HASHAMOMUCK COVE
COASTAL STORM RISK MANAGEMENT
FEASIBILITY STUDY

DRAFT

APPENDIX C

COASTAL ENGINEERING

June 2016

1.0 Introduction

The U.S. Army Corps of Engineers (USACE) New York District is conducting a coastal storm risk management study for Hashamomuck Cove, in the Town of Southold, NY (Suffolk County). The study area includes approximately 1.5 miles as shown in Figure 1. The ultimate goal of the study is to formulate a coastal storm risk management plan/project for Hashamomuck study area covering a 50 year period of analysis with a projected construction start date of 2019 that maximizes net economic benefits and is feasible from both an environmental and constructability standpoint.

Figure 1: Project Location

The purpose of this appendix is to describe, in detail, the Coastal Engineering input driving the Beach-fx software for the Hashamomuck Cove study area. This includes developing the representative reaches for the study area, a historical storm suite, historic shoreline change conditions, and profile response to the array of storm events using SBEACH.

1.1 Prior Reports: Prior reports that have been prepared documenting coastal erosion and storm damages along the north shore of Long Island Sound and the Hashamomuck Cove Study Area in Southold, New York include:

- USACE, New York District, June 2008, Section 905(b) Reconnaissance Study, New York District. The report recommended a Feasibility Study that included the Hashamomuck Cove study area.
- Long Island North Shore Heritage Area Planning Commission, 2005, Long Island North Shore Heritage Area Management Plan. This report includes information on resources in the study area.
- USACE, New York District, 1995, North Shore of Long Island, New York, Storm Damage Protection and Beach Erosion Reconnaissance Study, New York District. This report further described erosion (including erosion rates) and coastal storm damage along the north shore of Long Island, including discussion of the Hashamomuck Cove area.
- New York State University, circa 1973, North Shore of Long Island Sound, Technical Report #18. Report evaluates areas along the north shore but did not include Hashamomuck Cove study area specifically.
- USACE, New York District, 1969 Survey Report of the North Shore of Long Island. This Survey Report addressed conditions along the entire north shore of Long Island, including within the study area. Erosion and coastal storm damage problems were identified, and general opportunities to address these problems for the North Shore of Long Island were discussed.

2.0 Coastal Setting and Processes

This section provides a summary of the key environmental conditions, active coastal processes, and the geological framework that characterize the vulnerability of Hashamomuck Cove to economic losses through coastal storm-induced damages to existing infrastructure.

2.1 Coastal Setting

Climate. Suffolk County has a moderate coastal climate with warm, humid summers and moderately cold winters. The temperature averages 51 degrees Fahrenheit (°F) annually, ranging from a low monthly average of 32°F in February to a high monthly average of 72°F in July. The average annual precipitation ranges from 40 to 45 inches and is fairly evenly distributed throughout the year.

2.2 Sediment Grain Size Analysis

Twenty-eight sediment samples were analyzed for grain size distribution (ASTM D 422-63, reapproved 2002) in the New England District's Environmental Laboratory. Sediment samples were collected from ten transects within the Study Area, three in West Cove, four in Central Cove, and three in East Cove as part of environmental sampling for the study (see Appendix A2). Within these transects, samples were collected from the low intertidal zone, the medium intertidal zone, and the high intertidal zone and submitted for grain size analyses. The locations of the transects are illustrated in Figure 2.

Figure 2 – Sediment Transects

The results of the grain size analysis are summarized in Table 1 below. The sediments collected from all stations were generally represented by various fractions of gravel and sand. The data show that 10 stations were dominated by gravels, 5 stations were dominated by sands, 12 stations had a similar mix of sands and gravels, and 1 station was dominated by cobble. The presence of cobble at all stations may be underrepresented due to the nature of the sediment sampling device used (a 0.003 m^2 core), however, it is noted that cobble was not specifically avoided during sampling.

Table 1 - Grain Size Summary

Sample ID	%Cobble	%Gravel		%Sand			%Fines
		Coarse	Fine	Coarse	Medium	Fine	
T1-H	0.0	11.0	35.6	13.6	33.3	2.7	3.8
T2-H	0.0	64.5	0.4	0.4	22.9	11.8	0.0
T3-H	0.0	53.2	16.1	0.5	26.3	4.0	0.0
T4-H	0.0	15.1	62.8	6.4	15.3	0.4	0.0
T6-H	0.0	34.8	2.5	1.1	26.6	35.0	0.0
T7-H	0.0	52.1	10.1	0.1	22.8	14.8	0.0
T8-H	0.0	28.6	24.4	4.0	41.2	1.8	0.0
T9-H	0.0	35.2	18.0	0.5	40.3	6.0	0.0
T10-H	0.0	24.3	48.0	6.4	18.0	3.4	0.0
T1-M	0.0	6.2	38.7	24.1	29.8	1.2	0.0
T2-M	0.0	7.0	22.0	32.6	36.2	2.2	0.0
T3-M	0.0	19.7	39.4	19.7	19.8	1.4	0.0
T4-M	0.0	35.9	44.0	9.8	9.8	0.4	0.0
T6-M	0.0	9.2	17.7	8.3	49.3	15.4	0.0
T7-M	0.0	17.0	25.8	14.8	39.8	2.5	0.0
T8-M	0.0	44.8	31.3	8.0	14.5	1.5	0.0
T9-M	0.0	31.3	22.5	9.2	36.1	0.8	0.0
T10-M	0.0	39.8	45.4	10.6	4.1	0.1	0.0
T1-L	0.0	15.5	77.0	6.7	0.9	0.0	0.0
T2-L	0.0	7.1	40.9	24.7	24.5	2.7	0.0
T3-L	0.0	14.0	31.9	34.4	19.3	0.5	0.0
T4-L	78.3	15.6	3.3	1.3	1.4	0.1	0.0
T5-L	0.0	3.5	17.2	13.9	63.3	2.0	0.0
T6-L	0.0	27.3	31.6	9.5	26.5	5.1	0.0
T7-L	0.0	7.5	24.2	12.3	45.1	10.9	0.0
T8-L	0.0	28.4	31.2	13.3	22.5	4.6	0.0
T9-L	59.7	51.7	5.0	1.8	1.2	0.0	0.0
T10-L	0.0	13.0	63.1	5.7	15.3	2.9	0.0

The sediment to be used for initial fill and future nourishment will be compatible with the native beach material. Additional data to characterize the beach material including the foreshore will be collected during pre-construction engineering and design (PED). On-shore sand sources will be determined during the PED phase of the project.

2.3 Sea Level Rise

The mean sea level trend at Montauk, New York (NOAA 8510560) is 0.00961 feet/year based on regionally corrected mean sea level data from 1947 to 2014 (Figure 3). This gauge was selected to represent the project site because it was the closest long term gauge to the project location. The only other gauge on Long Island is short term < 50 years and was therefore excluded.

