constant b is equal to 0.0 (Baseline), 2.71E-5 (Intermediate), and 1.13E-4 (High).

The St. Lucie project area is located approximately 101 miles from the NOS gage #8723170 at Miami Beach, Florida, and approximately 132 miles from NOS gage #8721120 at Daytona Beach Shores, Florida. Due to the distance, the historic sea level change at St. Lucie was approximated by a linear interpolation between the Miami and Daytona gages. The historical relative, local sea level change rates *(e+M)* taken from NOS gage #8721120 at Daytona Beach Shores, Florida and NOS gage #8723170 at Miami Beach, Florida were determined to be 2.32 mm/year (0.0076 ft/year) and 2.39 mm/year (0.0078 ft/year), respectively. The resulting averaged historical sea level change rate for St. Lucie County then equals 2.36 mm/yr.

Given a project base year of 2020 and a project life of 50 years, a table of sea level change rates was produced for each of the three required scenarios.

Table 3-7 shows the sea level change rates in five year increments, starting from the base year of 2020. Figure 3-7 provides a graphic representation of the three levels of projected future sea level change for the life of the project.

The local rate of vertical land movement is found by subtracting regional MSL trend from local MSL trend. The regional mean sea level trend is assumed equal to the eustatic mean sea level trend of 1.7 mm/year. Therefore in St. Lucie County, there is 0.66 mm/year of local sea level change.

3.5.2 Beach Responses to Sea Level Change

Sea level change scenarios outlined in the preceding section can affect future shoreline behavior in the project area. On an open coast, sandy beach affects would be in the form of change in shoreline position and beach volume. Evaluation of affects are based on the assumption that sea level change would cause a change in the horizontal and vertical position of the beach profile. This phenomenon was first outlined by Per Bruun (1962). The theory states that an increase in water level causes the beach profile to shift upward and landward in response, in order to maintain an equilibrium shape. This shift causes both a shoreline change and a volumetric change as described in the following paragraphs. Additional information on incorporating sea level change into the evaluation of coastal flood management alternatives for St. Lucie County is provided in Section 5.3.2 - Applied Shoreline Change.

Table 3-7. Relative Sea Level vs Year-St. Lucie County

	Baseline (Historic)			Intermediate (Curve I)			High (Curve III)		
	Year	mm	ft	Year	mm	ft	Year	mm	ft
Base Year	2020	0.0	0.00	2020	0.00	0.00	2020	0.00	0.00
	2025	11.8	0.04	2025	18.8	0.06	2025	41.5	0.14
	2030	23.6	0.08	2030	38.9	0.13	2030	88.7	0.29
	2035	35.3	0.12	2035	60.4	0.20	2035	141.6	0.46
	2040	47.1	0.15	2040	83.3	0.27	2040	200.1	0.66
25 Year	2045	58.9	0.19	2045	107.5	0.35	2045	264.2	0.87
	2050	70.7	0.23	2050	133.0	0.44	2050	334.0	1.10
	2055	82.4	0.27	2055	159.9	0.52	2055	409.5	1.34
	2060	94.2	0.31	2060	188.2	0.62	2060	490.6	1.61
	2065	106.0	0.35	2065	217.8	0.71	2065	577.3	1.89
50 Year	2070	117.8	0.39	2070	248.8	0.82	2070	669.7	2.20

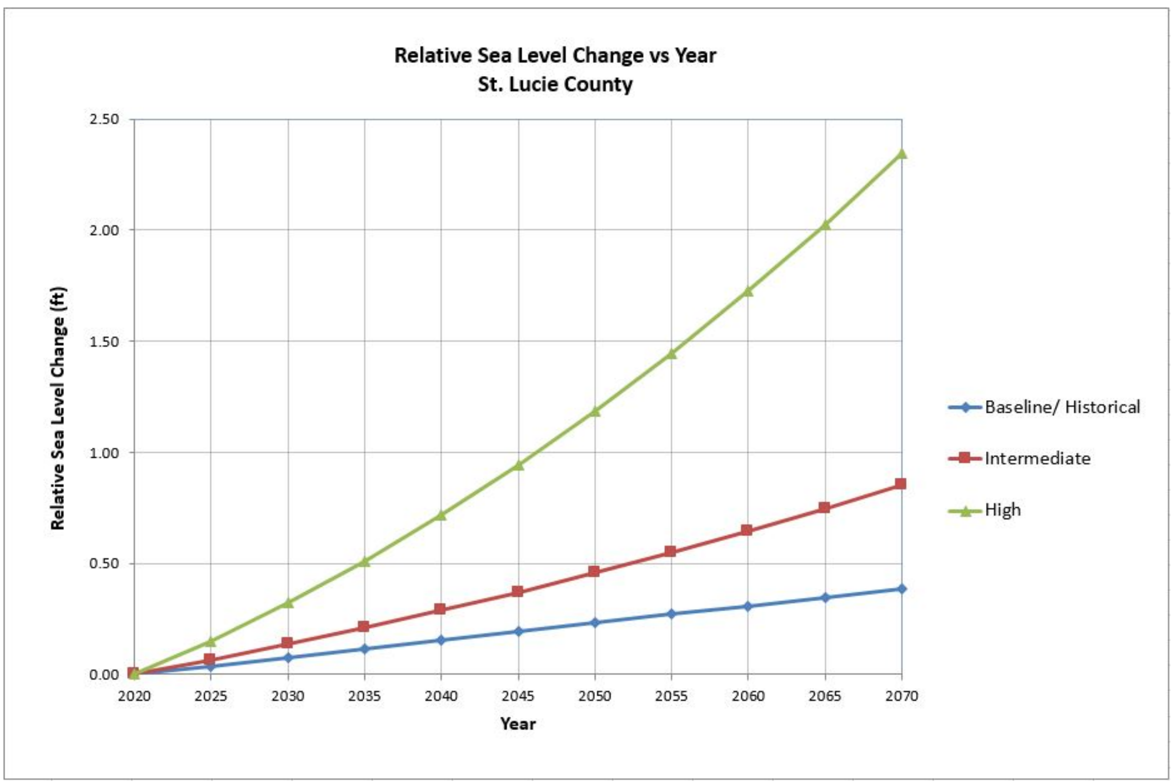

Figure 3-7. Relative Sea level Change, St. Lucie County

Shoreline Change

Per Bruun (1962) proposed a formula for estimating the rate of shoreline recession based on the local rate of sea level change. This methodology also includes consideration of the local topography and bathymetry. Bruun's approach assumes that with a change in sea level, the beach profile will attempt to reestablish the same bottom depths relative to the surface of the sea that existed prior to sea level change. That is, the natural profile will be translated upward and shoreward to maintain equilibrium. If the longshore littoral transport in and out of a given shoreline is equal, then the quantity of material required to re-establish the nearshore slope must be derived from erosion of the shore. Shoreline recession, X, resulting from sea level change can be estimated using Bruun's Rule, as defined below:

$$X = \frac{-SW_*}{(h_* + B)}$$

Where S is the rate of sea level change; B is the berm height (approximately 7.0 feet NAVD88); h_* is depth of closure (estimated to be -18.7 feet NAVD88); and W_* is the width of the active profile (approximately 1,800 feet).   Figure 3-8 provides the resulting shoreline recession versus year for each of the three sea level change scenarios.

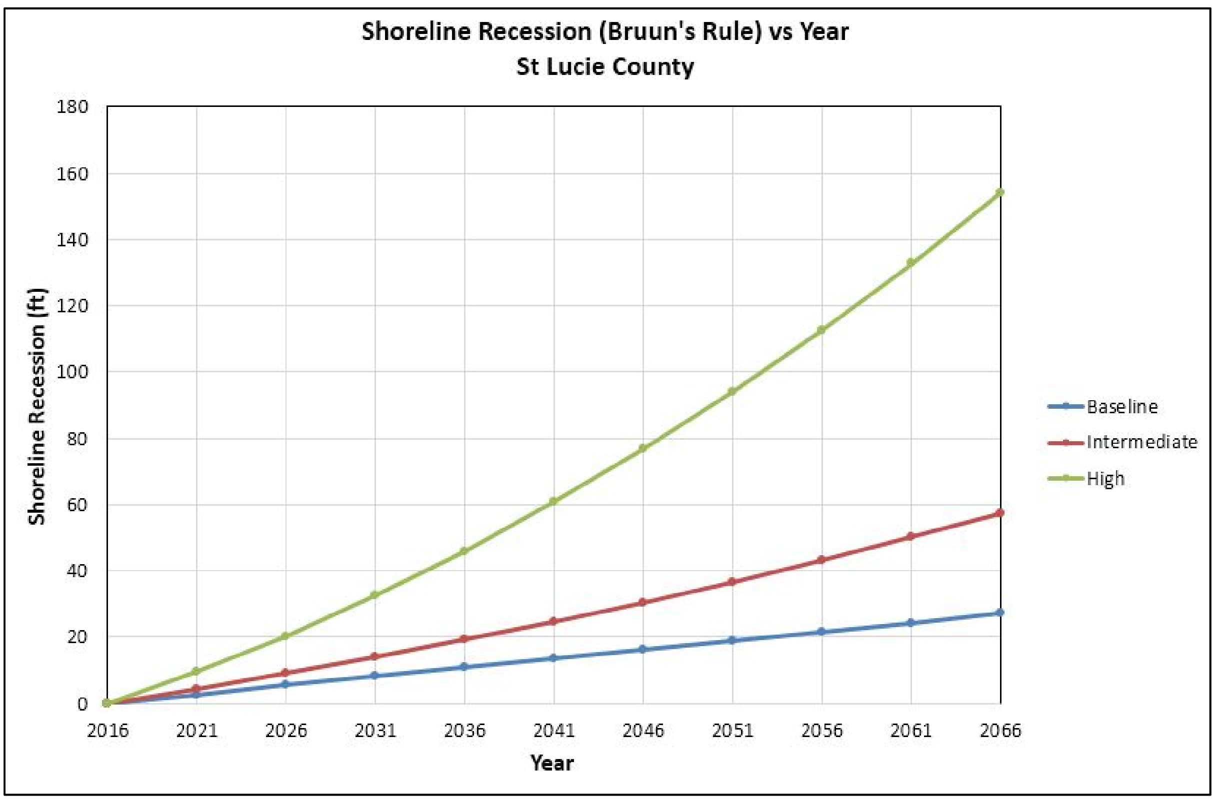

Figure 3-8. Shoreline Recession versus Year

The Bruun Rule is applicable to long straight sandy beaches with an uninterrupted supply of sand. Little is known about the rate at which profiles respond to changes in water level; therefore, this procedure should only be used for estimating long-term changes. The procedure is not a substitute for the analysis for historical shoreline and profile changes. If little or no historical data is available, then historical analysis may be supplemented by this method to provide an estimate of the long-term erosion rates attributable to sea level change. The offshore contours in the project area are not entirely straight and parallel; however, Bruun's Rule does provide an estimate of the potential shoreline changes within the project area attributable to a projected change in sea level.

Volumetric Change

Engineering Manual (EM) 1110-2-3301 (USACE, 1995) provides guidance on how to calculate beach volume based on berm height, depth of closure, and translation of the shoreline (in this case, shoreline recession). Assuming that as an unarmored beach erodes, it maintains approximately the same profile above the seaward limit of significant transport the volume can be determined as:

$$V = (B + h_*)X$$

Where B is the berm height, h* is the depth of closure, and X is the horizontal translation of the profile. Figure 3-9 provides the resulting volume lost versus year for each of the three sea level change scenarios.

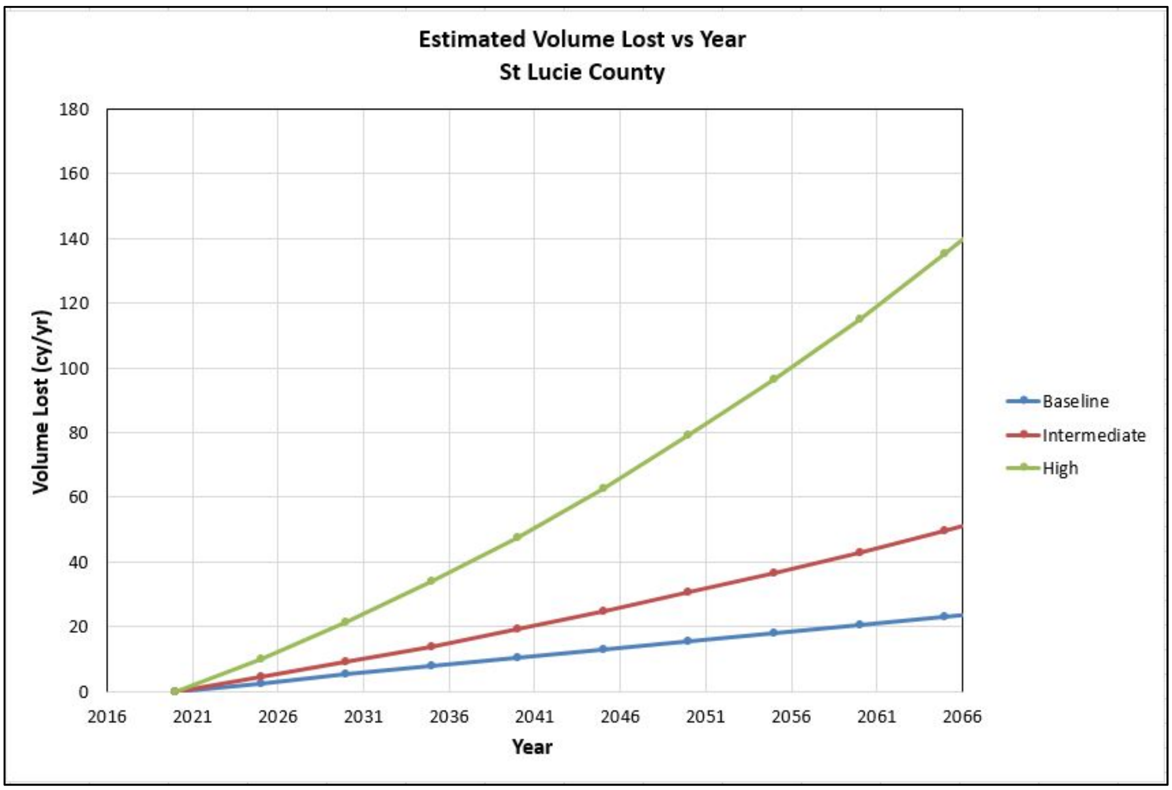

Figure 3-9. Volume Lost Versus Year

4 Historic Shoreline Change

Changes in mean high water (MHW) position provide a historical view of the behavior of the shoreline along the length of the study area (R-77 to R-115). A number of beach profiles (and more recently, LIDAR surveys) have been performed by the State of Florida Department of Environmental Protection (FDEP), the local sponsor, and the U.S. Army Corps of Engineers. Available beach surveys go back as far as 1882. However, the reliability of such historical profiles may be questionable. Based on a review of all available surveys, it was determined that profiles taken prior to 1970 would not be included in the MHW analysis.

MHW shoreline positions were measured at each FDEP survey monument (formerly known as a DNR monument) location, for each survey, along the proper azimuth (70 degrees, measured from north, clockwise). Resulting differences in MHW position, between available surveys, are tabulated in Table 4-1. Note that MHW position changes are only computed at locations of actual profile data; no interpolated profile data was used in this analysis.

Table 4-1. Mean High Water Shoreline Position Change

DNR	MHW Shoreline Position Change in Feet												
Monument	Jan70-Jan72	Jan72-Feb83	Feb83-Jun84	Jun84-Feb87	Feb87-Dec87	Dec87-Jan94	Jan94-Jul97	Jul97-Jun01	Jun01-Jul02	Jul02-May04	May04-Nov04	Nov04-Aug06	Aug06-Aug08
R- 77	4							16	-26	3	-111	55	8
R- 78	13	-11	26	-27	-6	-16	20	-6	-10	4	-94	47	39
R- 79	-20							-20	4	-6	-79	22	26
R- 80	20							-9	9	1	-90	21	26
R- 81	21	-2	14	-8			11	3	-6	15	-65	-6	29
R- 82	-1							15	-16	4	-62	8	19
R- 83	20							29	-35	14	-40	10	-4
R- 84	14	-42	29	11	-9	5	-1	17	-33	6	-36	21	-4
R- 85	32							20	-24	-9	-45	47	-12
R- 86	40							19	-21	-10	-30	29	-8
R- 87	65	-43	14	-1			28	-16	16	-5	-40	25	1
R- 88	41							9	2	-10	-24	8	8
R- 89	54						-16	13	-10	4	-17	2	8
R- 90	37	-20	-8	-8	1			18	-15	14	-26	6	7
R- 91	50							13	-3	7	-18	-8	9
R- 92	39							8	17	1	-27	-8	25
R- 93	55	-13	6	-4			3	7	11	23	-49	-9	29
R- 94	19							13	1	6	-34	-18	41
R- 95	15							2	1	-16	-38	14	32
R- 96	16	-8	-1	-31	3	4	-12	12	-6	-2	-29	8	22
R- 97	-18							-1	5	-7	-17	2	4
R- 98	7							-3	-12	10	-21	7	12
R- 99	10	5	-19	-8			-6	1	-28	10	0	4	-15
R-100	8							-14	-5	8	4	-3	-10
R-101	0							-13	2	-1	4	9	-9
R-102	8	9	-5	-8	11		4	-13	5	9	-11	10	-6
R-103	8							-5	3	2	-10	7	3
R-104	7							8	-3	-2	-6	18	2
R-105	-28	15	7	-3			27	-24	15	4	2	9	-4
R-106	-29							-11	-6	6	3	5	3
R-107	-31							-26	5	15	8	-30	15
R-108	-14				-11			-9	-6	9	19	-25	11
R-109	-41				-15	8	36	-22	-15	18	0	-15	15
R-110	-8							2	-7	-6	12	-12	6
R-111	8	-22	7	-21	5	2	-5	5	-1	-4	11	1	30
R-112	-27				-22			-51	37	24	-58	35	11
R-113	-14	-15			-37			-14	16	4	-38	40	6
R-114	-8			4	-7	5	17	-18	-13	13	-25	35	-4
R-115	0							-21	-9	12	-26	27	18
Average	10	-12	6	-9	-8	1	8	-2	-4	4	-28	10	10

In order to better interpret the shoreline change, the data was put into a graphical format as shown in Figure 4-1. Shoreline changes during each survey interval are shown on this graph. As seen in this figure, shoreline changes are highly variable over time along the study area. The only exception is during the survey interval, May 2004 through November 2004, which coincides with the highly active 2004 hurricane season. During this period, five storms impacted the study area: Hurricanes Charley, Frances, Jeanne, and Ivan, and the strong Northeaster of September 20. Of these storms, Hurricanes Frances and Jeanne had the strongest impacts, each making landfall near the study area as 100-year storm events. The cumulative erosion caused by these five major storm events is evident in the shoreline response between May 2004 and November 2004 as shown in Figure 4-1.

Figure 4-2 provides a summary of all measured shoreline changes (January 1970 to August 2008) as well as a summary of shoreline changes prior to the influences of 2004 hurricane season (January 1970 to May 2004). This figure shows the cumulative changes based on the data presented in Table 4-1. The erosive trend shown by the January 1970 to August 2008 line, particularly in the northern project area (R-77 to R-99) is due largely to the storms of the 2004 hurricane season as discussed above and indicates that recovery in this area has been relatively slow.

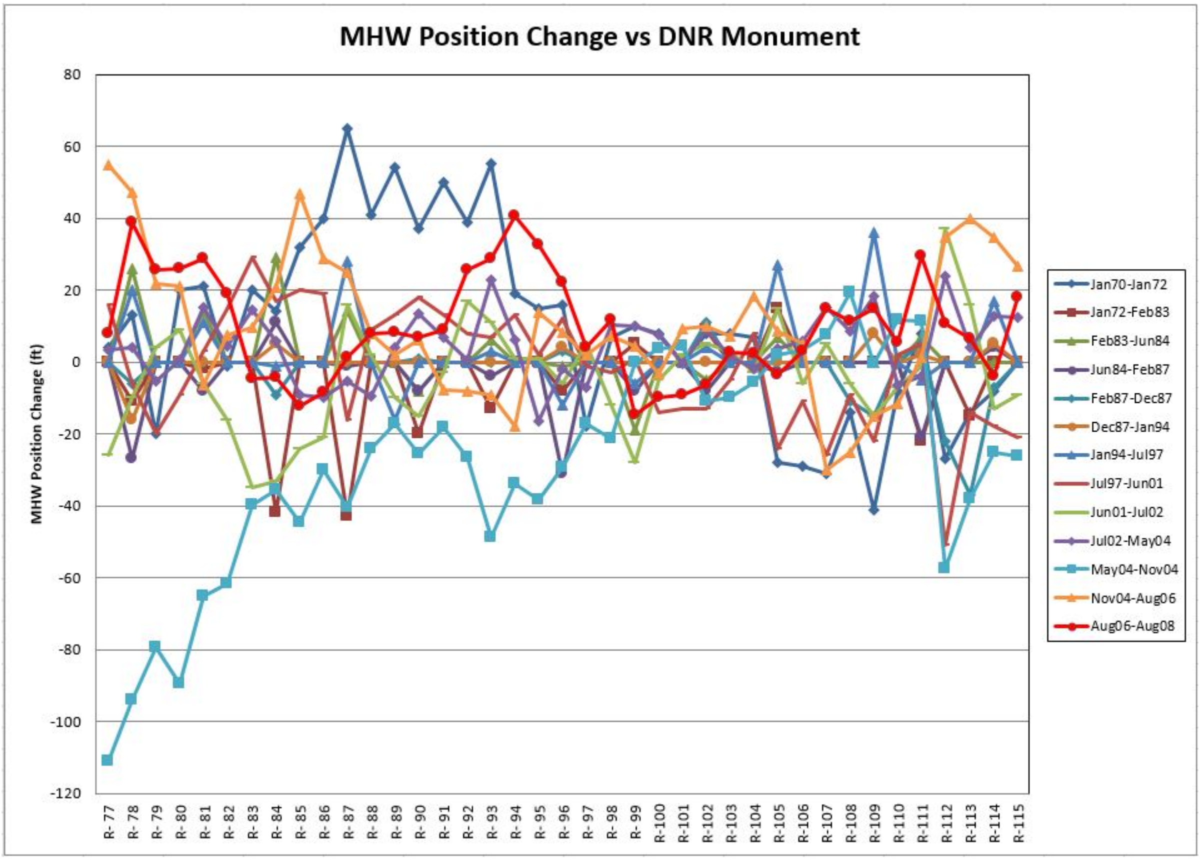

Figure 4-1. MHW Changes along St. Lucie County Study Area.

Due to a combination of geographic and natural factors, the St. Lucie County shoreline experiences regions of both erosion and accretion. Based on all available survey data (January 1970 to August 2008), the northern (less developed) portion of the project (R-77 to R-99) experiences an annual erosion rate of -0.31 feet per year, while the southern (significantly developed) portion of the project (R-100 to R-115) experiences an annual erosion rate of -0.18. The most developed, southernmost portion of the project which is not in the CBRA restricted zone (R-104 to R-115) has experienced an average annual erosion rate of -0.12 feet per year during this time period. Overall, the project area (R-77 to R-115), has an annual erosion rate of -0.26 feet per year.

Prior to the 2004 hurricane season, the northern and southern portions of the project experienced an average annual shoreline change rates of +0.18 feet per year and -0.36 feet per year, respectively. The southernmost portion of the project had an annual shoreline change rate of -0.38 feet per year for the same time period. The overall average annual erosion rate for the same time period was -0.04 feet per year. This indicates that prior to the impact of severe storms, the northern portion of the project experienced mild accretion while the southern portions of the project have been historically erosional.

Both the north and south portions of the project experienced dramatic erosion due to the 2004 and 2005 storm seasons. This has been followed by significant post-storm recovery.

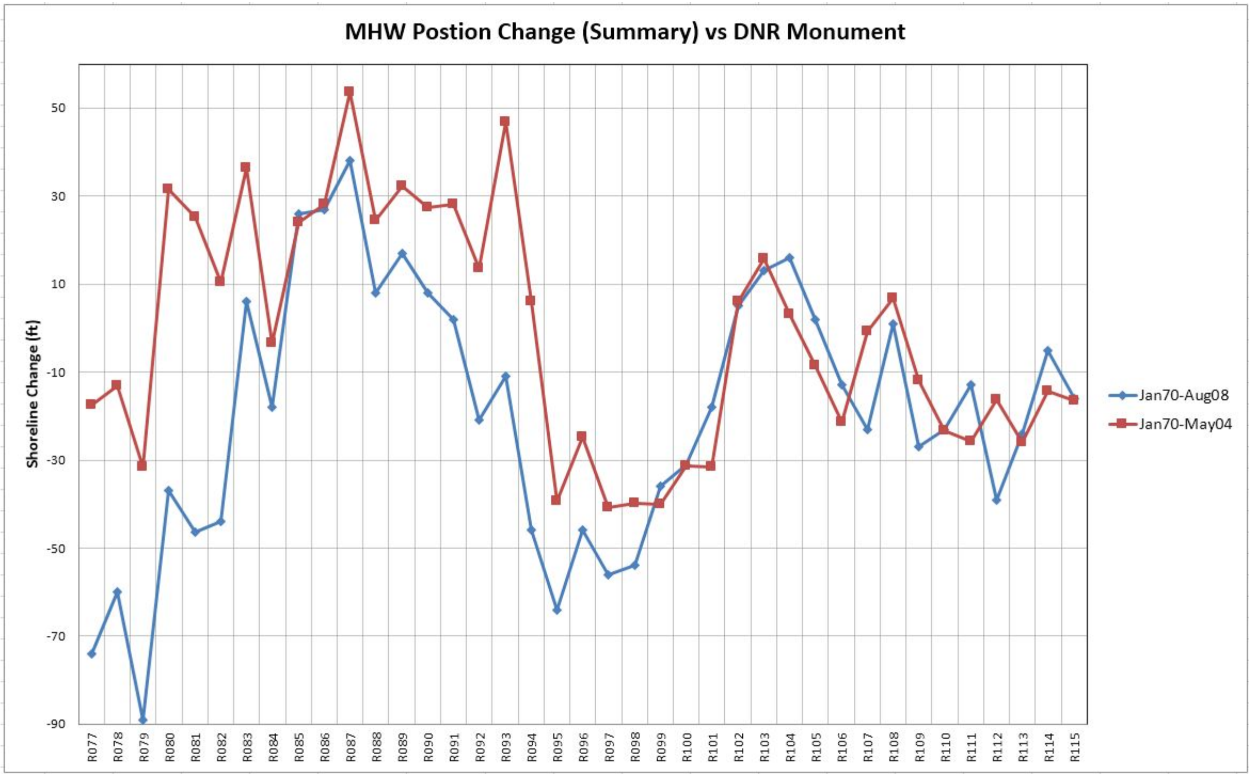

Figure 4-2. Summary of MHW Changes.

4.1 Effects of Other Shore Protection/Navigation Projects

4.1.1 General

To date, no large-scale Federal beach renourishment projects have been constructed along the study area (R-77 to R-115). However, several beach fill placements have been made on either side of the study area. To the north of the study area, several large-scale placements of material have been made under the authority of the Federal shore protection project at Ft. Pierce. Additionally, numerous placements of smaller volumes of material dredged from the Federal navigation project at Ft. Pierce Inlet have been made along this same reach of shoreline over the past 26 years. These two Federal projects result in the periodic placement of large volumes of material along the shoreline about 12 miles north of the study area of this report. Due to the predominant southward littoral transport of material along this region of coast, these fill placements may provide indirect nourishment of the study area. A detailed history of all beach fill placements completed under the authority of the Ft. Pierce SPP and the Ft. Pierce Inlet navigation project is provided in Sections 4.1.2 (Ft Pierce Shore Protection Project) and 4.1.3 (Ft Pierce Inlet).

South of the study area, the Martin County Shore Protection project extends from St. Lucie Inlet northward to the Martin County/St. Lucie County line, which is the southern limit of this study. Material placed along northern Martin County near the county line can be transported northward from the fill area by diffusion (end) losses, and may provide a source of nourishment along the southernmost reach of the St. Lucie County study area. A detailed history of all beach fill placements completed under the authority of the Martin County SPP is provided in Section 4.1.4 (Martin County Shore Protection Project).

In addition to the large-scale Federal projects at Ft. Pierce and Martin County, several small-scale shore protection projects have been implemented along the study area. In 1990, a beach-scraping project was performed along the southern reach of the project. Several privately-funded shore protection measures have also been constructed in front of individual properties. Each of these small-scale projects are described in Section 4.1.5 (Small Scale Shore Protection Projects).

4.1.2 Ft. Pierce Shore Protection Project

The Ft. Pierce SPP was authorized in 1965 and initial construction was completed, with the placement of 718,000 cubic yards of material from an offshore borrow site, in 1971. The initial fill extended from the south jetty at Ft. Pierce Inlet southward 1.3 miles to the southern boundary of Kimberly Bergalis Park (R-41). The first renourishment took place in 1980, with the placement of 346,000 cubic yards. Between first renourishment and 2014, eight additional renourishments (from offshore borrow sources) were completed (Taylor, 2008): 1999 (830,000 cubic yards), 2003 (336,000 cubic yards), 2004 (406,000 cubic yards), 2005 (616,000 cubic yards), 2007 (503,800 cubic yards), April-May 2009 (189,600 cubic yards), 2011 (480,200 cubic yards), and 2014 (290,100 cubic yards).

At the time of initial authorization, data indicated that the authorized project would require periodic nourishment at intervals of about five years. Based on performance, however, the renourishment interval was re-authorized to two years. Presently, design alternatives are being considered that would extend the renourishment interval to four years. Based on the data presented above, a total of 4,716,000 cubic yards of offshore borrow material have been placed over the 43-year period from 1971 to 2007. Based on this data the average actual renourishment rate (from offshore sources) has been approximately 110,000 cubic yards per year.

4.1.3 Ft. Pierce Inlet

Ft. Pierce Inlet is a deep-draft navigation channel located near survey monument R-34, approximately 8 miles north of the north end of the study area. Maintenance dredging of this Federal project occurs once every two years on average. Any beach-compatible material is typically placed south of the inlet, within the limits of the Ft. Pierce SPP, supplementing the Ft. Pierce SPP renourishment events. Seven placements of channel material were made between 1971 and 2007 (Table 4-2) (Taylor, 2008). Between 2007 and 2013, no maintenance material was placed on Ft. Pierce Beach. In July 2014, one additional placement was made, 431,000 cubic yards from the Federal Navigation Project.

Including the supplemental beach material added from maintenance dredging of the Ft. Pierce Inlet and two emergency truck haul fill events (14,400 cubic yards in 1993 and 54,400 cubic yards in 1995), a total of 4,204,900 cubic yards of material was placed at Ft. Pierce between 1971 and 2007. This equates to an average total renourishment rate of 116,800 cubic yards per year.

Table 4-2. Beach Placement of Ft. Pierce Inlet Dredge Material

Date	Volume (cubic yards)
July 1978	49,800
December 1987	29,800
January 1989	47,800
March 1990	55,700
November 1993	7,200
January 1995	166,700
January 1998	23,300

4.1.4 Martin County Shore Protection Project

The Martin County Shore Protection Project was authorized in 1990. Initial construction of the project was performed between December 1995 and April 1996, with the placement of 1.34 million cubic yards of fill extending from survey monuments R-1 (St. Lucie/Martin County line) southward to R-25, a distance of 4.0 miles. The source of fill was a borrow site offshore of the Stuart public beach. The first nourishment of the project was performed in 2001, with the placement of 178,000 cubic yards along the southern half of the project only (R-16.2 – R-22.3). Since that time, there have been three additional renourishment events. 126,000 cubic yards of material were placed in 2002, 895,000 cubic yards were placed in 2005, and 613,000 cubic yards were placed in 2013.

4.1.5 Additional Shore Protection Projects

Walton Rocks, St. Lucie County R80-R90.3: This 1.9 mile segment of shoreline in southern St. Lucie County includes St. Lucie Nuclear Power Plant facilities, Walton Rocks Bounty Park, and private condominium developments. This area was severely impacted by Hurricanes Frances and Jeanne in 2004. In 2007, dune restoration was conducted from R88 to R90 in the stretch of beach known as Sand Dollar Shores. This restoration included 1,900 linear feet of dune, using 15,000 tons of sand trucked in from an upland borrow site (EAI, 2009).

South St. Lucie County Beaches, R98-R115+1000 (County Line): This 3.4 mile segment of shoreline in southern St. Lucie County includes predominantly private residential condominium developments. This area was severely impacted by Hurricane Irene (1999) and Hurricanes Frances and Jean (2004). In 2005 and 2006, a locally funded dune restoration project was constructed from R97.7 to R114 using 160,000 cubic yards of sand. The dune project was impacted by Hurricane Sandy. Storm repairs, in conjunction with a locally sponsored, full beach restoration project were completed in May 2013. The project placed 635,000 cubic yards of sand from R98 to the south county line (R115 + 1000'). (FDEP, 2015).

4.1.6 Inlet Effects

Ft. Pierce Inlet

Ft. Pierce Inlet is a federal navigation project located in northern St. Lucie County in the proximity range monuments R-33 and R-34. Following completion of the initial dredging of the Ft. Pierce navigation project by local interests in 1930, severe scouring occurred along the channel across the Indian River, leading to an increase in the volume of littoral material and a resulting pattern of accretion along most of the shoreline adjacent to the inlet. After the inlet channel stabilized (1930-1935), erosion began to occur along the shoreline south of the inlet. Research conducted in support of the Ft. Pierce SPP has determined that there is no evidence that the navigation works have significantly affected sediment transport processes further south of the inlet than 14,000 feet (R-48) (USACE, 2000).

St. Lucie Inlet

St. Lucie Inlet is a Federal navigation project located in northern Martin County (just south of St. Lucie County) in the proximity of range monuments R-44 and R-45. Initially excavated in 1892, St. Lucie Inlet separates Hutchinson Island to the north and Jupiter Island to the south. The introduction of a north jetty in the late 1920, worsened erosional patterns already present due construction of the inlet. The north jetty trapped south moving sand, stabilizing the northern shoreline (southern Hutchinson Island) while causing shoreline erosion on Jupiter Island. Due to the predominantly southern transport of material, inlet impacts are to the south of the inlet channel, along approximately 5.8 miles of Jupiter Island shoreline (FDEP, 1995).

5 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, to form the basis for determining the justification for Federal participation. This section describes the engineering aspects of the Beach-*fx* model.

5.1 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 fully incorporating risk and uncertainty throughout the modeling process (input, methodologies, and output). Over the project life-cycle, typically 50 years, the model estimates shoreline response to a series of historically based storm events applied for each of the three sea level change scenarios (Section 3.5 Sea Level). 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 within the project area. Uncertainty is incorporated not only within the input data (storm occurrence and intensity, structural parameters, structure and contents valuations, and damage functions), but also 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, Beach-*fx* reaches will be referred to in this appendix as "Model reaches". Model 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 5-1 shows a conceptual representation of the model setup. For further details about the specifics of Lot extents and DE grouping (see the Economics Appendix).

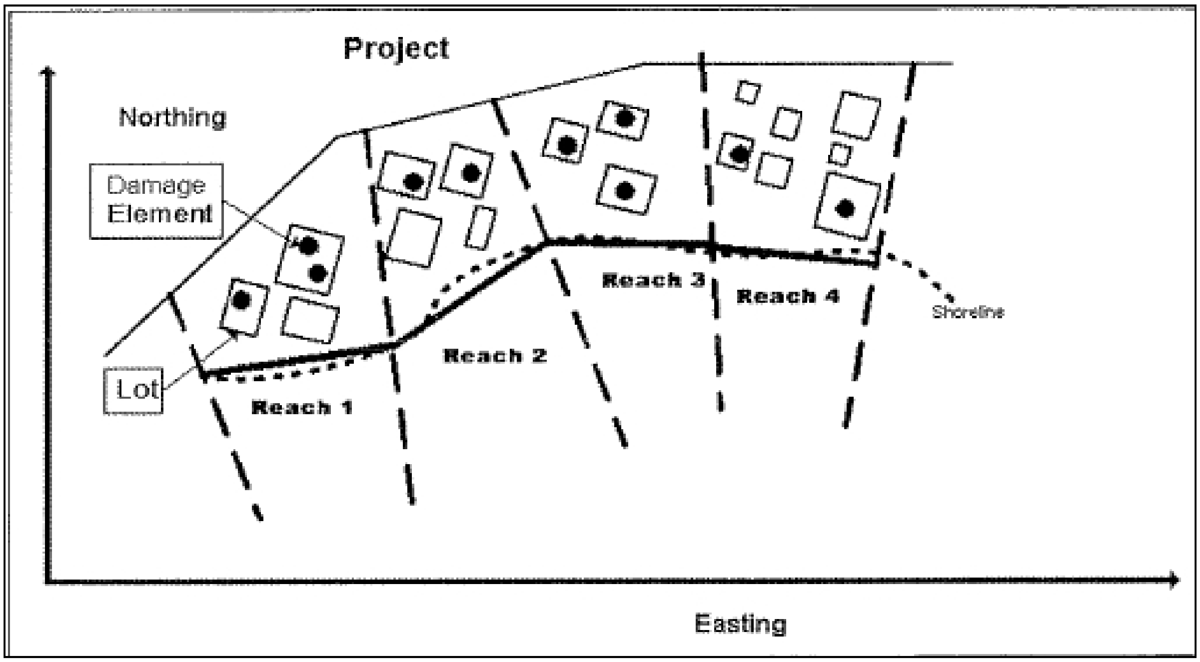

Figure 5-1. Beach-*fx* Model Setup Representation

Each model reach is associated with a representative beach profile that approximates the cross-shore profile and beach composition of the reach. Multiple model reaches may share the same representative beach profile while groupings of model reaches may represent a single design reach. For St. Lucie, the project area consists of four design reaches, divided into thirty-nine model reaches. Table 5-1 provides design and model reach identifiers as well as corresponding Beach-*fx* representative profiles (see Section 5.3.1.1 – Representative Profiles) and FDEP R-monument coverage. Figure 5-2 to Figure 5-4 shows design reach and model reach locations graphically.