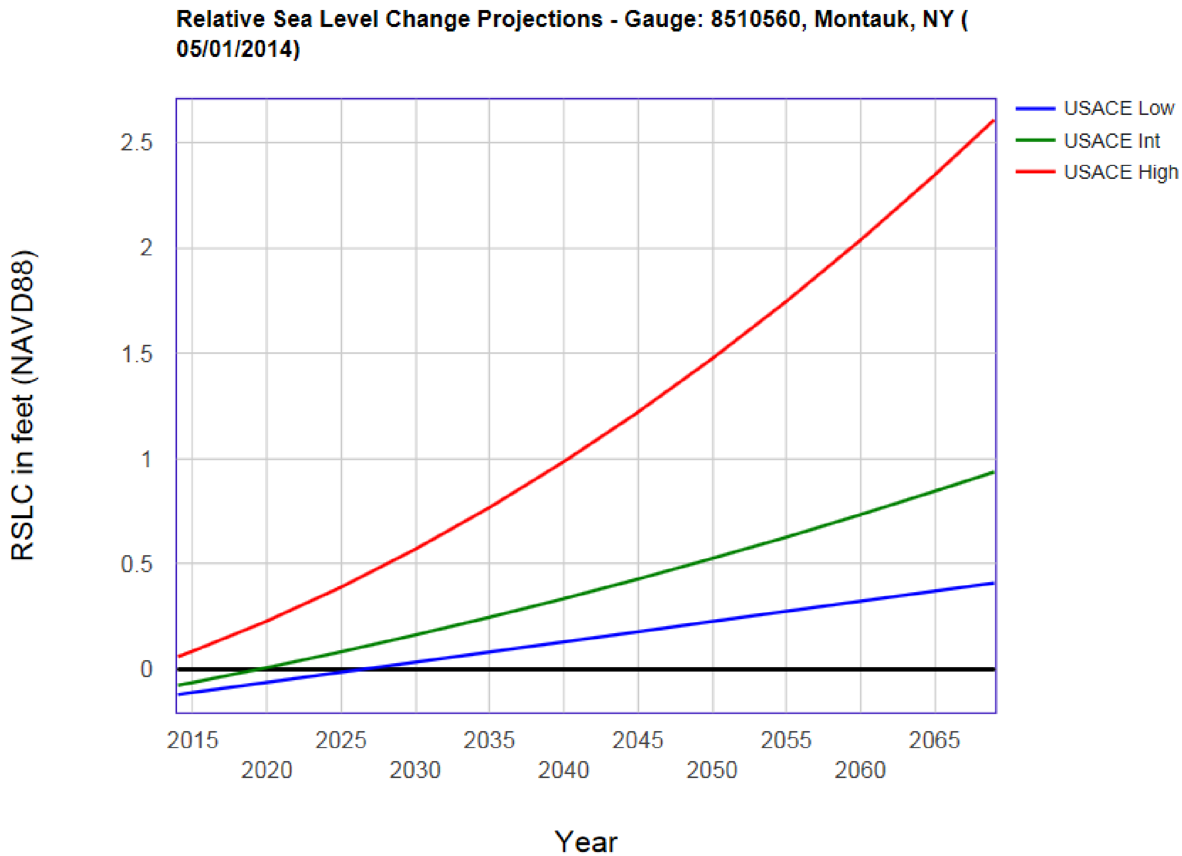

Figure 3: Mean sea level change trend at Montauk, NY.

This historical rate of mean sea level change trend of 0.00961 feet/year was applied in all Beach-fx simulations representing the "Low" future rate of sea level change in accordance with EC 1165-2-212. The "Intermediate" rate of future sea level change was computed using modified NRC Curve 1 and equations 2 and 3 in EC-1165-2-212 Appendix B. The "High" rate of future sea level change was computed using modified NRC Curve III and equations 2 and 3 in EC-1165-2-212 Appendix B. The relationships for future sea level change as outlined in EC-1165-2-212 are coded within Beach-fx and sea level change is internally computed continuously throughout the simulated project lifecycle.

2.4 Coastal Storm Climatology

Historical Storms: Two types of storms of primary significance along the North Shore are tropical storms (hurricanes), which typically impact the New York area in summer and fall and extratropical storms (nor'easters), which are primarily winter storms. Nor'easters are usually less intense than hurricanes but tend to have much longer durations. These storms often cause high water levels and intense wave conditions and are responsible for significant erosion and flooding throughout the coastal region of the north shore. For general information purposes, Table 2 lists several storms that have had impacts in the New York area. For the coastal modelling, the NACCS data (2015) was used (see Section 3.2).

Table 2 – List of Historical Storms

Hurricane		**Nor'easter**	
Date	Name	Date	Name
14 Sep 1904		03 Mar 1931	
08 Sep 1934		17 Nov 1935	
21 Sep 1938		25 Nov 1950	
14 Sep 1944	-	06 Nov 1953	
31 Aug 1954	Carol	11 Oct 1955	
02 Sep 1954	Edna	25 Sep 1956	
05 Oct 1954	Hazel	06 Mar 1962	
03 Aug 1955	Connie	05 Nov 1977	
12 Sep 1960	Donna	17 Jan 1978	
10 Sep 1961	Esther	06 Feb 1978	
20 Aug 1971	Doria	22 Jan 1979	
14 Jun 1972	Agnes	22 Oct 1980	
06 Aug 1976	Belle	28 Mar 1984	
27 Sep 1985	Gloria	09 Feb 1985	
19 Aug 1991	Bob	30 Oct 1991	
08 Oct 1996	Josephine	01 Jan 1992	
07 Sep 1999	Floyd	11 Dec 1992	
01 Sep 2006	Ernesto	02 Mar 1993	
28 Aug 2011	Irene	12 Mar 1993	
29-30 Oct 2012	Sandy	28 Feb 1994	
		21 Dec 1994	
		05 Jan 1996	
		06 Oct 1996	
		02 Feb 1998	
		14 Apr 2007	
		15 Nov 2009	Nor'Ida
		13 Mar 2010	
		25 Dec 2010 (added)	
		17 Apr 2011	
		7 Nov 2012 (added)	
		26 Dec 2012 (added)	

Notes: Nor'easters generally have no assigned names. Hurricane Sandy affected the project area in late October, 2012, followed by two Nor'easters. This table list historical storms affecting the New York Area.

SOURCE: Beach Erosion Control and Storm Damage Reduction Feasibility North Shore Of Long Island, Asharoken, New York, Engineering Appendix, Draft March 2014.

Coastal Processes: Existing coastal processes at Hashamomuck Cove are driven by high energy waves and water levels generated by both tropical and extratropical storms. Based on data from the North Atlantic Coast Comprehensive Study (NACCS, 2015), significant tropical storm events impacted the Hashamomuck Cove shoreline at a frequency of approximately once every 6.8 years. These tropical storms occur between June and November with 74 percent of them occurring in the months of August and September. Extratropical storms, on the other hand, are a frequently occurring storm type that impacts Hashamomuck Cove annually with significant events occurring at a rate of approximately 1.2 storms per year. Extratropical storms typically occur at the project location between early fall through the spring (October through May) with most occurring in the months of November through February. Tropical storm events are typically fast moving storms associated with elevated water levels and large waves whereas extratropical storms are slower moving with comparatively lower water level elevations and large wave conditions. Both storm types can produce beach erosion and morphology change as well as coastal inundation leading to economic losses to improved property within the study area.

Although economic losses are most often realized in the wake of major storm events, it is long-term chronic erosion that creates the vulnerability to major economic losses through volumetric depletion of beach material in the active profile, reduction in beach berm width and reduction in dune crest elevation and dune volume. Not all storms in the storm climatology produce measurable economic damages but they contribute to setting up vulnerability for economic losses. The long-term chronic erosion is driven by gradients in the longshore sand transport rate and depends on sediment supply from updrift beaches.

Beach Erosion: Coastal erosion is a shore process that reduces the width of the beach. These processes include long-shore and cross-shore sediment transport resulting from both typical and storm induced wave conditions. In some cases, the storm-induced erosion component of beach change, although devastating to development, may be short-term in nature. Following storms, the coastline tends to reshape itself into its former configuration, and some of the sand displaced from the beach is returned by wave action. The beach shape then conforms to the prevailing wave climate and littoral processes. However, over time, portions of the beach can experience permanent land loss. In developed areas bulkheads and revetments will help to limit landward erosion but may these structures may fail due to toe erosion and wave overtopping.

3 Beach-fx Modelling

3.1 Introduction

The Beach-fx software was utilized to analyze the physical performance of storm damage reduction alternatives in the Hashamomuck cove study area as well as the economic benefits and costs. Beach-fx is an event-based, Monte Carlo life cycle simulation tool capable of estimating storm damage along coastal zones caused by erosion, flooding, and wave impact. The software also calculates the economic benefits and costs associated with alternatives designed to reduce storm damages. Inputs are required from meteorology, coastal morphology, economics, and management processes. Within Beach-fx, data elements are stored in a relational database where rules for applying the data elements are inherent in the program (Gravens et. al. 2007). The data necessary to run a Beach-fx project provide a full description of the coastal area under study. The software requires an inventory of structures susceptible to damage, a set of historically-based possible storms that can impact the area, the estimated morphology response of the beach to each storm in the storm set, and damage-driving parameters for estimating inundation, erosion, and wave impact damages on the structures. The collection of beach profile responses to various historical storms was developed using SBEACH (Storm induced BEAch CHange), a cross-shore beach morphology program within the CEDAS (Coastal Engineering Design & Analysis System) package.

The unit of analysis in a shoreline storm damage reduction project is the shoreline area. Within the Beach-fx planning context, the project is divided into reaches, which are defined as contiguous, morphologically homogeneous areas. Reaches are defined and grouped by profile, or cross sections of the beach which characterize the beach morphology. Each reach contains a given number of lots and each lot contains one or more damage element, such as a residential home or nonresidential structure.

3.2 Development of Storm Suite

The North Atlantic Coast Comprehensive Study (NACCS) addresses the coastal areas defined by the extent of Hurricane Sandy's storm surge in the District of Columbia and the States of New Hampshire, Massachusetts, Connecticut, Rhode Island, New York, New Jersey, Pennsylvania, Delaware, Maryland, and Virginia. The Engineer Research and Development Center (ERDC) conducted rigorous regional statistical analysis and detailed high-fidelity numerical hydrodynamic modeling for the North Atlantic coastal region to quantify coastal storm wave, wind, and storm-driven water level extremes. The NACCS modeling efforts included the latest atmospheric, wave, and storm surge modeling and extremal statistical analysis techniques. Products from this work incorporated into the Coastal Hazards System (CHS) database include simulated winds, waves, and water levels for approximately 1,050 synthetic tropical events and 100 extratropical events computed at over 3 million computational locations. A smaller number -18,000 locations -save the same information at higher frequency for more convenient/concise data handling. These storm events are determined to span the range of practical storm probabilities.

Figure 3 shows the location of the storm surge (ADCIRC) and wave (STWAVE) save points in the Hashamomuck project area. Storm surge data was extracted at ADCIRC save point 5020 and STWAVE 1346 located at 41.1025 N and 72.4009 W in water depth of 11.9952 m (see figure 1). This save point was considered as representative of the farthest offshore extent of the representative profiles in the area. The extratropical storms cover the period from January of 1938 to December of 2012.

Figure 4 - CHS Save Points Location Map

Extratropical storms were identified based on a minimum storm surge threshold of 1 foot and a minimum duration of 12 hours. Time series and peak surge and wave data were obtained from CHS database for the 100 Extratropical storm events. Table 3 shows the number of storms occurring within specified surge and wave height ranges. Time series of wave data for storms 55, 9, 71, 97, 98, 99 and 100 was not available and accordingly, these storms were not included in the analysis. Additionally, storm 3 was ignored in the analyses with storm surge less than 1.0 ft. This resulted in a total of 92 storms included in the analysis over a 75 year time period.

To reduce the number of storms response runs required in SBEACH the time series of storm surge and wave height, within each range shown in Table 4, were examined and representative storms were selected for the set of storms. The 100 Extratropical storm events were reduced to 25 events listed in Table 5. Figure 5 shows the storm surge and wave height for the selected representative Extraropical storm events.

Storm Surge (ft)	Wave Height ,Hs (ft)	Storms	Representative Storm
>5		7, 62,11,27,37,41,35	7,62,11,27,37,41,35
5-Apr	>5	21,26,33,13,22,39	26,33,13,39
	5>Hs>4	25,23,50,60	50
	4>Hs>1	4,31,86	31
3.5-4	>5	2,29,54	29
	5>Hs>4	49,20,17,5	17
	4>Hs>1	28	28
3-3.5	>5	68,64,67	67
	5>Hs>4	53,90,69,19,14,58,15,43	58
	4>Hs>1	16,66,94,72	
2.5-3	>5	24,6,83,88,18,12	83
	5>Hs>4	56,70,77	77
	4>Hs>1	47,34,48,1,78,51,93,61,52	1
2-2.5	>5	32,30,57,81,8,74	32
	5>Hs>4	73	
	4>Hs>1	65,40,80,63,79,44,89,10	10
2-Jan	>5	96,36,45	96
	5>Hs>4		
	4>Hs>1	91,76,95,75,42,85,84,92,59,87,38,82,46	75

Table 3 - Extratropical storm events

Storm Event No.	Start Date		End Date	
1	21-Jan-38	0:10:00	29-Jan-38	0:00:00
7	21-Nov-50	0:10:00	29-Nov-50	0:00:00
10	17-Nov-52	0:10:00	25-Nov-52	0:00:00
11	3-Nov-53	0:10:00	11-Nov-53	0:00:00
13	15-Feb-60	0:10:00	23-Feb-60	0:00:00
17	3-Mar-62	0:10:00	11-Mar-62	0:00:00
26	31-Jan-72	0:10:00	8-Feb-72	0:00:00
27	15-Feb-72	0:10:00	23-Feb-72	0:00:00
28	5-Nov-72	0:10:00	13-Nov-72	0:00:00
29	12-Dec-72	0:10:00	20-Dec-72	0:00:00
31	28-Nov-74	0:10:00	6-Dec-74	0:00:00
32	29-Jan-76	0:10:00	6-Feb-76	0:00:00
33	6-Jan-77	0:10:00	14-Jan-77	0:00:00
35	16-Jan-78	0:10:00	24-Jan-78	0:00:00
37	3-Feb-78	0:10:00	11-Feb-78	0:00:00
39	21-Dec-78	0:10:00	29-Dec-78	0:00:00
41	21-Oct-80	0:10:00	29-Oct-80	0:00:00
50	25-Mar-84	0:10:00	2-Apr-84	0:00:00
58	26-Oct-91	0:10:00	3-Nov-91	0:00:00
62	10-Mar-93	0:10:00	18-Mar-93	0:00:00
67	20-Dec-94	0:10:00	28-Dec-94	0:00:00
75	15-Apr-97	0:10:00	23-Apr-97	0:00:00
77	1-Feb-98	0:10:00	9-Feb-98	0:00:00
83	24-Oct-06	0:10:00	30-Oct-06	7:00:00
96	11-Oct-10	0:10:00	19-Oct-10	0:00:00