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

- Meteorologic 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.

Table 5-1. Model Reaches

Design Reach	Beach-*fx* Model Reaches	Representative Profile	FDEP R-monuments
North Hutchinson Island (NHI)	R077 to R080	P1	R-77 to R-80
Power Plant Area(PP)	R081 to R083	P1	R-81 to R-83
	R084 to R090	P2	R-84 to R-90
Narrows of Hutchinson Island (NH)	R091 to R098	P1	R-91 to R-98
South Hutchinson Island (SHI)	R099 to R102	P1	R-99 to R-102
	R103 to R104	P3	R-103 to R-104
	R105 to R106	P4	R-105 to R-106
	R107 to R110	P5	R-107 to R-110
	R111	P6	R-111
	R112	P7	R-112
	R113 to R115	P8	R-113 to R-115

5.2 Meteorologic 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 eastern coast of Florida 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 St. Lucie County is made up of both types. Derived from the historical record of the region, the plausible storm set is based on 30 tropical storms, occurring between 1887 and 2004 and 57 extra-tropical storms, occurring between 1994 and 2005.

Because tropical storm events tend 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 30 tropical storms surge hydrographs 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 distinct combinations for each historically based tropical storm and a total of 360 tropical storm conditions in the plausible storm dataset.

Due to their generally extended durations, extra-tropical storms in the historical record tend to occur over complete tide cycles. Therefore, it can be assumed that the storm hydrograph of each of the 56 historical extra-tropical storms is sufficient without combining with possible variations of the astronomical tide. The entire plausible storm suite therefore consists of a total of 416 tropical and extra-tropical storms.

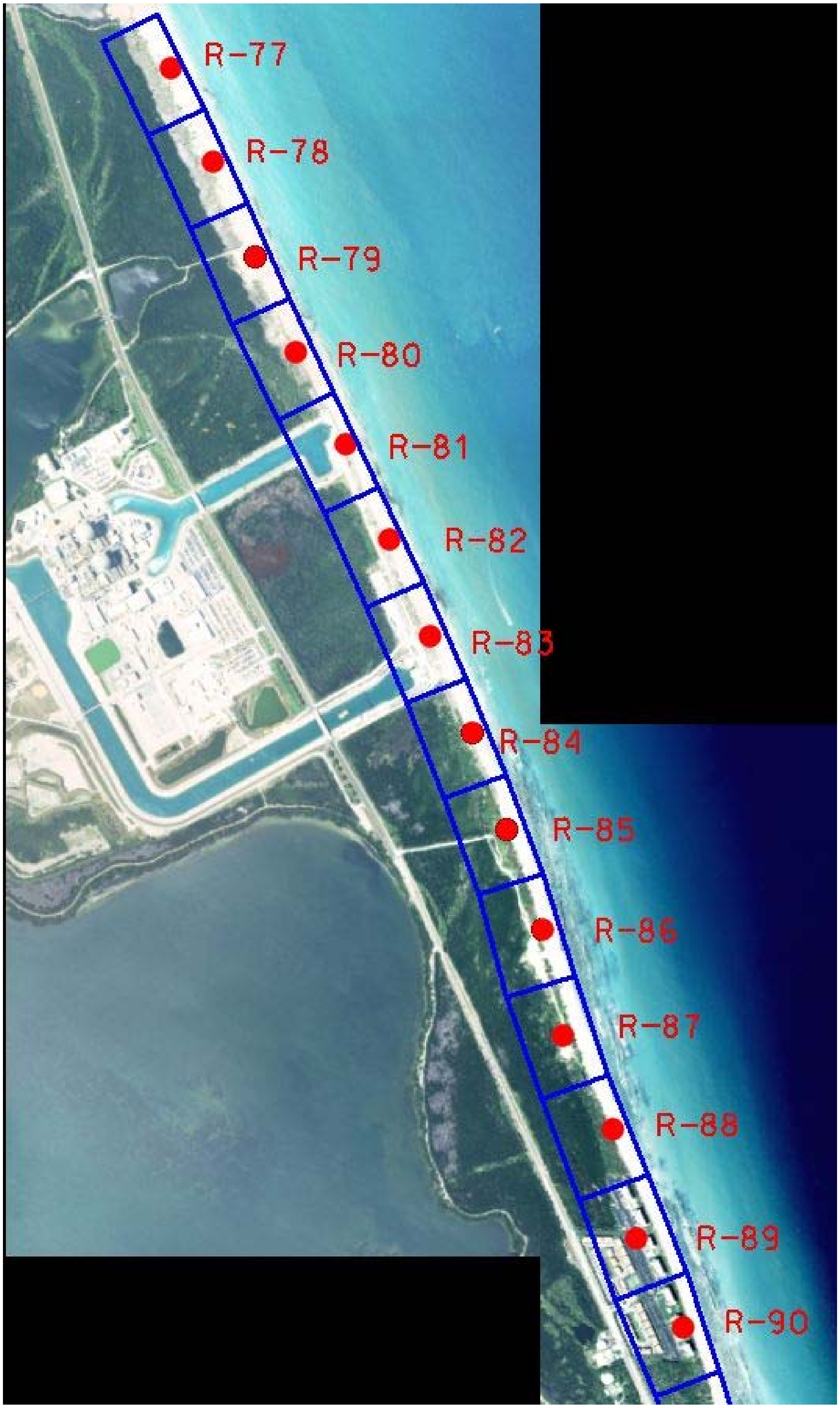

Figure 5-2. North Hutchinson Island and Power Plant Model Reaches Relative to FDEP R-monuments

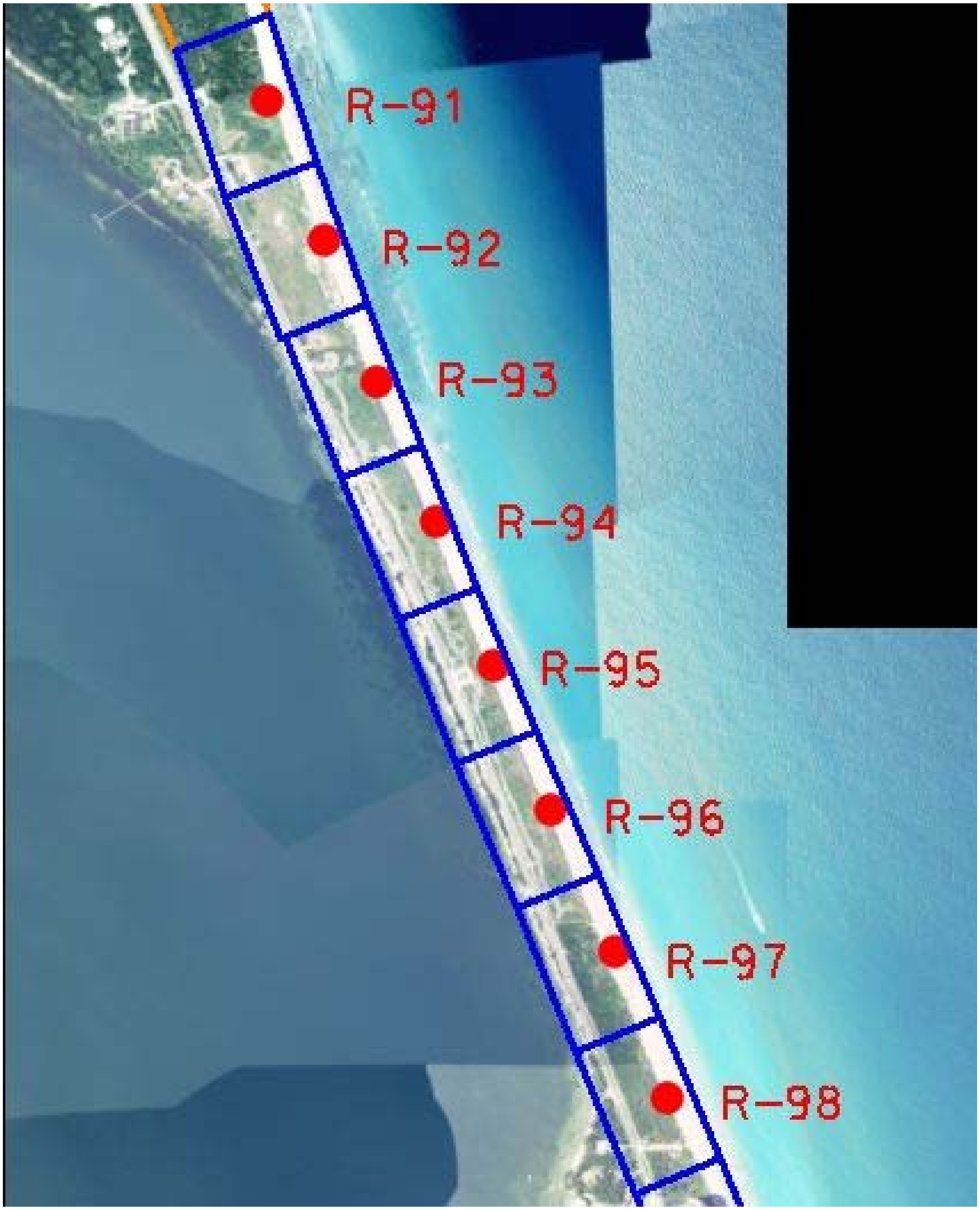

Figure 5-3. Narrows of Hutchinson Island Model Reaches Relative to FDEP R-monuments

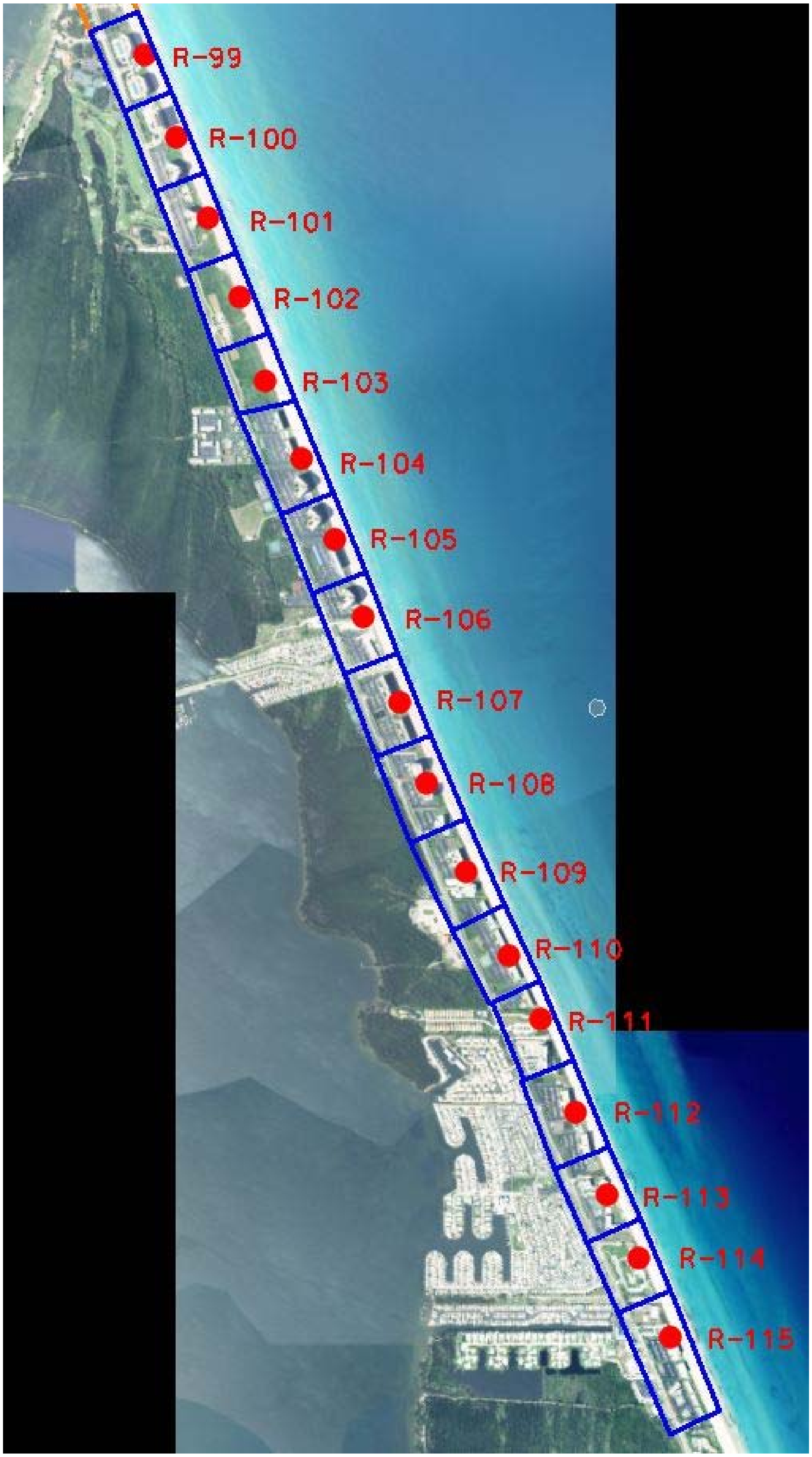

Figure 5-4. South Hutchinson Island Model Reaches Relative to FDEP R-monuments

In addition to the plausible storm dataset, the seasonality of the storms must also be specified. The desired storm seasons are based on the assumption that each plausible storm takes place within the season in which the original historical storm occurred. The probability of both tropical and extra-tropical storms is defined for each season through the Probability Parameter. The Probability Parameter 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). Four storm seasons were specified for St. Lucie County (Table 5-2).

Table 5-2. St. Lucie County Beach-*fx* Storm Seasons

Storm Season	Start Date	End Date	Probability Parameter Extra-Tropical Storm	Probability Parameter Tropical Storm
Extratrop Winter/Spring	Nov 1	May 31	3.33	0.00
Tropical Early Summer	June 1	Jul 31	0.08	0.03
Tropical Peak	Aug 1	Sep 30	0.67	0.19
Extratrop/Tropical	Oct 1	Oct 31	0.67	0.03

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. A minimum arrival time of 7 days was specified for St. Lucie County. Based on this interval, the model attempts to place subsequent storm events outside of a 14 day window surrounding the date of the previous storm (i.e. a minimum of 7 days prior to the storm event and a minimum of 7 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.

5.3 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.

5.3.1 Shoreline Storm Response

Shoreline storm response is determined by applying the plausible storm set that drives the Beach-*fx* model 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.

5.3.1.1 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, historical profiles at each FDEP R-monument are compared over time, aligned, and then averaged into a composite profile representative of the shoreline shape at a given R-monument location. Composite profiles are then compared and separated into groupings according to the similarity between the following seven dimensions:

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

In order to ensure that emergency nourishment efforts in response to the 2004 and 2005 hurricane season (completed in May 2013) did not influence the outcome of the ongoing feasibility study, it was agreed that the representative "without project" shoreline for the study would be established using survey data collected in the summer of 2006. However, subsequent analysis of the data showed that the 2006 survey did not provide adequate foreshore and offshore coverage of the project area to complete the Beach-*fx* analysis. A comparison of the available portions of the 2006 survey and a comprehensive shoreline survey taken in August 2008 showed insignificant difference in shoreline dimensions between the two. Therefore, the 2008 shoreline was determined to be a good representation of the "without project" condition.

From the 2008 survey data, eight groupings of similarly dimensioned beach profiles were identified. Within each grouping, the composite profiles were averaged into a single (without project) profile representative of a portion of the project shoreline. Using these representative profiles, idealized profiles representing the major dimensions of the profile were defined (Figure 5-5 through Figure 5-12). Representative profiles are not referenced to a specific R-monument location and are shown with generic "X-Distances" for scaling purposes. Note that determination of the final idealized profile dimensions (which are meant to represent entire model reaches) also considers survey data, such as topographic lidar, that cover a larger extent than the single cross-shore transects taken at R-monument locations. In some cases, analysis of topographic contours of the upland result in final idealized representative profile dimensions that differ from those that would have resulted from using the average measured cross-shore profiles alone. Table 5-3 provides dimensions for each of the idealized without project Beach-*fx* profiles.

5.3.1.2 SBEACH Methodology

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 two-dimensional model that considers only cross-shore sediment transport; that is, the model assumes that simulated profile changes are produced only by cross-shore processes. Longshore wave, current, and sediment transport processes are not included in SBEACH and are computed externally when required.

Table 5-3. Dimensions of Idealized Without Project Representative Profiles

Profile	R-monuments Represented	Upland Elevation (ft-NAVD88)	Dune Height (ft-NAVD88)	Dune Width (ft)	Dune Slope (V:H, ft)	Berm Elevation (ft-NAVD88)	Berm Width (ft)	Foreshore Slope (V:H,ft)
P1	R-77 to R-80, R-84 to R-102	4.5	11.0	55	1:7	7.0	0.0	1:9
P2	R-81 to R-83	5.0	13.0	35	1:6	7.0	0.0	1:10
P3	R-103 to R-104	5.0	11.0	50	1:6	7.0	0.0	1:8
P4	R-105 to R-106	3.0	11.0	120	1:6	7.0	0.0	1:9
P5	R-107 to R-110	3.0	11.0	40	1:6	7.0	0.0	1:9
P6	R-111	5.0	11.0	60	1:6	7.0	0.0	1:9
P7	R-112	5.0	14.0	25	1:5	7.0	0.0	1:8
P8	R-113 to R-115	4.0	13.0	50	1:5	7.0	0.0	1:9

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.

It should be noted that SBEACH is the USACE recommended model for shoreline response. The Beach-*fx* model, also developed by USACE, is specifically 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).

5.3.1.3 SBEACH Calibration and Verification

Calibration of the SBEACH model was performed using wave height, wave period, and water level information from Hurricanes Frances and Jeanne (2004) (Figure 5-13). Calibration of the model is required to ensure that the SBEACH model is tuned to provide realistic shore responses that are representative of the specific project location. Calibration is determined by comparing modeled post-storm beach profiles with measured post-storm profile data.

Measured pre- and post-storm shoreline profiles were obtained from FDEP. Using the pre-storm profiles, SBEACH was then run with a range of values for an array of calibration parameters. Table 5-4 provides the relevant beach characteristic and sediment transport calibration parameters as well as their final calibrated values. Calibration parameters were verified using wave height, wave period, and water level information from a combination of two storm events occurring in September 2007 (unnamed) and October 2007 (Hurricane Noel).