Table 4 - Selected Extratropical storm events dates

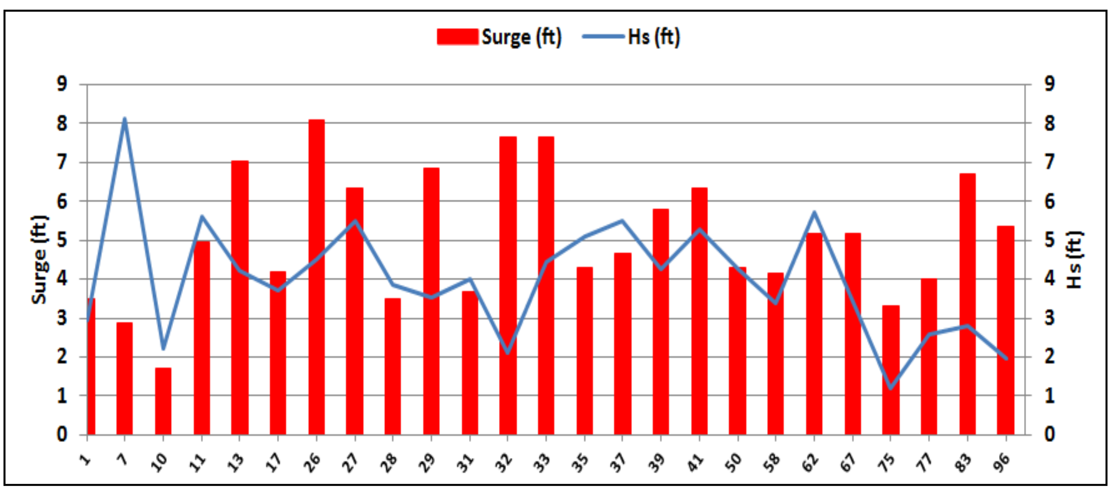

Figure 5 - Peak Storm Surge and Wave Height (Extratropical Storm Events)

Visual quality assessment was conducted on each storm by looking at the storm duration and the numerical stability of the data. The portion of storm that was judged to be important in the context of beach profile response modeling was clipped. Time series of wave data was estimated, mainly at the beginning and end of some storms, to match the storm surge. Also, for some storms, the wave data was shifted in time due to incompatibility between the timing of the surge and wave data. In such cases the wave data was shifted in time such that the wave height peak coincides with the surge peak (Gravens, 2005). Figure 6 shows an example of the original and the adjusted clipped storm data.

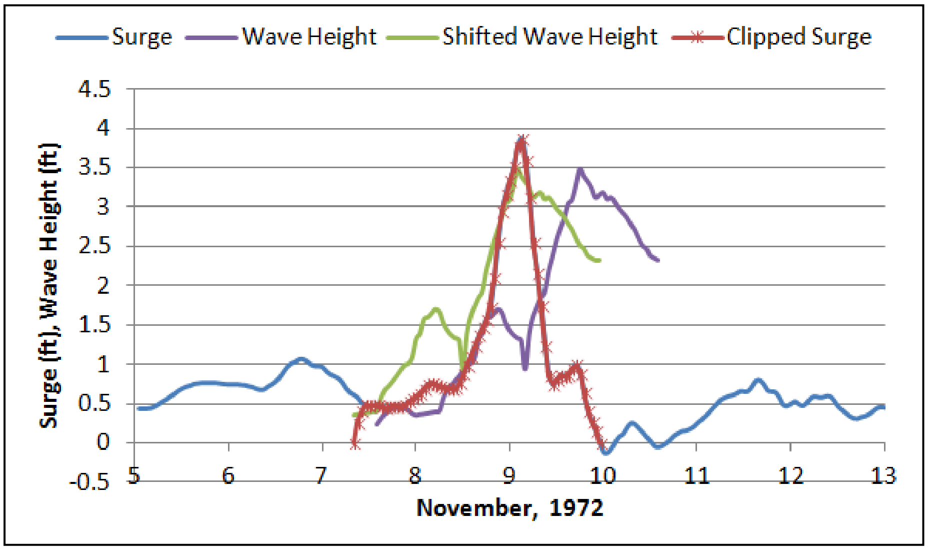

Figure 6 – Original and adjusted storm data

Time series and peak surge and wave data were obtained from the Coastal Hazards Systems database for the 1,050 synthetic tropical storm events. The method of analyses for the tropical storms adopted for use in this study was developed by ERDC. The extratropical storm analyses was completed before obtaining ERDC tropical analyses approach and consequently ERDC approach was not addressed in the selection of the representative extratropical representative storms. The synthetic tropical storms are separated into Region1, Region2, and Region3 bypass and landfall groups (Melby and Green, 2015). The storm tracks occurring within a circle of 400 KM in diameter around Hashamomuck (Figure 7) were extracted from the above mentioned groups. Within this area of influence, 432 storms occurred of which 66 storms did not meet the 1-Year return period storm. The remaining 366 storm events were clustered according to stage frequency for different storm return periods. Time series of storm surge values for storms within each cluster were examined and peak surge values were aligned to select representative storms for each cluster. Figure 8 shows the aligned storm surge hydrographs for the 50-Yr return period cluster with the black bold lines depicting the representative storms. From the cluster of 366 storms, 31 representative storms were selected. Table 5 shows the number of storms occurring within each cluster and the selected representative storm ID numbers. The portion of storm that was judged to be important in the context of beach profile response modeling was clipped and the corresponding wave height and period time series was prepared with matching time interval.