For details of the SBEACH calibration and verification procedure and results see Sub-Appendix A-1: St Lucie County Shore Protection Project, SBEACH Calibration and Verification.

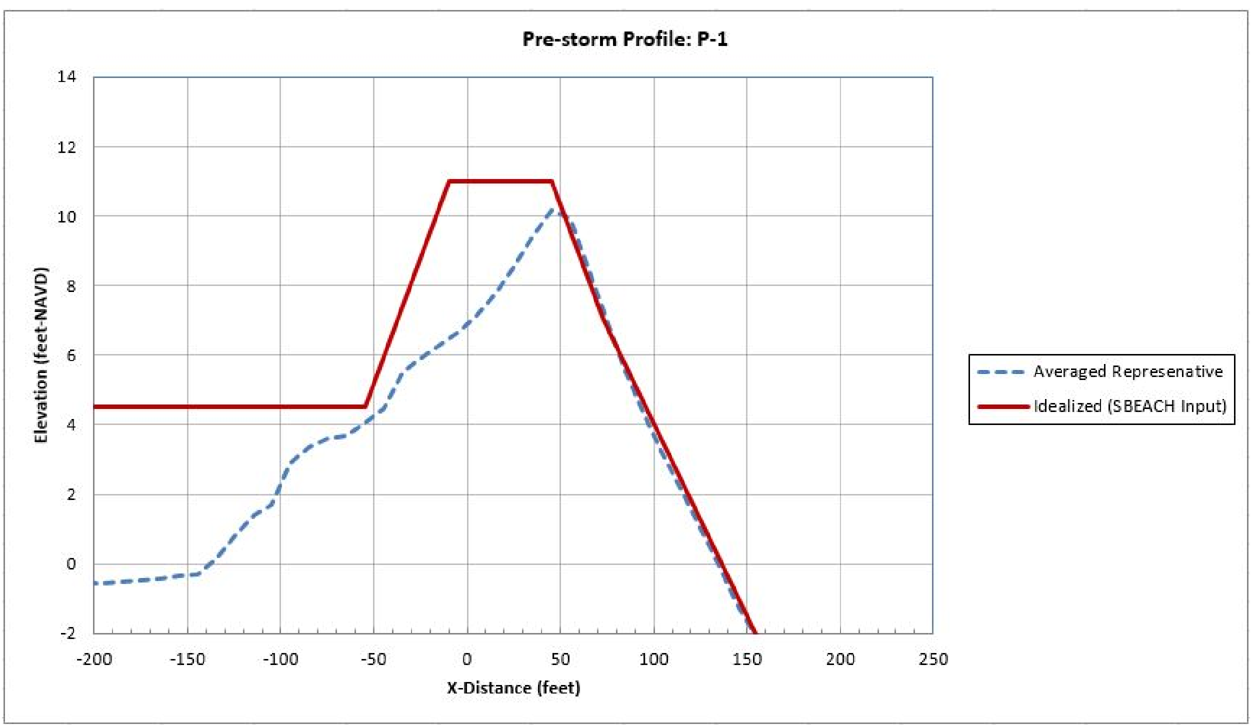

Figure 5-5. Average Measured and Idealized Beach-*fx* Profiles: P1 Grouping

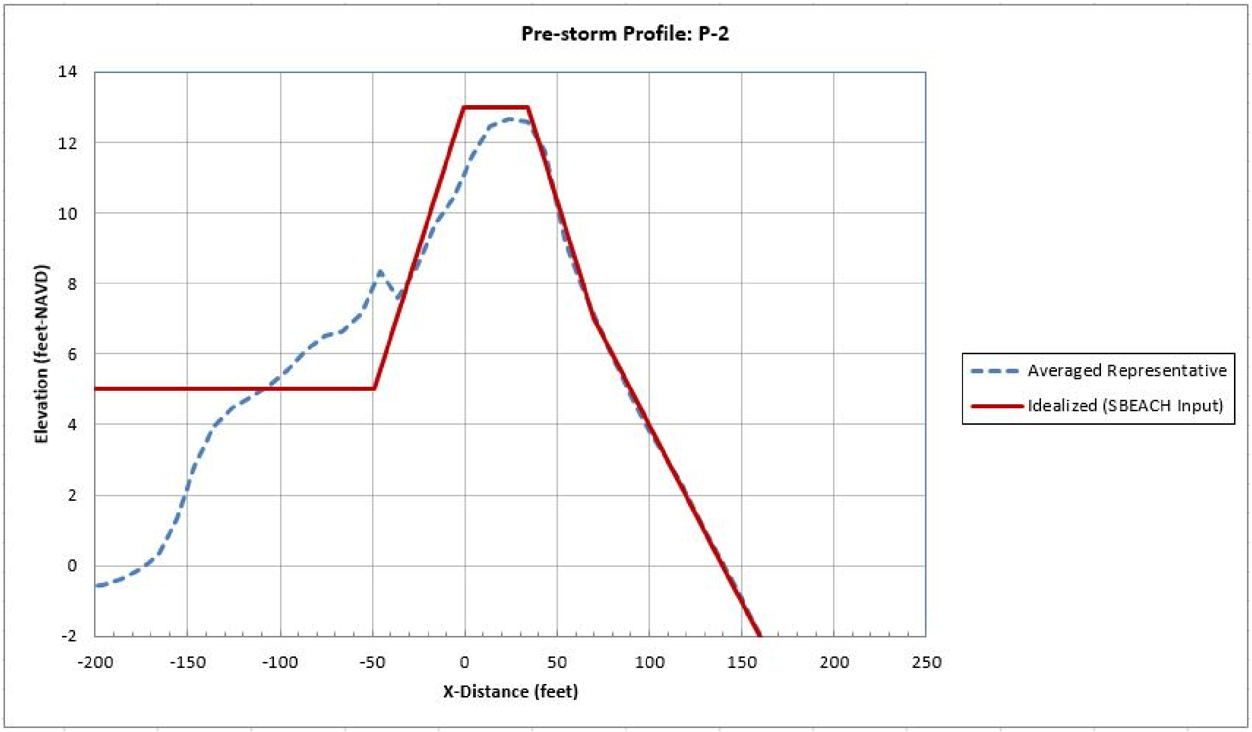

Figure 5-6. Average Measured and Idealized Beach-*fx* Profiles: P2 Grouping

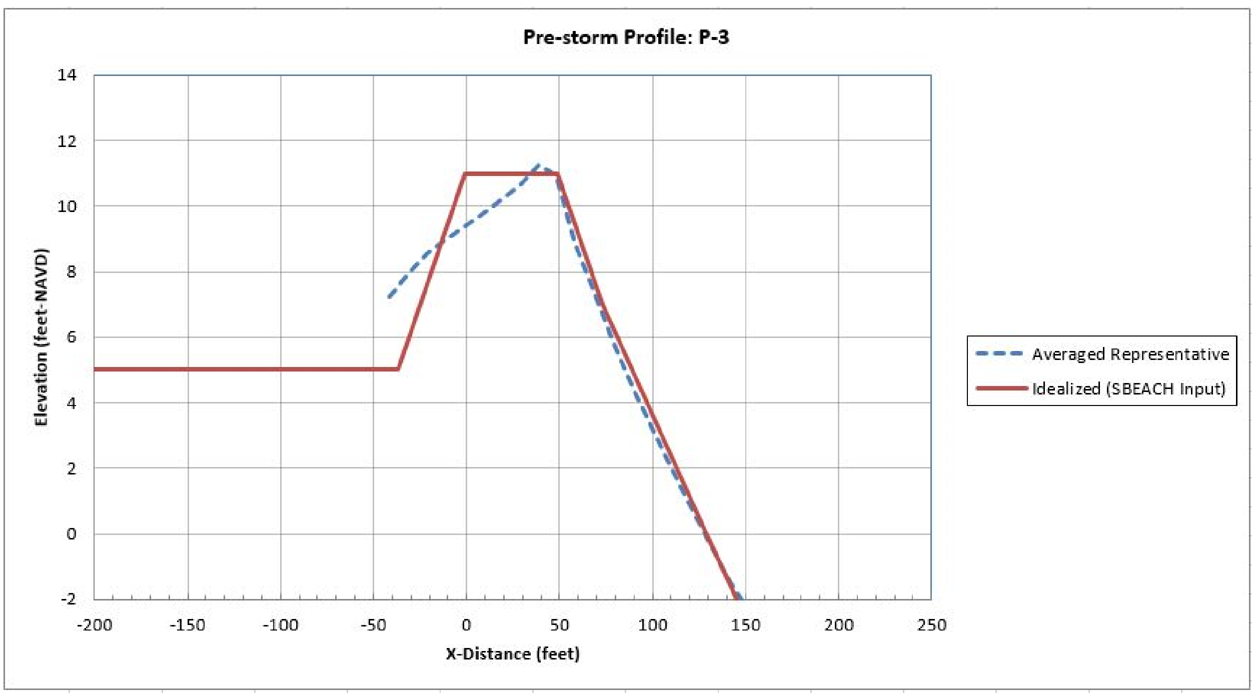

Figure 5-7. Average Measured and Idealized Beach-*fx* Profiles: P3 Grouping

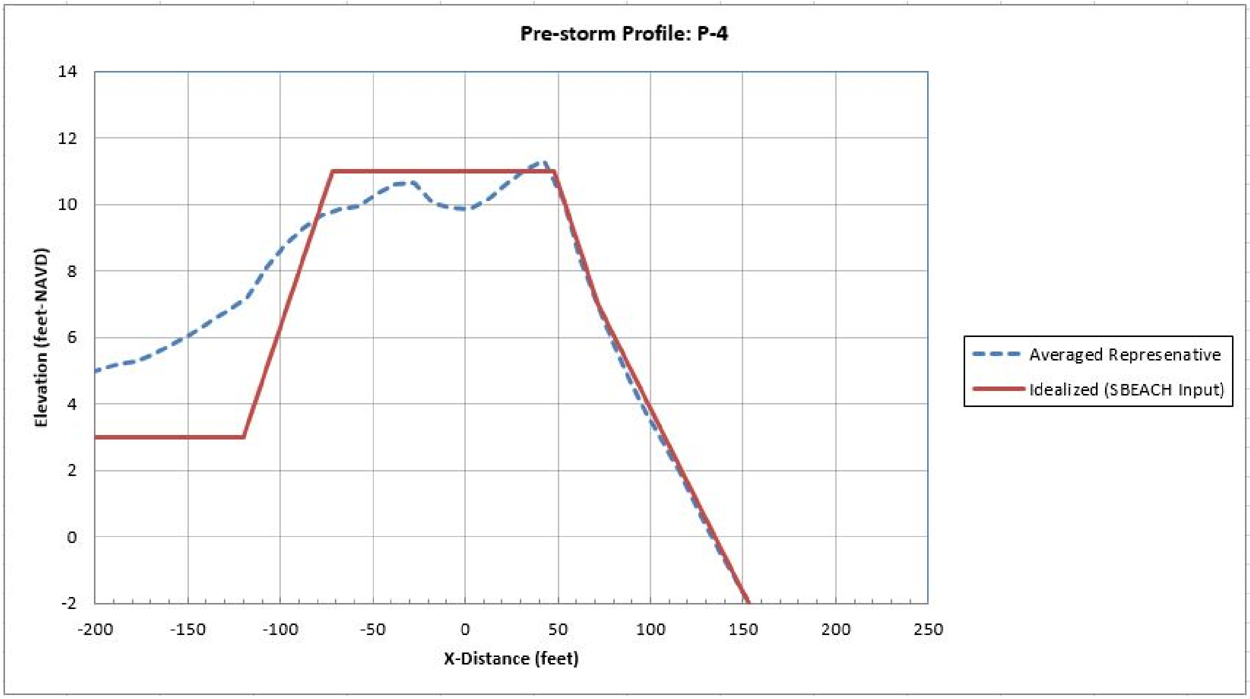

Figure 5-8. Average Measured and Idealized Beach-*fx* Profiles: P4 Grouping

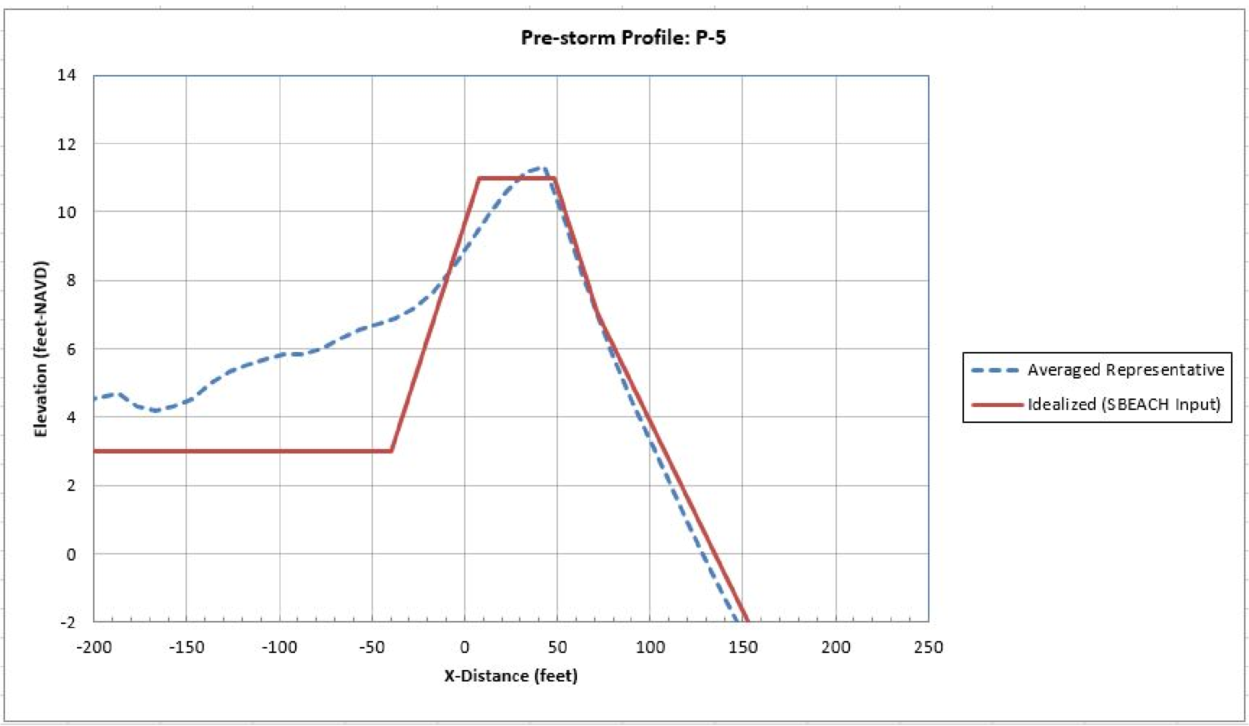

Figure 5-9. Average Measured and Idealized Beach-*fx* Profiles: P5 Grouping

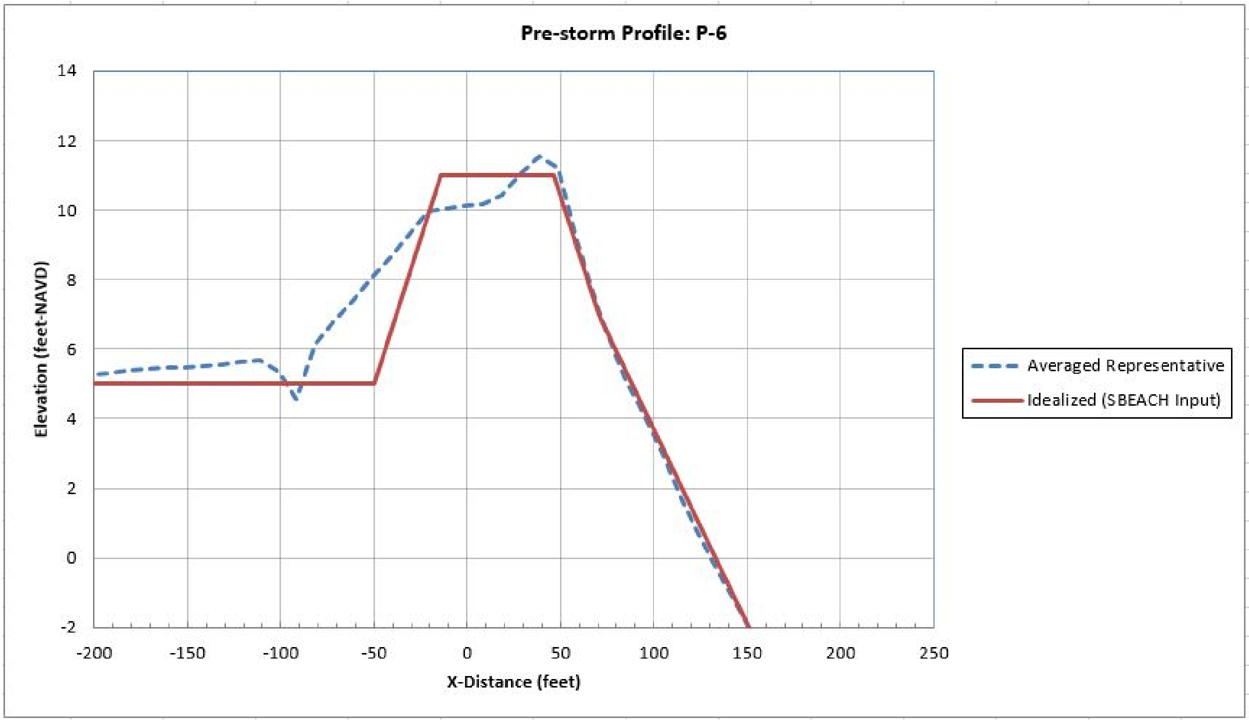

Figure 5-10. Average Measured and Idealized Beach-*fx* Profiles: P6 Grouping

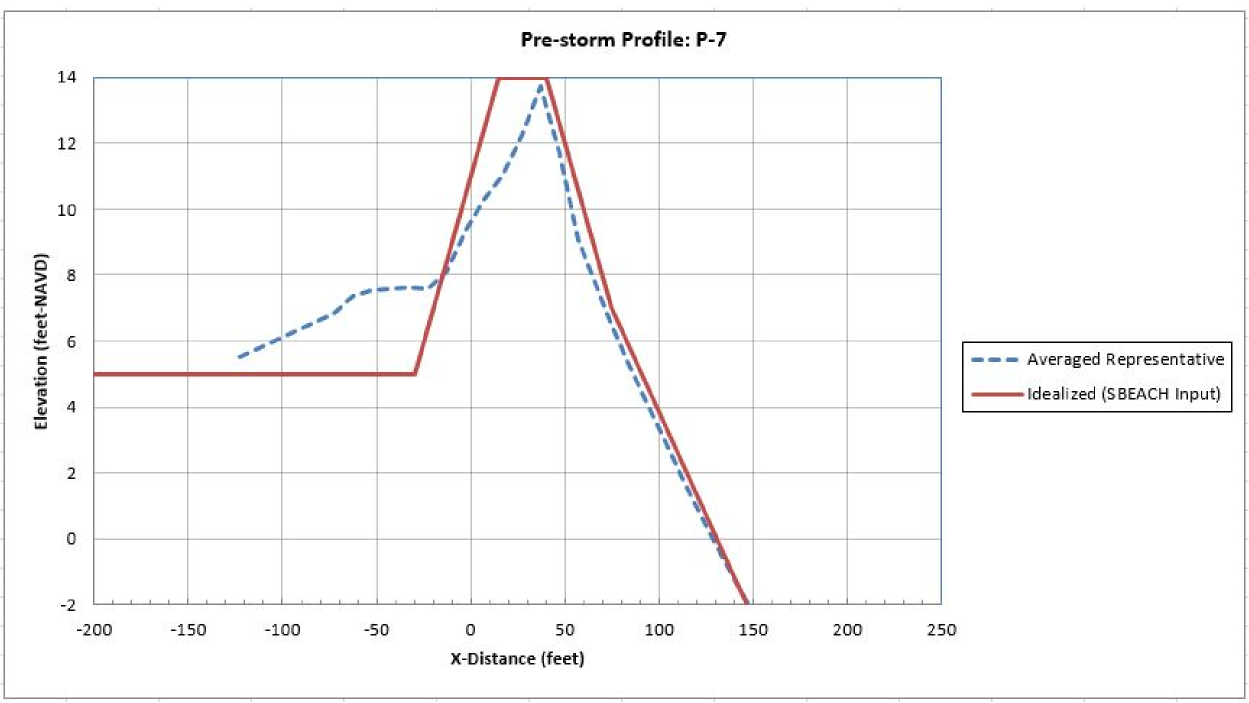

Figure 5-11. Average Measured and Idealized Beach-*fx* Profiles: P7 Grouping

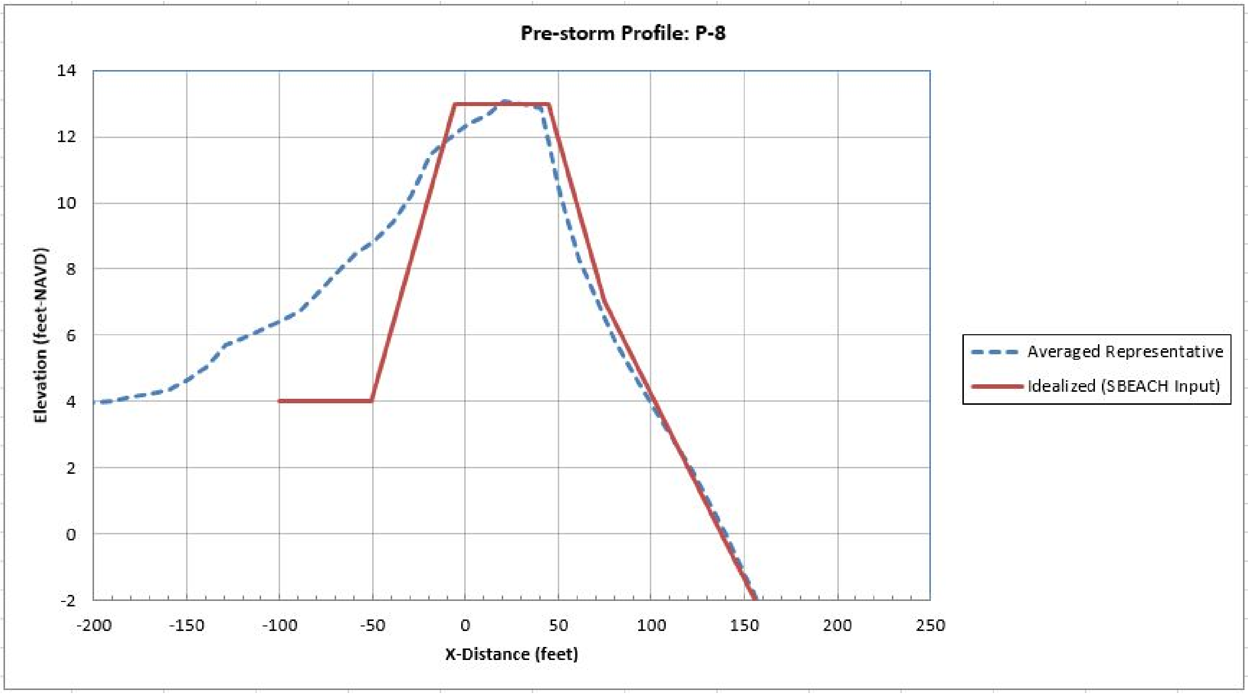

Figure 5-12. Average Measured and Idealized Beach-*fx* Profiles: P8 Grouping

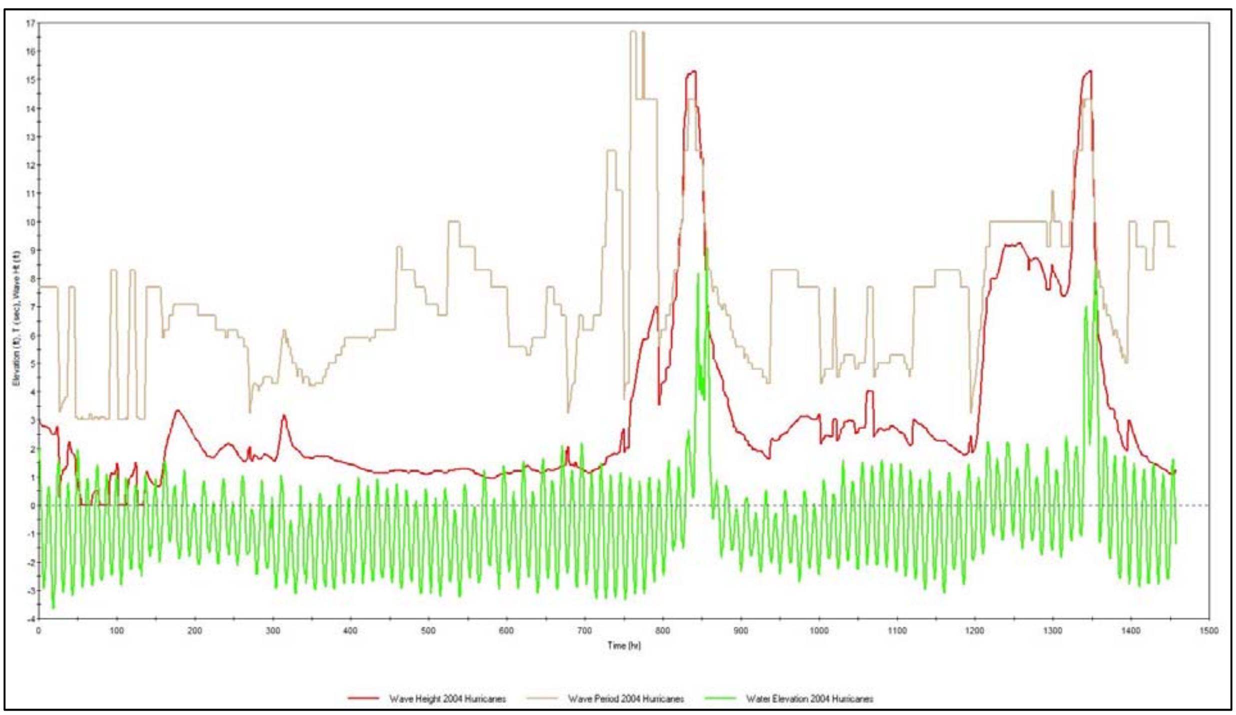

Figure 5-13. Hurricane Frances and Jeanne Wave and Water Level Data for SBEACH Calibration

5.3.1.4 SBEACH Simulations

Calibrated St. Lucie County SBEACH simulations were completed for each of the without project and with-project idealized profiles 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 St. Lucie County Beach-*fx* SRD.

Table 5-4. SBEACH Calibrated Beach Characteristic and Sediment Transport Parameters

<table>
<tr><th colspan="2">Beach Characteristic</th><th colspan="2">Sediment Transport</th></tr>
<tr><th>Parameter</th><th>Calibrated Value</th><th>Parameter</th><th>Calibrated Value</th></tr>
<tr><td>Landward Surf Zone Depth</td><td>1.0 m</td><td>Transport Rate Coefficient</td><td>2.3e-006 (m4/N)</td></tr>
<tr><td rowspan="2">Effective Grain Size</td><td rowspan="2">0.45 mm</td><td>Overwash Transport Parameter</td><td>0.001</td></tr>
<tr><td>Coefficient for Slope-Dependent Term</td><td>0.002</td></tr>
<tr><td rowspan="2">Maximum Slope Prior to Avalanching</td><td rowspan="2">30</td><td>Transport Rate Decay Coefficient Multiplier</td><td>0.2</td></tr>
<tr><td>Water Temperature</td><td>30degC</td></tr>
</table>

5.3.2 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, combined with the storm-induced change generated internally by the Beach-*fx* model, returns the historical shoreline change rate for that location. Calibration is essential to insure that the morphology behavior is appropriate and representative of the study area.

The target shoreline change rate is an erosion or accretion rate derived from the historical MHW rate of change (from January 1970 to August 2008) determined at each R-monument location. Although the MHW rate of change represents the historical behavior of the project shoreline, when it is calculated at single point locations, such as R-monuments, there is a high degree of variability between consecutive locations. This variability results in a similar variability in the Beach-*fx* results, specifically in project costs and predicted damages. Because this does not reflect actual shoreline behavior and leads to inconsistencies between adjacent economic reaches, the target shoreline change rate is determined by averaging adjacent MHW change rates to allow for smoother transitions along the length of the project shoreline. Figure 5-14 shows the smoothed target shoreline change rates along with the original MHW shoreline change rates (January 1970 to August 2008) from which they were derived.

During Beach-*fx* calibration, applied erosion rates were adjusted for each model reach and the Beach-*fx* model was run for hundreds of iterations over the 50-year project life cycle. Calibration is achieved when the rate of shoreline change, averaged over hundreds of life cycle simulations, is equal to the target shoreline change rate.

It is through the applied erosion rates that sea level change is incorporated into the Beach-*fx* shoreline change simulations. The calibrated applied erosion rates, based on historical shoreline change and the existing measured sea level rate of change, represents the baseline (Low) sea level change condition. By adding the change in shoreline recession for the Intermediate and High sea level change scenarios, as predicted by Bruun's Rule (Section 3.5.2 Beach Responses to Sea Level Change), to the calibrated applied erosion rates at each Model Reach, adjusted applied erosion rates can be determined. Figure 5-15 shows target erosion rates, corresponding calibrated applied erosion rates (Baseline sea level change), and resulting adjusted applied erosion rates (Intermediate and High) sea level change.

5.3.3 Project Induced Shoreline Change

The placement of additional sand on a beach will increase the rate of erosion of that beach since the beach fill material represents a perturbation in the shoreline that is diffused by incident waves. Beach-*fx* requires with-project shoreline change rates in order to represent the planform diffusion of the beach fill alternatives in the Beach-*fx* model simulations. The USACE one-dimensional shoreline change model GenCade was applied to evaluate St. Lucie County beach nourishment alternatives (detailed in Section 5.6: Beach-*fx* Project Design Alternatives). The difference in shoreline change rate for each with-project alternative versus the without-project calculated within GenCade represents the diffusion rate of each alternative that is applied to the Beach-*fx* model.

The GenCade model (Frey et al., 2012) was developed by combining the USACE project-scale, shoreline change model GENESIS and the regional-scale, transport model Cascade. The GENESIS component of the GenCade model was used for the project analysis that is detailed herein. GenCade can be set up and executed within the Surface-Water Modeling System (SMS) or executed as a stand-alone model through the MS-DOS interface and calculates both shoreline change and alongshore sand transport due to wave forcing.

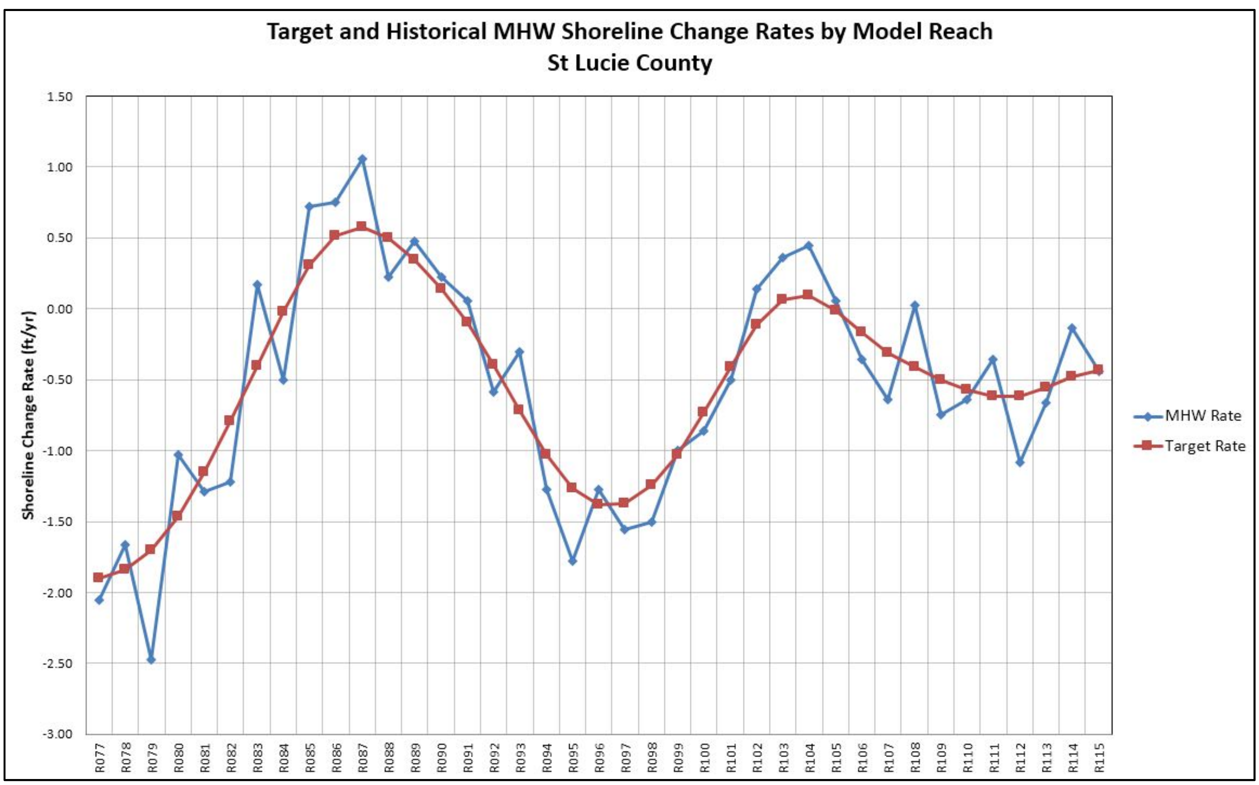

Figure 5-14. Target MHW Shoreline Change Rate

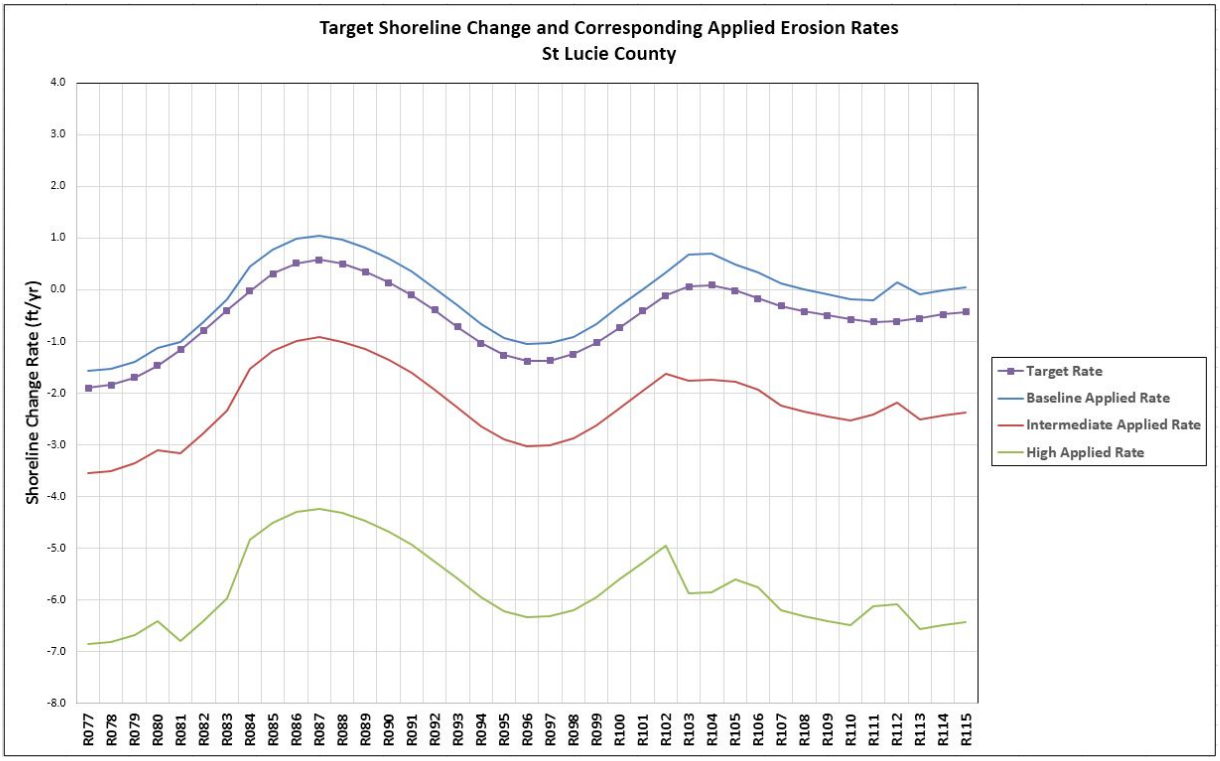

Figure 5-15. Target MHW Shoreline Change and Applied Erosion Rates

5.3.3.1 CMS Wave Model

The GenCade model requires breaking wave heights as a model input to calculate sediment transport rates which are then used to calculate shoreline change. Since breaking wave heights are rarely measured and are not readily available, the GenCade model package includes an internal wave model that transforms waves from a given offshore depth to breaking depth using linear wave theory. Alternatively, if the local bathymetry is complex, an external wave model such as STWAVE or CMS Wave can be used. The contours off of St. Lucie County are generally straight and parallel; however, the nearshore region contains scattered hardbottom formations and shoals, which can significantly influence the shoaling and refraction of incident waves. To account for this influence, the wave transformation model within the Coastal Modeling System (CMS Wave) was used to shoal and refract the hindcast waves over the irregular bathymetry to a location seaward of the breaking depth. The transformed wave data output from the CMS-Wave model were then input into GenCade.