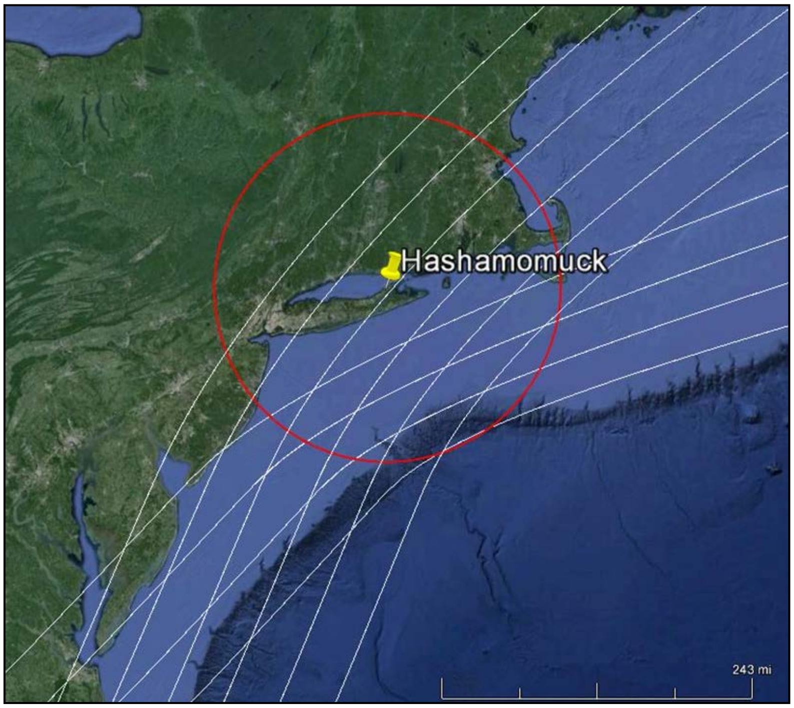

Figure 7 – Storm tracks within 200 KM circle around Hashamomuck

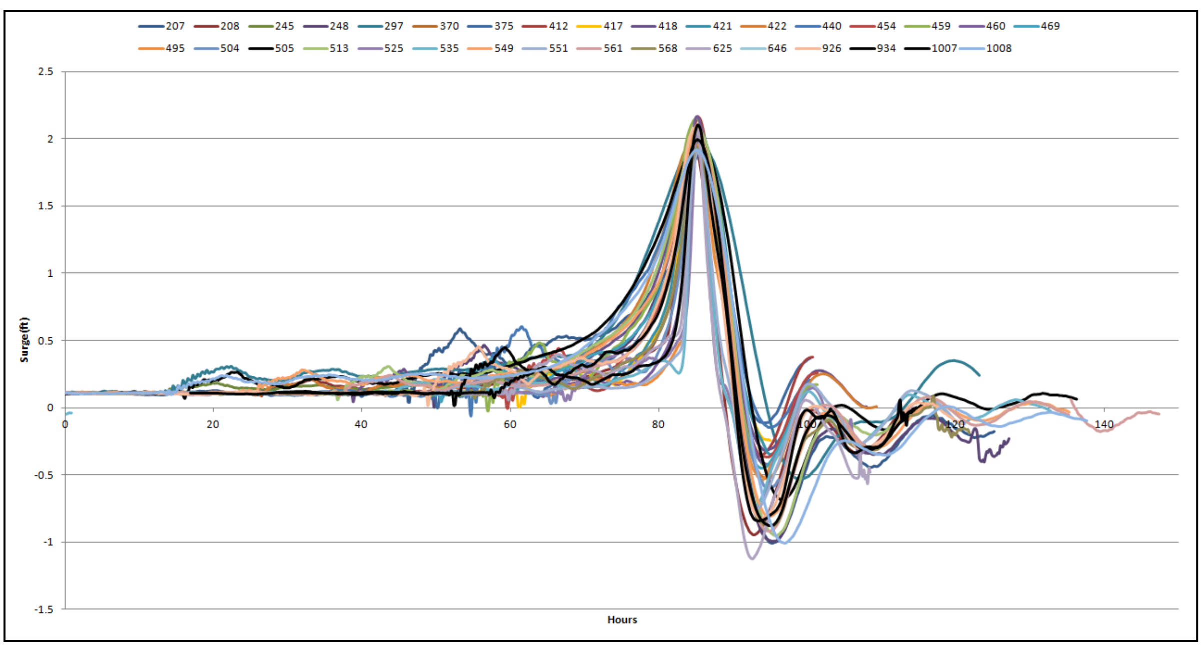

Figure 8 – Surge hydrographs for the 50-Yr return period cluster
(black bold lines depict the representative storms)

Storm Return Period (Yr)	Stage (Ft)	No. of Storms (in each cluster)	Selected Storms IDs
1	0.88	21	281, 663
2	1.21	107	253,472,790,941,1011,1022
5	1.58	73	510,564,844,932,1019
10	1.84	47	462,648,943,1016
20	2.09	36	362,406,935
50	2.42	33	505,934,1007
100	2.69	18	463,494
200	3.02	17	557,925
500	3.48	8	634
1000	3.78	4	458
2000	4.06	1	415
5000	4.38	1	457
10000	4.61		

Table 5 - Selected synthetic tropical storms

Each storm surge hydrograph (extratropical and synthetic tropical) was combined with a cosine representation of the astronomical tide to generate a plausible total water level elevation. Each storm surge was combined with three representative tidal ranges (spring, mean, and neap) and the peak surge elevation was aligned with four tidal phases (high tide, mid-tide falling, low tide, and mid-tide rising) to create suite of 12 storms of each historical storm surge hydrograph. The spring, mean and neap tidal ranges (3.42, 2.52 and 1.93 ft) were obtained from 20-year-long equilibrium tide at ADCIRC station 368 (Figure 9).

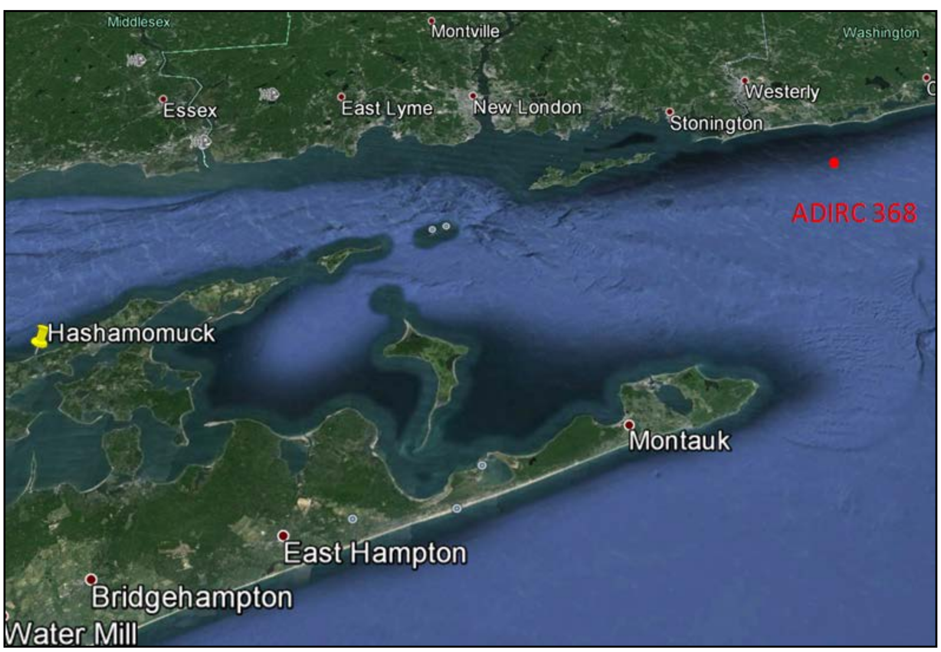

Figure 9- ADCIRC station 368

Combining N storm events with three tidal ranges at four phases will result in a total of NX3X4 storm events. The water level information to this point in the analysis has been referenced to Mean Sea Level (MSL). Datum conversion to NAVD88 was performed for compatibility with the profile input to SBEACH. The **National Oceanic and Atmospheric Administration (NOAA)** station 8510560 (Montauk, NY) datum data was adopted in this study. Datum conversion from MSL to NAVD88 was calculated by subtracting 0.33 from the output water elevation for compatibility with the profile input to SBEACH.