The CMS Wave model uses wave conditions at the offshore boundary to drive the model. The most complete hindcast wave data available for St. Lucie County covers the period from 1980-2012 and is produced by USACE Wave Information Studies (WIS). The WIS wave hindcast is developed using the WISWAVE model, a discrete spectral wave model that solves the energy balance equation for the time and spatial variation of a 2-D wave spectrum from wind forcing (See Section 3.2: Waves). The WIS program archives the wave hindcast at discrete stations that are located approximately every 0.10 degrees of latitude (approximately every 4.5 nautical miles) along the shoreline of the U.S. The WIS station used for this analysis is 63452, which is located at 27.33° latitude and -80.00° longitude—approximately 18 nautical miles east of the center of the study area. The water depth is approximately 66m (216 feet) at WIS Station 63452.

For the this study, a CMS grid was created that extended 22 miles in the alongshore, centered at the project site and extended 15 miles offshore, approximately 3 miles offshore of the WIS station. It was oriented with an azimuth of 293°, measured counter-clockwise from due north (0°) so that the y-axis of the wave grid was aligned with the study area shoreline (Figure 5-16).

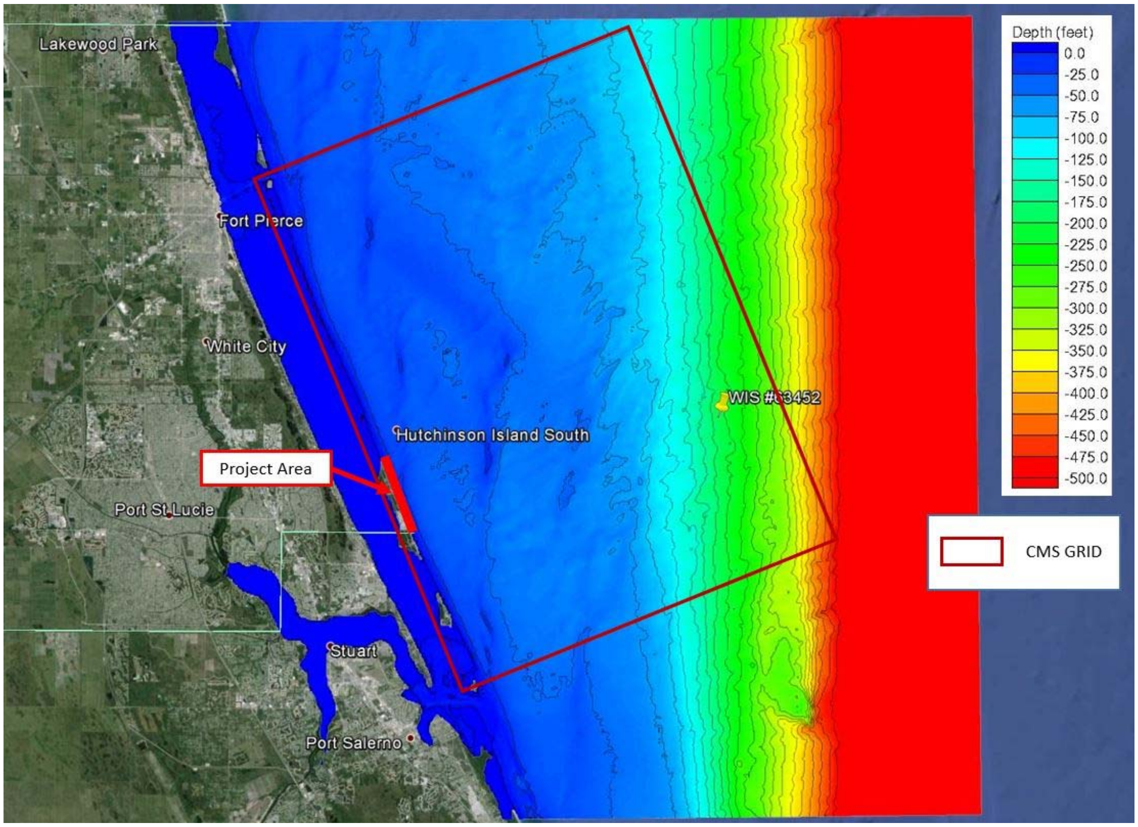

Figure 5-16. CMS Modeling Grid Layout

The CMS model runs were driven at the offshore boundary using WIS wave data for the entire hindcast period of 1980—2012. These data were pre-processed using procedures to assimilate measured and hindcast wave data into wave climatology statistics and representative data subsets (Connell and Permenter, 2013; Permenter et al., 2013). Resulting wave statistics are then used as input into CMS. This process accurately represents the overall wave climate while drastically reducing the number of CMS wave simulations that are needed to represent the wave climate, thereby saving considerable time and effort.

5.3.3.2 GenCade Model Setup

In order to fully capture the shoreline changes within St. Lucie County and to minimize any boundary effects to the study area, the GenCade model domain was extended to include approximately 3 miles north of the project (vicinity of R-60) and 2.5 miles south of the St. Lucie County line (R-15 of Martin County). The model grid was located sufficiently landward so that the modeled shoreline never intersects with or recedes landward of the grid. Additionally, the grid was oriented so that it was approximately parallel to the St. Lucie County shoreline.   The project site does not include any shore protection structures (seawalls, revetments, etc.) that required inclusion in the model.

Shoreline change modeling with GenCade includes model calibration, which tunes the model to approximate site specific conditions, model verification over a different time period in order to verify that the model adequately represents other time periods, and finally production runs which evaluate the diffusion rates of the different beach nourishment alternatives.

The computation time step was set at a one hour interval and modeled shoreline data were output were at 168 hours (1 week). Grid cell sizes were set at 100 meters (~328 feet). As discussed previously, the GenCade grid extends 50 cells north of the study area and 43 cells south of the southern study limit in order to limit model error associated with model boundaries. The CMS Wave breaking wave data were used to drive the GenCade model.

Beach profile surveys were analyzed through time to find the average berm height (6.9 feet; 2.1 meters) and depth of closure (15 feet; 4.6 meters) for the study area; these values are required model input and define the zone of sediment movement in the model. Geotechnical investigation of the beach sediments in St. Lucie County indicate that the median grain size (d50) is 0.45 mm, which was used for all GenCade calibration, verification and production model runs. The lateral boundary condition at the north and south ends of the model grid were set to “pinned” for all model runs, meaning the shoreline doesn’t change position at the model limits.

5.3.3.3 GenCade Calibration

The calibration procedure optimizes site specific model parameters for a given study area by comparing model predicted shoreline change with measured shoreline change from survey data. For St. Lucie County, calibration of model parameters was achieved through analysis of the modeled versus measured shoreline change for the time period from 1 August 2006 to 7 October 2012.

In order to preserve dominant regional shoreline characteristics, GenCade allows the use of a regional shoreline. If an open coast shoreline doesn’t have specified sediment sources, sinks, or structures (such as the St. Lucie County shoreline), the nature of the one-line model means that model simulations over long time periods will result in a straight coastline, which may not be representative of underlying geology that dictates a curved shoreline. By providing a regional contour, the modeled shoreline will be guided in its evolution and eventually will assume a shape parallel to the regional contour, if simulated over long enough time periods. The regional contour was varied during calibration to isolate one that provided the best overall model fit to the measured data, as outlined below. Once that contour was established during calibration, it was not varied for model verification so that a minimal number of model alterations would be made during final verification.

The calibration process began with the sediment transport coefficients K1 and K2 set to model default values of 0.50 and 0.25, respectively. The root mean square error (RMSE) of the modeled vs. measured shorelines for this initial run was 8.6 meters (28.2 feet). The model was relatively insensitive to smoothing of the 2006 regional contour as well as to changes in K1 and K2. Based on the initially poor calibration values and insensitivity to the K-parameters, the next step was the substitution of a regional contour based upon the 2012 MHW shoreline to see if the addition of a regional contour would improve the model calibration significantly. This reduced the RMSE of modeled vs. measured to 5.0 meters (16.4 feet) with a standard deviation of 4.9. This indicated that the changes were significantly improving model performance. Smoothing of this contour across three cells reduced the RMSE to 2.54 meters (8.33 feet) with K1=0.25 and K2=0.25 and a standard deviation of 2.11; this change brought the model into acceptable agreement with the measured shoreline values. The rest of the calibration process fine-tuned the sediment transport parameters to minimize the error.

First, the K1 was raised to 0.35, resulting in an increase of RMSE to 2.77 meters (9.10 feet). K1 was then lowered to 0.2 and K2 kept at 0.25 which resulted in an RMSE of 2.47 meters (8.10 feet). K2 was then lowered to 0.10, which resulted in an RMSE of 2.46 meters (8.07 feet). Finally, the K1 was reduced to 0.10 (K2 remained at 0.10) and the RMSE increased to 2.66 meters (8.72 feet). The final outcome of the calibrated model was therefore a regional contour based on the 2012 MHW contour, smoothed and offset 300 meters (984 feet) offshore with a K1 of 0.20 and K2 of 0.10. Table 5-5 summarizes relevant GenCade calibration settings and statistics.

Table 5-5. GenCade Calibration Settings and Statistics

Regional Contour Applied	Calibration Parameters		Root Mean Square Error (RMSE)	
	K1	K2	Meters	Feet
2006	0.50	0.25	8.60	28.21
2012	0.25	0.25	5.00	16.40
2012 smooth	0.25	0.25	2.54	8.33
2012 smooth	0.35	0.25	2.77	9.09
2012 smooth	0.20	0.25	2.47	8.10
2012 smooth	**0.20**	**0.10**	**2.46**	**8.07**
2012 smooth	0.10	0.10	2.66	8.72
Highlighted values carried forward for verification model runs				

5.3.3.4 GenCade Verification

Along with the parameters from the final calibration run, waves from the period between 1 August 1997 and 1 August 2002 (verification period) were input along with the corresponding MHW shoreline data from those two years. As with the calibration period, the final modeled shoreline position was compared with the final measured shoreline. Verification runs started with the calibrated model parameters of K1=0.20 and K2=0.10 and a regional contour derived from the 2012 MHW shoreline.

The verification process included fine tuning of the calibration settings. This involved changes to K1 while maintaining the regional contour and the secondary K2 variable. Comparison of the modeled and measured shorelines from 1997 to 2002 indicated an RMSE of 4.98 meters (16.33 feet) with K1=0.2 and K2=0.1. An increase of K1 to 0.30 resulted in a reduction of RMSE to 4.86 meters (15.94 feet). A slight reduction to K1=0.25 then resulted in an RMSE increase to 4.90 meters (16.07 feet). Based on these results, the optimum K1 value was determined to be 0.30 for the verification period.

To verify the optimized parameters, a recheck of the calibration period of 2006 to 2012 time period with K1=0.30, K2=0.10, and the 2012 regional contour was made. This resulted in an RMSE of 2.64 meters (8.66 feet), a nominal increase from the calibration value of 2.46 meters (8.07 feet). From this analysis it was determined that the production runs would use the optimized model parameters K1=0.30 and K2=0.10. Table 5-6 summarizes relevant Gencade verification settings and statistics.

Table 5-6. GenCade Verification Settings and Statistics

Regional Contour Applied	Calibration Parameters		Root Mean Square Error (RMSE)	
	K1	K2	Meters	Feet
2012 smooth	0.20	0.25	4.98	16.33
2012 smooth	**0.30**	**0.10**	**4.86**	**15.94**
2012 smooth	0.25	0.10	4.90	16.07
Highlighted values show optimized parameters for production runs				

5.3.3.5 Model Results

The calibrated and verified GenCade model for St. Lucie County provides a means to evaluate proposed shoreline protection measures so that the most economically beneficial alternative can be determined. In order to compare proposed alternatives, an input shoreline condition with no modifications was first used to project the future background conditions. This model run represented the future without-project condition. Following the without project condition run, each of the proposed alternatives (see Section 5.6: Beach-*fx* Project Design Alternatives for alternative details) were then added to the initial shoreline. These constituted the future with-project condition runs. Future with-project simulations shoreline changes were compared with the changes observed from the future without project run to determine the planform shoreline change rates that would be expected from a constructed project. Figure 5-17 provides example of the final project planform rates for one series of FWP alternatives.

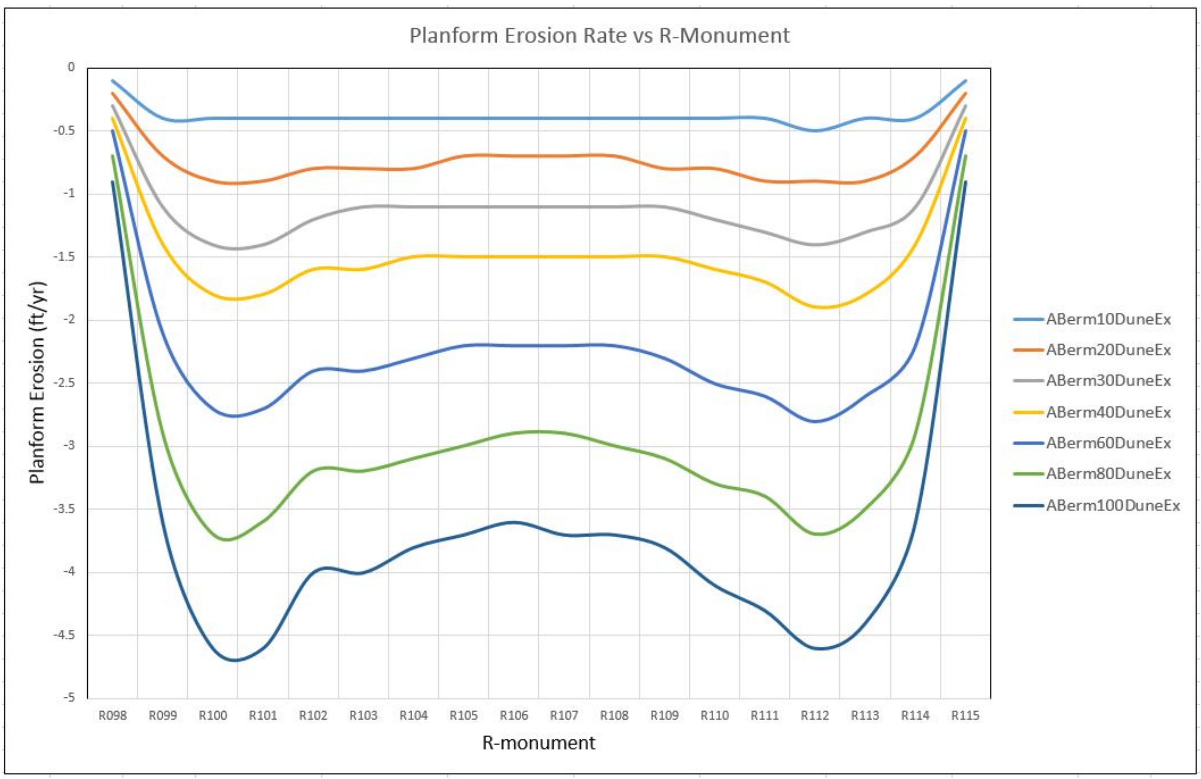

Figure 5-17. Example of Planform Rate Results for a Single Series of FWP Alternatives

The project induced shoreline change rates calculated by Gencade do not take into account the improved performance of beach nourishments projects that comes with project maturation. That is, theory and beach nourishment experience has shown that dispersion losses at a beach nourishment project tend to decrease with the number of project nourishments. Neither does Beach-*fx* factor in this phenomena. In order to prevent underestimating project performance and benefits, early Beach-*fx* users from within the coastal engineering community of practice determined that based on the behavior of previous storm damage reduction projects along the east coast of Florida, it can be assumed for the sake of this study that there will be a 20% reduction in shoreline change rates following each consecutive renourishment cycle.

5.3.4 Post Storm Berm Recovery

Post storm recovery of eroded berm width after passage of a major storm is a recognized process. Although present coastal engineering practice has not yet developed a predictive method for estimating this process, it is an important element of post-storm beach morphology. 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 5.3.2 Applied Shoreline Change).

Based on recommendations by the model developer regarding east coast Florida shorelines, review of available historical FDEP profiles that would qualify as pre- and post- storm, and successful model calibration a recovery percentage of 90% over a recovery interval of 21 days was determined to be appropriate for St. Lucie County.

5.4 Economic Evaluation

The Beach-*fx* model analyzes the economics of shore protection projects based on the probabilistic nature of storm associated damages to structures in the project area. Damages are treated as a function of structure location and construction, the intensity and timing of the storms, and the degree of protection that is provided by the natural or constructed beach. Within the model, damages are attributed to three mechanisms:

- Erosion (through structural failure or undermining of the foundation)
- Flooding (through structure inundation levels)
- Waves (though the force of impact)

Although wind may also cause shoreline damage, shore protection projects are not designed to mitigate for impacts due to wind. Therefore, the Beach-*fx* model does not include this mechanism.

Damages are calculated for each model reach, lot, and damage element following each storm that occurs during the model run. Erosion, water level, and maximum wave height profiles are determined for each individual storm from the lookup values in the previously stored SRD. These values are then used to calculate the damage driving parameters (erosion depth, inundation level, and wave height) for each damage element.

The relationship between the value of the damage driving parameter and the percent damage incurred from it is defined in a user-specified "damage function". Two damage functions are specified for each damage element, one to address the structure and the other to address its contents. Damages due to erosion, inundation, and wave attack are determined from the damage functions and then used to calculate a combined damage impact that reduces the value of the damage element. The total of all damages is the economic loss that can be mitigated by the shore protection project.

A thorough discussion of the economic methodology and processes of Beach-*fx* can be found in the **Economics Appendix.**

5.5 Management Measures

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

5.5.1 Emergency Nourishment

Emergency nourishments are generally limited beach fill projects conducted by local governments in response to storm damage. St. Lucie County does not have a consistent history of emergency nourishment in response to storm related erosion. Response to storm damage has been limited to isolated dune restoration projects, each having a different template, range, and volume. 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. The lack of consistency in the timing, location, volume, and dimensions of the post-storm shoreline prior to the historic fills, makes assigning realistic emergency fill triggers and specifications within Beach-*fx* impossible. Therefore, this management measure was not included in the St. Lucie Beach-*fx* analysis.

5.5.2 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 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.

5.5.2.1 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. For St. Lucie County, each model reach level template was developed based on a combination of three dune extensions (extension of the dune and beach, from dune crest to depth of closure): 0-foot, 10-foot, and 20-foot extension and five berm widths: 20-foot, 40-foot, 60-foot, 80-foot, and 100-foot. Template dune heights in each case were set to the elevation of the existing Beach-*fx* profile. Nourishment templates were developed for each representative profile within the model reaches. Table 5-7 provides dimensions for each of the design templates. Note that each dune and berm extension is referenced to the idealized "existing" (2008) representative profiles (See Section 5.3.1.1: Representative Profiles).

5.5.2.2 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 renourishment is indicated. For any project template, the berm width trigger can be set such that a minimum berm width (what has been traditionally referred to as a "design berm") can be maintained, allowing the remainder of the template to act as sacrificial fill (traditional "advance fill"). St. Lucie study alternatives included five maintained berm options: 0-foot, 20-foot, 40-foot, 60-foot, and 80-foot. Because the width of the berm governs for these alternatives, the dune width and dune height triggers were set to allow minimal erosion to the dune. For all cases that include a berm, the dune width and dune height triggers were set to 0.99 (1% loss of height allowed) and 0.90 (10% loss of height allowed), respectively.

The mobilization threshold (minimum nourishment volume required to trigger a nourishment cycle) was set to be approximately 10,000 cubic yards less than the volume of the sacrificial portion of the nourishment template. This ensures that both the berm width trigger and mobilization threshold act together to maintain the desired "design berm" for each alternative. Distance Triggers and Mobilization thresholds for St. Lucie project alternatives will be presented in greater detail under Section 5.6: Beach-*fx* Project Design Alternatives.

5.6 Beach-*fx* Project Design Alternatives

In order to determine the most effective and cost efficient protective beach design for St. Lucie County, alternatives were developed by combining the design reaches and nourishment templates discussed previously (Table 5-7). Additionally, for each template a series of minimum desired ("design") berm widths (as described in the previous section) was specified. Table 5-8 provides each of the project design alternatives as well as corresponding distance triggers and design thresholds.

Alternative names are descriptive, consisting of the total nourishment template berm width and the width of the dune extension, if any. For example, Berm20DuneEx represents an alternative with a 20 foot template berm width (Berm20) and no extension of the existing dune (DuneEx). Berm80Dune20 represents an alternative with an 80 foot template berm width and a 20 foot dune extension. Also, each "design berm" option has been given a designation: maintaining a 0-foot berm (A), a 20-foot berm (B), a 40-foot berm (C), a 60-foot berm (D), and an 80-foot berm (E). Therefore a combined alternative of CBerm80Dune10 consists of an 80 foot berm template with a 10 foot extension of the existing dune that will maintain a berm of 40 feet between renourishments.

Table 5-7. St. Lucie County Beach-*fx* Nourishment Design Templates

Design Reach	Beach-*fx* Model Reaches	Representative Profile	Template Dune Height (ft-NAVD88)	Template Dune Width (feet)			Template Berm Width (feet)					
			Existing (2008) Dune Height	Dune Extension Increments			Berm Extension Increments					
				+0'	+10'	+20'	+0'	+20'	+40'	+60'	+80'	+100'
North Hutchinson Island	R077 to R080	P1	11	55	65	75	0	20	40	60	80	100
Power Plant Area	R081 to R083	P1	11	55	65	75	0	20	40	60	80	100
	R084 to R090	P2	13	35	45	55	0	20	40	60	80	100
Narrows of Hutchinson Island	R091 to R098	P1	11	55	65	75	0	20	40	60	80	100
South Hutchinson Island	R098 to R102	P1	11	55	65	75	0	20	40	60	80	100
	R103 to R104	P3	11	50	60	60	0	20	40	60	80	100
	R105 to R106	P4	11	120	130	140	0	20	40	60	80	100
	R107 to R110	P5	11	40	50	60	0	20	40	60	80	100
	R111	P6	11	60	70	80	0	20	40	60	80	100
	R112	P7	14	25	35	35	0	20	40	60	80	100
	R113 to R115	P8	13	50	60	70	0	20	40	60	80	100

Table 5-8. Beach-*fx* Distance Triggers and Threshold Volumes

Alternative	Fill Volume (Idealized)			Distance Triggers and Threshold Volumes																			
	Berm (cy)	Dune (cy)	Total (cy)	Trigger at Existing Dune (A)			Threshold Vol. (cy)	Trigger at 20' Berm (B)			Threshold Vol. (cy)	Trigger at 40' Berm (C)			Threshold Vol. (cy)	Trigger at 60' Berm (D)			Threshold Vol. (cy)	Trigger at 80' Berm (E)			Threshold Vol. (cy)
				Berm	Dune	Dune Ht		Berm	Dune	Dune Ht		Berm	Dune	Dune Ht		Berm	Dune	Dune Ht		Berm	Dune	Dune Ht	
Berm20DuneEx	292,551	0	292,551	0.00	0.99	0.90	280,000	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Berm40DuneEx	585,102	0	585,102	0.00	0.99	0.90	570,000	0.50	0.99	0.90	285,000	---	---	---	---	---	---	---	---	---	---	---	---
Berm60DuneEx	877,653	0	877,653	0.00	0.99	0.90	860,000	0.33	0.99	0.90	576,200	0.67	0.99	0.90	283,800	---	---	---	---	---	---	---	---
Berm80DuneEx	1,170,204	0	1,170,204	0.00	0.99	0.90	1,160,000	0.25	0.99	0.90	870,000	0.50	0.99	0.90	580,000	0.75	0.99	0.90	290,000	---	---	---	---
Berm100DuneEx	1,462,756	0	1,462,756	0.00	0.99	0.90	1,450,000	0.20	0.99	0.90	1,160,000	0.40	0.99	0.90	870,000	0.60	0.99	0.90	580,000	0.80	0.99	0.90	290,000
Dune10	0	165,291	165,291	0.00	Variable[1]	0.90	150,000	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Berm20Dune10	292,551	165,291	457,842	0.00	0.99	0.90	280,000	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Berm40Dune10	585,102	165,291	750,394	0.00	0.99	0.90	570,000	0.50	0.99	0.90	285,000	---	---	---	---	---	---	---	---	---	---	---	---
Berm60Dune10	877,653	165,291	1,042,945	0.00	0.99	0.90	860,000	0.33	0.99	0.90	576,200	0.67	0.99	0.90	283,800	---	---	---	---	---	---	---	---
Berm80Dune10	1,170,204	165,291	1,335,496	0.00	0.99	0.90	1,160,000	0.25	0.99	0.90	870,000	0.50	0.99	0.90	580,000	0.75	0.99	0.90	290,000	---	---	---	---
Berm100Dune10	1,462,756	165,291	1,628,047	0.00	0.99	0.90	1,450,000	0.20	0.99	0.90	1,160,000	0.40	0.99	0.90	870,000	0.60	0.99	0.90	580,000	0.80	0.99	0.90	290,000
Dune20	0	330,583	330,583	0.00	Variable	0.90	320,000	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Berm20Dune20	292,551	330,583	623,134	0.00	0.99	0.90	280,000	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Berm40Dune20	585,102	330,583	915,685	0.00	0.99	0.90	570,000	0.50	0.99	0.90	285,000	---	---	---	---	---	---	---	---	---	---	---	---
Berm60Dune20	877,653	330,583	1,208,236	0.00	0.99	0.90	860,000	0.33	0.99	0.90	576,200	0.67	0.99	0.90	283,800	---	---	---	---	---	---	---	---
Berm80Dune20	1,170,204	330,583	1,500,787	0.00	0.99	0.90	1,160,000	0.25	0.99	0.90	870,000	0.50	0.99	0.90	580,000	0.75	0.99	0.90	290,000	---	---	---	---
Berm100Dune20	1,462,756	330,583	1,793,338	0.00	0.99	0.90	1,450,000	0.20	0.99	0.90	1,160,000	0.40	0.99	0.90	870,000	0.60	0.99	0.90	580,000	0.80	0.99	0.90	290,000

[1] Dune width triggers for Dune10 and Dune20 alternatives are dependent on the dune widths of individual representative profiles

It should be noted that for the two dune extension only alternatives (Dune10 and Dune20), the dune distance trigger rather than the berm distance trigger is the primary renourishment trigger. In each of these case, the dune distance trigger, which is dependent on the dimensions of the representative profile, is the fraction of the total dune template that would remain once the dune extension has eroded. For example, the total dune template width for the Dune10 alternative at representative profile P1 is 65 feet (55 foot existing dune + 10 foot extension). Allowing 10 feet of erosion of the 65 foot dune would leave 85% of the total template dune width remaining. Therefore, the dune width distance trigger for Dune10 and profile P1 is 0.85. Table 5-9 provides dune width triggers for each of the representative profiles for the Dune10 and Dune20 alternatives.

Table 5-9. Dune Distance Triggers for Dune Extension Only Alternatives

Representative Profile	Dune10		Dune 20	
	Template Dune Width (ft)	Dune Distance Trigger	Template Dune Width (ft)	Dune Distance Trigger
P1	65	0.85	75	0.87
P2	45	0.78	55	0.82
P3	60	0.83	70	0.86
P4	130	0.92	140	0.93
P5	50	0.80	60	0.83
P6	70	0.86	80	0.88
P7	35	0.71	45	0.78
P8	60	0.83	70	0.86

Preliminary Beach-*fx* runs, along with assessment of potential benefits, allowed the initial array of 47 alternatives to be screened down to those most likely to provide an effective and justified Federal project. Initially, three of the original alternatives detailed previously in Table 5-8 comprised the final array. These consisted of the 10 foot dune extension only alternative (Dune10) and two berm templates constructed without extension of the existing dune (ABerm20DuneEx and ABerm40DuneEx). In order to ensure that the most economical template was isolated and based on economic incremental analyses (See **Economics Appendix** and **Main Text** for details), four additional refined alternatives were included in the final Beach-fx assessment (Table 5-10). The additional refined alternatives were:

1) Berm10DuneEx - A 10 foot berm with the existing dune extending over reaches R98 to R115
2) Berm30DuneEx - A 30 foot berm with the existing dune extending over reaches R98 to R115
3) Berm20DuneEx_R104 - A 20 foot berm with the existing dune extending over reaches R104 to R115
4) Berm30DuneEx_R104 - A 30 foot berm with the existing dune extending over reaches R104 to R115

Each of the alternatives that include berm features called for maintaining only the existing dune between noursishments (e.g. a 0 foot "design berm"). The complete final array of alternatives is presented in Table 5-11.

Table 5-10. Additional Alternatives

Alternative	Fill Volume (Idealized)			Distance Triggers and Threshold Volumes			
	Berm (cy)	Dune (cy)	Total (cy)	Trigger at Existing Dune (A)			Threshold Volume
				Berm	Dune	Dune Ht	
Berm10DuneEx	146,276	0	146,276	0	0.99	0.90	140,000
Berm30DuneEx	438,827	0	438,827	0	0.99	0.90	430,000
Berm20DuneEx_R104	206,507	0	206,507	0	0.99	0.90	200,000
Berm30DuneEx_R104	309,760	0	309,760	0	0.99	0.90	300,000

Table 5-11. Refined Array of Project Alternatives

Alternative	Description	Dune Extension (ft)	Maintained ("Design") Berm (ft)	Sacrificial ("Advance") Berm (ft)
Dune10	10' extension of the existing dune and beach profile	10	0	0
ABerm10DuneEx	0' extension of the existing dune and beach profile with a 10' berm template (0' design + 10' advance)	0	0	10
ABerm20DuneEx	0' extension of the existing dune and beach profile with a 20' berm template (0' design + 20' advance)	0	0	20
ABerm20DuneEx_R104	0' extension of the existing dune and beach profile with a 20' berm template (0' design + 20' advance) from R104 to R115	0	0	20
ABerm30DuneEx	0' extension of the existing dune and beach profile with a 30' berm template (0' design + 30' advance)	0	0	30
ABerm30DuneEx_R104	0' extension of the existing dune and beach profile with a 30' berm template (0' design + 30' advance) from R104 to R115	0	0	30
ABerm40DuneEx	0' extension of the existing dune and beach profile with a 40' berm template (0' design + 40' advance)	0	0	40

6 Protective Beach Design

Based on Beach-*fx* model results and economic evaluation, project alternative ABerm20DuneEx (a 20 foot berm template designed to maintain the existing dune between renourishments) was identified as the Recommended Plan for nourishment of St. Lucie County. Note that during economic incremental analysis it was found that reach R98 for this alternative was not economically justified. It was therefore removed. A description of this shore protection plan is provided in the following sections.

6.1 Project Length

The full study area (7.4 miles), extending from FDEP monument R-77 to the Martin County line, was initially considered during project evaluation using Beach-*fx*. The selected alternative, ABerm20DuneEx, covers approximately 3.2 miles of the study area. The beach fill will be placed from FDEP monument R-99 to the Martin County line with tapers extending approximately 1,000 feet to the north of R-99 and approximately 1,000 feet south of the Martin County line. As Martin County, south of St. Lucie is part of an authorized Federal project, future nourishment events may be timed to tie into the southern project, negating the need for a taper.

6.2 Project Design

The project design can be described by three factors, the dimensions of the dune, dimensions of the berm, and shoreline slopes.

6.2.1 Project Dune

Existing dune elevations in the project area are between 11 and 14 ft-NAVD88. Evaluation of the design alternatives has shown that the existing elevations, when combined with a berm and/or dune extension, provide sufficient protection. No additional elevation is included in the selected design plan.

Existing dune widths in the project area are variable, with average widths between 25 feet and 120 feet between R-99 and the Martin County line (see Table 5-3). No additional elevation is included in the project design plan.

6.2.2 Project Berm

The design berm elevation in the project area is 7 ft-NAVD88, which approximates the natural berm elevation. 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 may increase the probability of overtopping, thereby offering less protection to upland development and/or existing dunes, by allowing more wave energy (which increases with depth) to reach the dune. A higher berm may also be more susceptible to wind-induced erosion.

The project berm template consists of 20 feet of sacrificial fill (traditionally referred to “advance” fill) designed to protect and maintain the existing dune between renourishment events.

6.2.3 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. In St. Lucie County, the native beach slopes in the project area are approximately 1 (vertical) on 6 (horizontal) at the dune, 1 on 10 from the berm to MLW (-2.5 ft-NAVD88), and 1 on 40 to 1 on 70 below MLW. The estimate of the slope of the material after adjustment is based on averaging the beach profile slopes of the native beach from the mean low water datum to the approximate location of the 15 foot depth contour. Sand from the project borrow site was determined to be a near match to the gradation and shell content of the existing beach. This will allow the beach fill to equilibrate to a shape similar to the existing profile.

It is unnecessary and impractical to artificially grade beach slopes below the low water elevation since they will be shaped by wave action. For this reason, 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.

6.2.4 Project Volumes

Traditionally, beachfill designs have been presented as a set of three cross-sectional templates, the design template, which is based on an equilibrium profile translated seaward by the desired width of the berm or MHW extension; the advanced nourishment template, which represents the volume of material that is expected to erode between successive renourishment intervals; and the construction template, which includes both the design and advanced fill quantities, but incorporates the wider berm and steeper slope that reflects the capabilities of the construction equipment. Beach-*fx* does not automatically incorporate "design" and "advance" features. Instead, the user can loosely establish these separate features within the nourishment template through the use of renourishment triggers and the threshold volume. The traditional "design berm" becomes the minimum width past which further erosion will trigger an assessment of the project's volume requirements compared against the volume threshold. By default, the portion of the nourishment template allowed to erode as sacrificial fill prior to triggering the volume assessment fulfills the role of the traditional "advance fill". This allows the user to optimize the total nourishment template based on a risk based, comprehensive assessment of the complete project.

Beach-*fx* begins with a designated nourishment template. Each life-cycle simulation then applies randomly generated storms, storm erosion, and natural background shoreline change rates. At one year intervals the model evaluates the resulting shoreline against two criteria (1) whether shoreline position at one or more reaches has exceeded one or more planned nourishment triggers and (2) whether the total volume presently required to fill the original nourishment template exceeds the mobilization threshold. If both criteria are met then a renourishment event is initiated. There are three planned nourishment triggers in Beach-*fx*: berm width, dune width, and dune height. Each trigger indicates what percentage of the design template berm width, dune width, or dune height must be present to *prevent* a renourishment (for example, a 0.90 dune width trigger means that 90% of the total template dune width must remain intact. If 10% or more of the template dune width is eroded, the first criteria for initiating a planned renourishment event has been met). Should the allowable erosion be exceeded in one or more reaches, then Beach-*fx* computes the volume required (over all of the *triggered* nourishment reaches) required to fill the original design template and compares that volume to the mobilization threshold. If the mobilization threshold is exceeded a renourishment over *all* planned nourishment reaches occurs and the model continues through the remainder of the life-cycle.

For St. Lucie County ABerm20DuneEx_R104, the berm width, dune width, and dune height planned nourishment triggers were set at 0, 0.91, and 0.9, respectively. The mobilization threshold was set to 280,000 cubic yards. Together, the triggers and the mobilization threshold allow for the optimization of the beach fill based on the physical dimensions of the project as well as assumptions regarding tolerable erosion limits and reasonable fill volumes (See Section 5.5.2.2: Nourishment Distance Triggers and Mobilization Threshold).

Each complete Beach-*fx* model run consists of 100 iterations, each iteration representing the life of the project (50 years for St. Lucie). Based on the ABerm20DuneEx alternative (100 iteration runs), a range of volumes 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, Intermediate, and High. Table 6-1 provides minimum, maximum, and average fill volumes (for both initial and renourishment events) and renourishment intervals over the life of the project. Based on the 100 Beach-*fx* life-cycle iterations from which this data is drawn, the 90% confidence interval for each parameter was determined and is also presented in Table 6-1.

Table 6-1. Project Volumes

Project Volumes (Over 100 Beach-*fx* Life-cycle Iterations)					
Sea level change Case	Volume Description	Initial Fill Volume (cubic yards)	Renourishment Interval (years)	Average Volume per Interval (cubic yards)
Base	Min - Max	329,100 – 842,700	1 – 38	282,900 – 705,200
	Average	422,000	18	390,000
	90% Confidence Interval	406,700 – 437,400	17 - 19	315,300 – 412,600
Intermediate	Min - Max	355,900 – 549,400	1 – 10	291,600 – 737,600
	Average	364,400	8	391,900
	90% Confidence Interval	359,600 – 369,200	7 - 8	372,400 – 411,300
High	Min - Max	422,800 – 631,100	1 - 4	319,300 – 773,400
	Average	434,900	4	418,000
	90% Confidence Interval	429,700 – 440,100	4 - 4	406,200 – 429,800

Note that the 90% confidence interval indicates a 90% confidence that the average parameter (volume, interval) will fall within the indicated range of values. Average values are generally used for design purposes and project volumes within the 90% confidence interval are available (over the life of the project) from the identified borrow site (See the Geotechnical Appendix for borrow site specifics). However, for a better understanding of the risk level(s) associated with the minimum and maximum values indicated in Table 6-1 a more detail statistical presentation is required.