A MATLAB script was used to read the ASCII input files containing the clipped and adjusted storm surge hydrograph time series with one value on each line for each of the identified significant storm events. The script finds the peak storm surge elevation and computes the offset start indices such that the peak surge elevation will align with the Cosine tide at high tide, mean tide falling, low tide and mean tide rising when the two are combined. The 12 plausible variants of the total water level hydrograph are then computed. Also, the script plots the storm surge hydrograph, the Cosine tide signal for each of the three tide ranges with markers indicating the location of the peak surge and the locations on the Cosine tide where the peak surge will be combined, and the resulting twelve total water level hydrographs as illustrated in Figure 10.

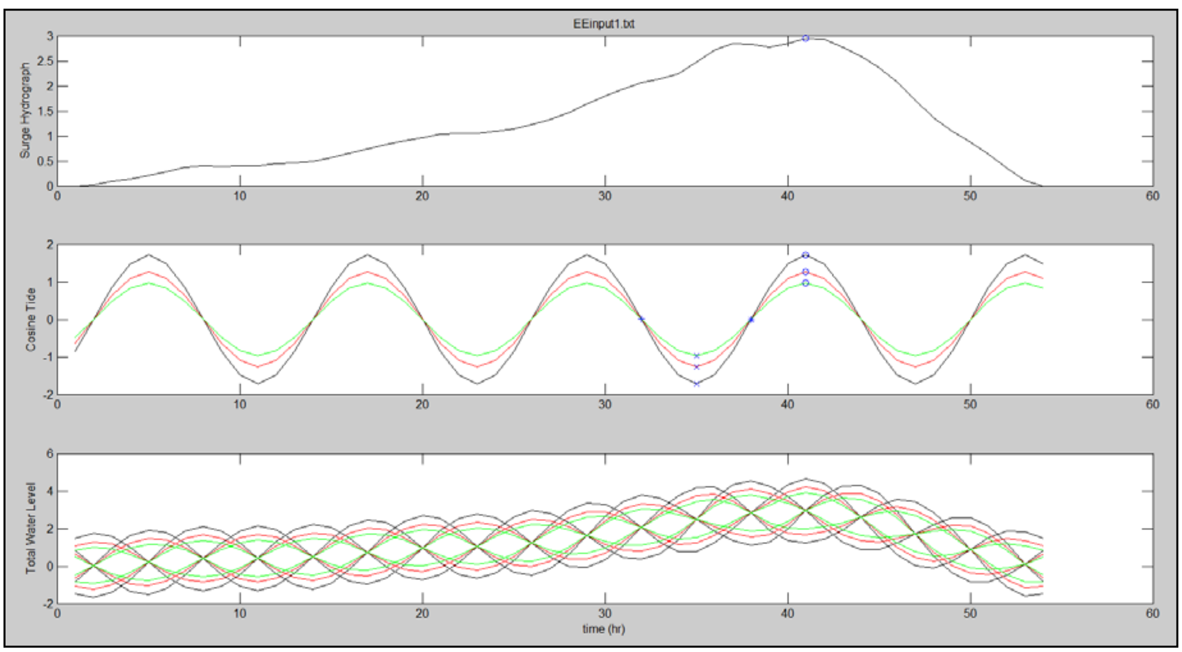

Figure 10 – Storm Surge Hydrograph, Cosine Tide and 12 Total Water Levels Extratropical Storm Event 1

The script will also open 12 output files (*.elv) and write the computed total water level hydrograph to the output applying any required datum shift in the process. The output files are named according to the input file name with an appended alpha numeric suffix where H designates high tide range, M designates mean tide range and L designates low tide range. The number that follows the tide range character specifies the tide phase at which the peak surge was aligned; 1 indicates high tide, 2 mean tide falling, 3 low tide and 4 mean tide rising. The script will also create ASCII files (*.wav) containing the wave height and period information for input to SBEACH for each of the significant storm events (Gravens 2005). The 25 extratropical storms were expanded to a plausible storm suite consisting of 300 events and the 31 Tropical storms were expanded to a plausible storm suite consisting of 372 events.

4 Representative Beach Profiles

The Coastal Engineering Manual (CEM) provides some guidance on how to determine baseline damages by including the existing or without-project condition of the project study domain. Morphologic features of the existing beach, such as dune height, berm width, and offshore profile shape, typically vary along the project study domain. To accurately estimate storm erosion response for the existing condition, the CEM suggests developing a set of representative morphologic reaches to describe variations in profile shape along the project domain. Morphology analysis software applications such as BMAP or RMAP can be used to define morphologic reaches by analyzing profiles, grouping similar profiles, and calculating an average representative profile for each reach. According to the CEM, the profile characteristics that should be considered when developing morphologic reaches include dune height and width, berm width, nearshore and offshore profile slopes, sand grain size, presence of seawalls or other structures, and proximity to inlets.

The Hashamomuck Cove Coastal Storm Risk Management feasibility study will employ Beach-*fx*, the Corps' Monte Carlo life-cycle simulation model for estimating shore protection project evolution and cost benefit analyses. For a general description of the principles upon which Beach-*fx* operates the reader is directed to Gravens, et al. (2007). An overview of the general hierarchical data structure employed in Beach-*fx* is provided in Figure 11. Within Beach-*fx* the overall unit of analysis is the "project," a shoreline area for which the analysis is to be performed. The project is divided, for purposes of analysis, into "reaches," which are contiguous, morphologically homogeneous areas. The structures within a reach are referred to as Damage Elements (DEs), and are located within lots. All locations are geospatially referenced using a cartographic coordinate system such as state plane coordinates. This project definition scheme is shown schematically in Figure 12, in which the shoreline is linearized into reaches. Each reach is associated with a representative beach profile that describes the shape of the cross-shore profile and beach composition.

The profile is the basic unit of beach response. Natural beach profiles are complex; for the modeling, a simplified or idealized beach profile, representing key morphological features defined by points, is used as shown in Figure 13. The idealized profile represents a single trapezoidal dune with a horizontal berm and a horizontal upland landward of the dune feature.