Figure 6-1 provides the frequency distribution of initial fill volumes over the 100 iterations of the 50 year life of the project for the Base SLC scenario. From this figure it can be seen that majority (95%) of initial fill volumes fall between 350,000 cubic yards and 550,000 cubic yards with minimal occurrences (5% or less) of volumes greater or less than these values.

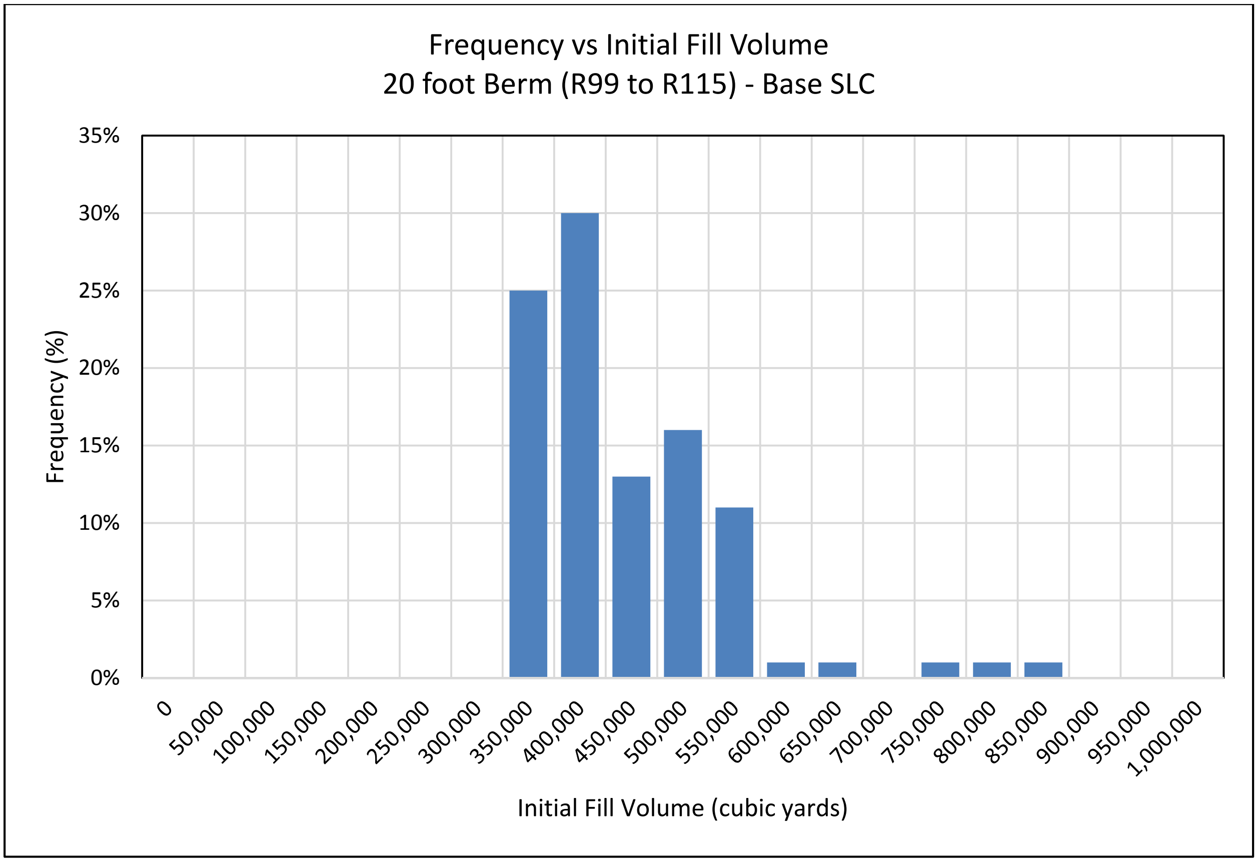

Figure 6-1. Frequency Distribution: Initial Fill Volume

Figure 6-2 provides the frequency distribution of renourishment fill volumes over the 100 iterations of the 50 year life of the project for the Base SLC scenario. In this case the majority (94%) of the renourishment fill volumes fall between 300,000 cubic yards and 550,000 cubic yards with minimum occurrences (5% or less) of volumes greater or less than these values.

To determine the risk associated with a given volume requirement, cumulative distributions were estimated for both the initial fill and renourishment fill volumes. Table 6-2 provides a look-up table for both the frequency and cumulative frequency distributions. For each volume the cumulative frequency indicates the probability that the volume required to complete a fill will exceed the volume indicated. For example, in Table 6-2 the probability of the initial fill volume exceeding a volume of 350,000cy is 75% while the probability of the initial fill volume exceeding 550,000 cubic yards is only 5%. Similarly, the probability that the renourishment volume will exceed 300,000 cubic yards is 90% while the probability that the volume will exceed 550,000 cubic yards is only 6%.

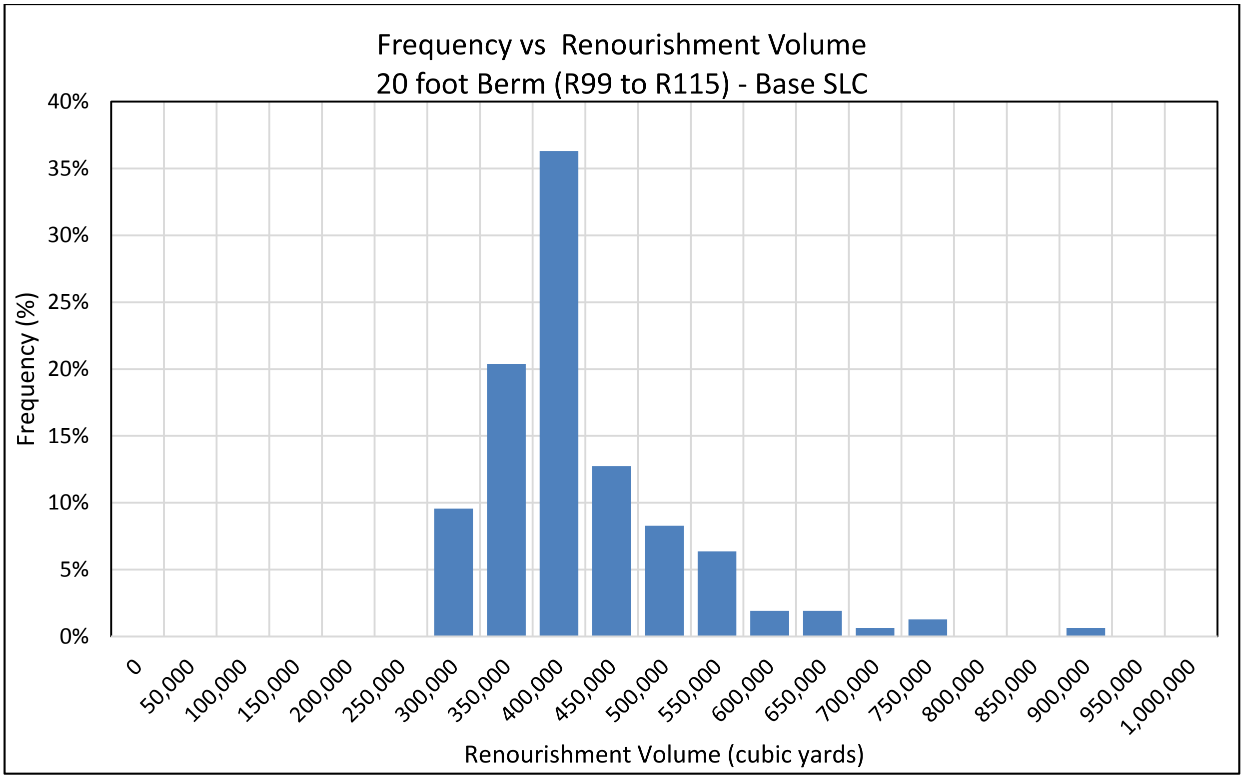

Figure 6-2. Frequency Distribution: Renourishment Fill Volume

6.3 Project Construction

The Recommended Plan for St. Lucie County results in a protective berm that extends the entire (2008) beach profile (7 ft-NAVD88 to depth of closure) 20 feet seaward from the existing dune. Due to erosion, foot traffic, and intermittent repairs and maintenance, the project shoreline does not have a smooth, consistent dune feature. In order for the nourishment project to provide the maximum benefit and perform as predicted during the Beach-*fx* shoreline analysis, it is necessary to establish a smooth, relatively straight base construction reference line and to ensure that the dune is free of gaps and low points that would allow storm surge to penetrate at elevations inconsistent with the representative dune height(s) specified for the model reaches.

Beach-*fx* estimates that initial construction of the ABerm20DuneEx template will require between 329,100 and 842,700 cubic yards of material. The wide difference between the minimum and maximum estimate is due to the probabilistic nature of the Beach-*fx* model. At the time of initial construction, the total volume required to complete the project template depends upon how much of the shoreline has eroded between the start of the simulation and the projected date of project completion. During the 100 iterations of the 50 year lifecycle that were modeled for each alternative design, randomly generated storm activity varied from mild to intense. This allowed for light and heavy degrees of erosion to occur between the model start date (2019) and the model base year (2020). The minimum predicted initial placement volume reflects mild storm activity prior to construction, while the maximum predicted initial placement volume reflects intense storm activity. The average initial construction volume over all iterations was determined to be 422,000 cubic yards.

Table 6-2. Frequency Distribution Tabulated Values

Volume	Frequency Distribution		Cumulative Frequency Distribution	
(cubic yards)	Initial Fill	Renourishment	Initial Fill	Renourishment
0	0%	0%	100%	100%
50,000	0%	0%	100%	100%
100,000	0%	0%	100%	100%
150,000	0%	0%	100%	100%
200,000	0%	0%	100%	100%
250,000	0%	0%	100%	100%
300,000	0%	10%	100%	90%
350,000	25%	20%	75%	70%
400,000	30%	36%	45%	34%
450,000	13%	13%	32%	21%
500,000	16%	8%	16%	13%
550,000	11%	6%	5%	6%
600,000	1%	2%	4%	4%
650,000	1%	2%	3%	3%
700,000	0%	1%	3%	2%
750,000	1%	1%	2%	1%
800,000	1%	0%	1%	1%
850,000	1%	0%	0%	1%
900,000	0%	1%	0%	0%
950,000	0%	0%	0%	0%
1,000,000	0%	0%	0%	0%
1,050,000	0%	0%	0%	0%
1,100,000	0%	0%	0%	0%
1,150,000	0%	0%	0%	0%
1,200,000	0%	0%	0%	0%
1,250,000	0%	0%	0%	0%
1,300,000	0%	0%	0%	0%
1,350,000	0%	0%	0%	0%
1,400,000	0%	0%	0%	0%

6.4 Renourishment Events

Traditionally, renourishment events take place based on both an economically optimized renourishment interval and the physical performance of the project. Project performance, in the past, has been determined by assessing the condition of the design template. Should the design template be breached, the project is no longer providing the required level of protection and is considered for renourishment. Part of this consideration is how close the project may be to the designated renourishment interval.

While the basic principles of renourishment still apply, due to the probabilistic nature of Beach-*fx* and the way in which the model assesses renourishment requirements, a new means of assessing project performance must be employed. The former concepts of "design template" and "advance fill" are only loosely applicable. As shown in Figure 6-3 the entire 20 foot berm and beach profile extension template acts as the "advance fill", while the existing beach profile is the minimum acceptable profile (making it akin to what was formerly the "design template").

Assessing the performance of the project fill now has two stages. First, a survey of the project area (such as a monitoring or post-storm survey) will be assessed to determine if the shoreline at any of the R-monument locations within the project have receded past the pre-project (2008) condition. If recession beyond the pre-project condition has occurred at one or more of the R-monuments, then a summation of the volume required to restore those profiles to the initial construction template will be made. If the total volume required to restore the receded profiles exceeds the threshold volume

(280,000 cubic yards), then a renourishment event is recommended. The decision to renourish may then be made based on traditional concerns, including such factors as budget cycle and available funding.

6.5 Project Construction

As previously discussed, the front slope of the beach fill placed at the time of construction or future renourishment may differ from that of the natural profile. This reflects the capabilities of the construction equipment that will be used to build the shore protection project. Within the first year or two after placement of the beachfill, the construction profile will be reshaped by waves into an equilibrium profile, causing the berm to retreat to a position more characteristic of the project design template.

Based on the estimated **average** initial fill volume and constructability considerations, a construction template applicable to ABerm20DuneEx was determined. The construction template (shown in Figure 6-3) consists of a variable width berm with a 1 on 100 slope and foreshore fill extending to approximately -5.0 ft-NAVD88 with a slope of 1 on 5.   This template, dimensioned for constructability, will then equilibrate into the project (20 foot berm and profile extension) template. The volume of material in the equilibrated profile (between the template and the "existing" condition) represents the material that is expected to erode between successive nourishment events.

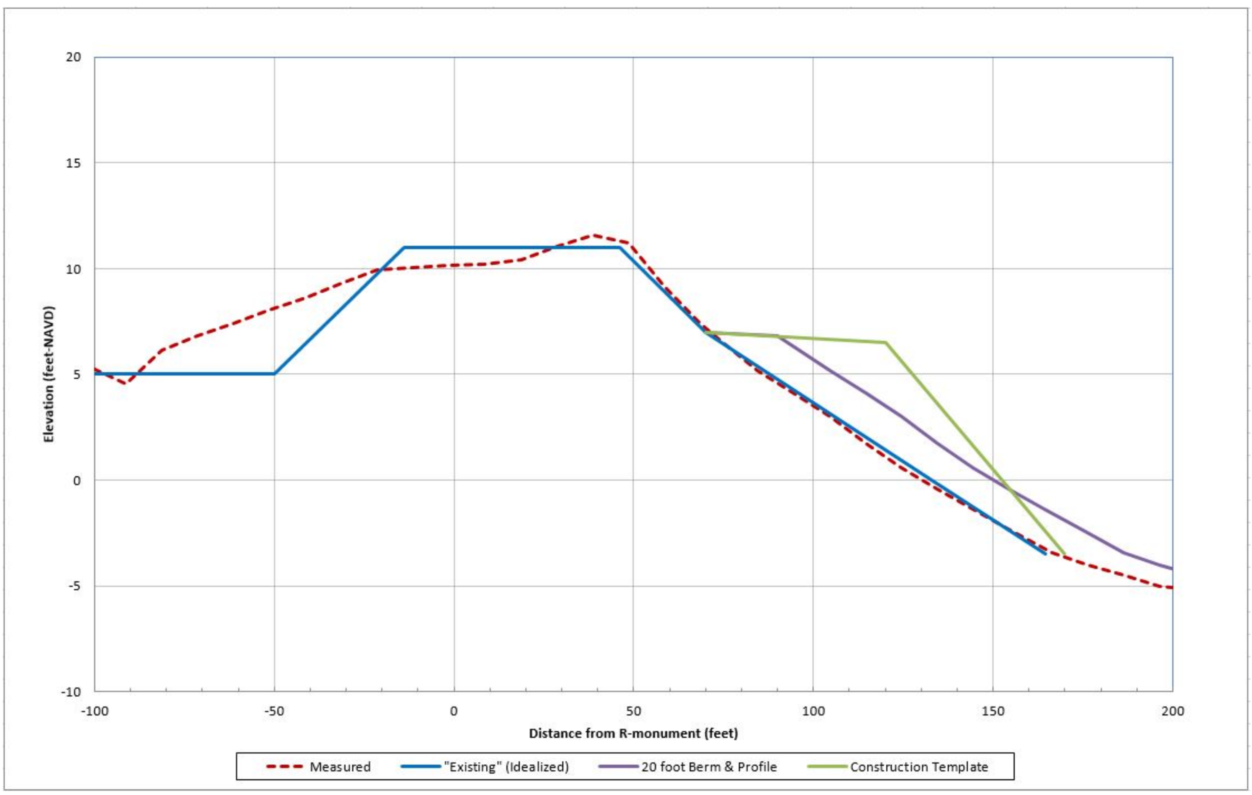

Figure 6-3. Typical Profile Sketch

6.6 Project Construction Line

The project construction reference line was established based on the 2008 “existing” dune and profile survey. The seaward toe of the dune (intersection between the dune and berm) was determined. Table 6-3 provides the location of the construction reference line relative to each FDEP R-monument. The elevation of the construction reference line is a consistent +7 ft-NAVD88 (the nourishment template berm elevation). Initial project construction will complete the entire beach-*fx* nourishment template for the ABerm20DuneEx plan. This will include restoration and/or leveling of the 2008 dune behind the construction reference line as well as extension of the berm.

Table 6-3. St. Lucie Project Construction Reference Line

FDEP R-Monument	Distance Relative to R-mon (feet)
R-99	14
R-100	8
R-101	22
R-102	25
R-103	114
R-104	75
R-105	62
R-106	95
R-107	63
R-108	132
R-109	120
R-110	68
R-111	33
R-112	93
R-113	116
R-114	65
R-115	82

6.7 Project Monitoring

Physical monitoring of the project is necessary to assess project performance and to ensure that project functionality is maintained throughout the 50-year project life. The monitoring plan will be directed primarily toward accomplishing systematic measurements of the beach profile shape. Profile surveys should provide accurate assessments of dune and beach fill volumes and a basis for assessing post-construction dune and beach fill adjustments, as well as variation in the profile shape due to seasonal changes and storms. Monitoring will play a vital role in determining if project renourishment is necessary. Post construction monitoring activities include topographic and bathymetric surveys of the placement area on an annual basis for 3 years following construction and then biannually until the next construction event. The cost for this post construction monitoring is included in the cost shared total project cost.

Other monitoring efforts include bathymetric mapping of the borrow site, which will be done as part of the pre-construction engineering and design (PED) phase prior to each nourishment.

Measured wind, wave, and water level information will be obtained from the best available existing data sources. This data will be applied in support of previously discussed monitoring efforts. It will also be used to periodically assess the state of sea level rise and to determine if reassessment of the project volumes and/or renourishment intervals based on an intermediate of high SLR case is required.

7 Project Summary

This appendix summarizes the engineering design of a shore protection project proposed for construction in St. Lucie County, Florida. The project consists of beach nourishment/renourishment along approximately 3.2 miles of shoreline between FDEP monuments R-99 and the Martin County line. The design beach fill template is characterized by a 20 foot berm extension (+7 ft-NAVD88 to Depth of Closure) from the existing dune. Beach fill material required under the Base SLR case includes an average of 422,000 cubic yards for initial construction of the design beach profile and two to three renourishment events averaging 390,000 cubic yards each (Table 6-1). Total cost of initial project construction (based on average volume requirements) is estimated at $20.2 Million. Those costs would include the plans and specifications surveys of the project area and borrow site for construction, and the cost of a volumetric survey after initial construction for payment. Future periodic nourishment costs are estimated at $33 Million, with periodic nourishment expected at approximately 18 year intervals. Assuming that the Base SLR case applies, an estimate of the total cost incurred over the 50-year project life is $53.3 Million.

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