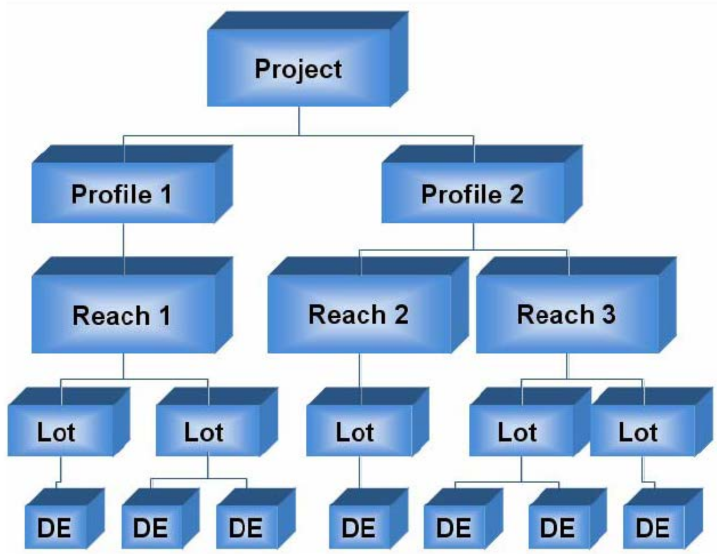

Figure 11: Hierarchical representation of Beach-fx data elements

(taken from Beach-fx Users Manual, Version 1.0).

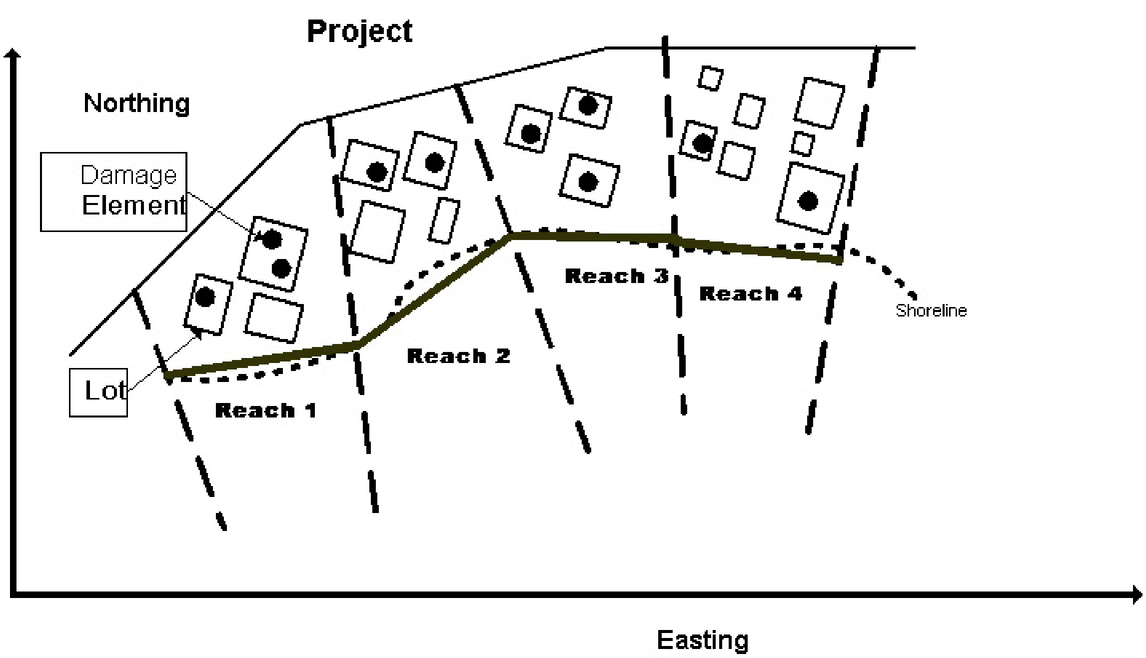

Figure 12: Beach-*fx* schematization of the project study area.

The submerged portion of the profile is represented by a detailed series of distance-elevation points that are determined through an analysis of available beach profile information. For the

Hashamomuck Cove project, the detailed submerged beach profile was developed by averaging across multiple surveyed beach transects containing similar offshore slopes.

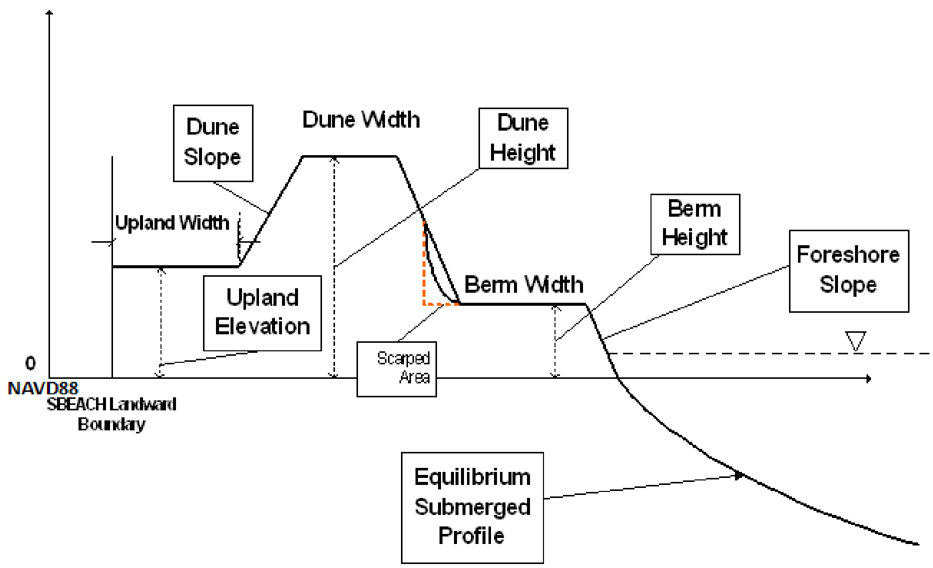

Figure 13: Beach-*fx* idealized beach profile.

The beach morphology of Hashamomuck Cove is heavily influenced by the presence of the groins, which are spaced as close as 150 feet to as far apart as 2000 feet and vary greatly in construction type and functionality. The initial project layout was selected to terminate at each end at the location of one of these groin locations in order to eliminate/reduce planform losses. The project consists of three cove areas as shown in Figure 14 and each cove was developed as a separate Beach-fx study. These three Beach-fx projects were named HashEast, HashCentral, and HashWest.

The beach profile analysis that lead to the development of the idealized representative beach profile was based on a combination of available LIDAR data from 2012 and a single profile survey that was obtained in December 2014 (Figure 15). After an extensive data search, there were no additional historic profiles available for analysis. However, there was a 1969 (USACE, 1969) beach erosion control study report that contained some hand drawn data that was used to compare the general shape of the profile with the current condition. Due to the curved shoreline located within each of the three cove project areas, the SBEACH reaches were relatively small. The size of the reaches was influenced by the fact that it is important to have the cross shore profile close to perpendicular to the SBEACH representative shoreline. The curved shoreline resulted in 13 SBEACH reaches (R1-R13) as seen in Figure 14. These 13 SBEACH reaches are further grouped into Economic reaches that use the same profile responses as the SBEACH reach they are contained within, but are grouped by economic factors such as structure type, value, etc. The 13 SBEACH reaches in this project were divided into 15 such economic reaches (E1-E15) represented by the blue lines in Figure 15.

Figure 14: Beach-fx project Areas

Figure 15: Profile Survey Transects

To develop the representative profiles for each reach, the 2014 profile survey was merged with the 2012 LIDAR data to fill in areas of missing data and a shore perpendicular profile was developed. The corresponding representative profiles are displayed in Figures 16 through 28.

Figure 16: Representative and idealized beach profile for Reach R1.

Figure 17: Representative and idealized beach profile for Reaches R2.

Figure 18: Representative and idealized beach profile for Reach R3.

Figure 19: Representative and idealized beach profile for Reach R4.

Figure 20: Representative and idealized beach profile for Reach R5.

Figure 21: Representative and idealized beach profile for Reaches R6.

Figure 22: Representative and idealized beach profile for Reaches R7.

Figure 23: Representative and idealized beach profile for Reach R8.

Figure 24: Representative and idealized beach profile for Reach R9.

Figure 25: Representative and idealized beach profile for Reach R10.

Figure 26: Representative and idealized beach profile for Reach R11.

Figure 27: Representative and idealized beach profile for Reach R12.

Figure 28: Representative and idealized beach profile for Reach R13.

5 Beach-fx Coastal Processes Input Data Development

Storm-Induced Beach Profile Responses

The availability of a large database of beach profile response to each storm in a plausible storm suite is central to the operation of Beach-fx. This database is known to Beach-fx modelers as the *shore response database* (SDB). Two kinds of data are stored in the SDB for each storm/profile simulation: changes in berm width, dune width, dune height and upland width, and cross-shore profiles of erosion, maximum wave height, and total water elevation. The morphology changes (berm width, dune width, dune height and upland width) are used to modify the pre-storm beach profile to obtain the post-storm profile. The damage driving parameters (cross-shore profile of erosion, maximum wave height, and total water elevation) are used in the estimation of damages to damage elements within reaches associated with that representative profile. The SDB is a pre-generated set of beach profile responses to storms comprising the plausible storm suite, for a range of profile configurations that are expected to exist for different sequences of storm events and management action scenarios. The numerical model for simulating storm-induced beach change (SBEACH), (Larson and Kraus, 1990) was used to estimate beach profile responses to each of the storms contained in the plausible storm suite. As discussed in section 3.0, the storm suite used to generate the SDB includes 31synthetic tropical storm events and 25 extratropical storm events. When these hypothetical storms were combined with the statistical representation of astronomical tides, the number of storms increased to 372 tropical and 300 extratropical events. A companion range of beach profile configurations were developed to encompass all expected beach configurations encountered under each of the evaluated without-project scenarios. Profiles were developed at 25 ft increments on berm width, 10 to 25 ft increments on dune width, and 2 ft increments on dune height between the most robust and most vulnerable beach profiles. This procedure generated a total of 2,535 unique beach profiles. The response of each of these beach profiles to the entire storm suite consisting of 672 plausible storm events was simulated using the SBEACH model. A total of 1,764,360 SBEACH simulations were performed and the results were imported to populate the SDB used as input to each of the three Beach-fx models. Because of the large size of the resulting SDB, the Hashamomuck project was divided into three project domains as discussed earlier:

1. Hashamomuck West: R1 (E1), R2 (E2), R3 (E3), and R4 (E4 & E5).
2. Hashamomuck Central: R5 (E6), R6 (E7), R7 (E8), R8 (E9), R9 (E10), and R10 (E11).
3. Hashamomuck East: R11 (E12), R12 (E13), and R13 (E14 & E15).

Profile Shoreline Position Changes

The next step required to fully implement the Hashamomuck Cove project in Beach-*fx* is calibration of Beach-*fx* such that the model reproduces, on average over multiple lifecycle simulations, the historical shoreline rate of change. To do this, one must first develop an estimate of the historical shoreline rate of change.

For this project area, there is no historic survey data available from which to extract the mean high water position which is typically used to determine shoreline change. As a result, the method used to calculate the rate of change was through comparison of historic aerial photography. Images were located and rectified for the project location from five time periods. Specifically, October 19, 1960, April 15, 1974, April 5, 1993, June 1, 2001, and June 10, 2010.

A shoreline change rate baseline for the project area was developed that followed the general contour of the land. From this baseline, 45 shoreline perpendicular transect locations were established as locations to calculate the shoreline change (Figure 28). From the available imagery, the wet/dry shoreline was extracted along project length at each transect location for each time period. A least squares regression was calculated through the extracted shoreline locations for each transect to develop the initial shoreline change rates. The rates were then smoothed by creating moving averages of the four surrounding rates for each transect. Table 4 displays the calculated shoreline change rate for each transect, along with the economic reach number the transect lies within. The change rates were then averaged based on the economic reach they were contained within (Table 5/Figure29) producing the final rates to which the model was calibrated.

Figure 29: Shoreline Change Baseline

Economic	Shoreline Transect Location	Change Rate (ft/yr)	Moving Average (ft/yr)
E1	1	-0.37	-0.06
E1	2	0.18	-0.37
E1	3	0.00	-0.60
E2	4	-1.29	-0.84
E2	5	-1.54	-1.22
E2	6	-1.57	-1.53
E2	7	-1.70	-1.57
E3	8	-1.55	-1.49
E3	9	-1.50	-1.38
E3	10	-1.13	-1.18
E3	11	-0.99	-0.99
E3	12	-0.70	-0.84
E3	13	-0.64	-0.75
E4	14	-0.72	-0.70
E4	15	-0.72	-0.70
E4	16	-0.74	-0.67
E4	17	-0.69	-0.62
E4	18	-0.46	-0.59
E4	19	-0.50	-0.51
E5	20	-0.54	-0.47
E6	21	-0.36	-0.56
E6	22	-0.48	-0.71
E6	23	-0.91	-0.87
E7	24	-1.24	-1.09
E8	25	-1.38	-1.28
E8	26	-1.46	-1.37
E8	27	-1.39	-1.30
E8	28	-1.36	-1.15
E8	29	-0.90	-0.96
E9	30	-0.63	-0.78
E9	31	-0.53	-0.65
E10	32	-0.51	-0.61
E10	33	-0.69	-0.55
E11	34	-0.66	-0.51
E12	35	-0.33	-0.44
E12	36	-0.34	-0.46
E12	37	-0.16	-0.37
E13	38	-0.79	-0.33
E14	39	-0.24	-0.26
E14	40	-0.13	-0.25
E14	41	0.04	-0.15
E15	42	-0.12	-0.20
E15	43	-0.29	-0.30
E15	44	-0.50	-0.38
	45	-0.61	-0.47

Table 6: Shoreline change rate (ft/yr) for each transect (Transect 45 did not fall within an Economic Reach)

Economic Reach	SL Change Rate (ft/yr)	Moving Average (ft/yr)
E1	-0.06	-0.35
E2	-1.53	-1.29
E3	-1.09	-1.10
E4	-0.64	-0.63
E5	-0.54	-0.47
E6	-0.59	-0.71
E7	-1.24	-1.09
E8	-1.30	-1.21
E9	-0.58	-0.72
E10	-0.60	-0.58
E11	-0.66	-0.51
E12	-0.28	-0.42
E13	-0.79	-0.33
E14	-0.11	-0.22
E15	-0.30	-0.29

Table 7: Shoreline change rate (ft/yr) by Economic Reach

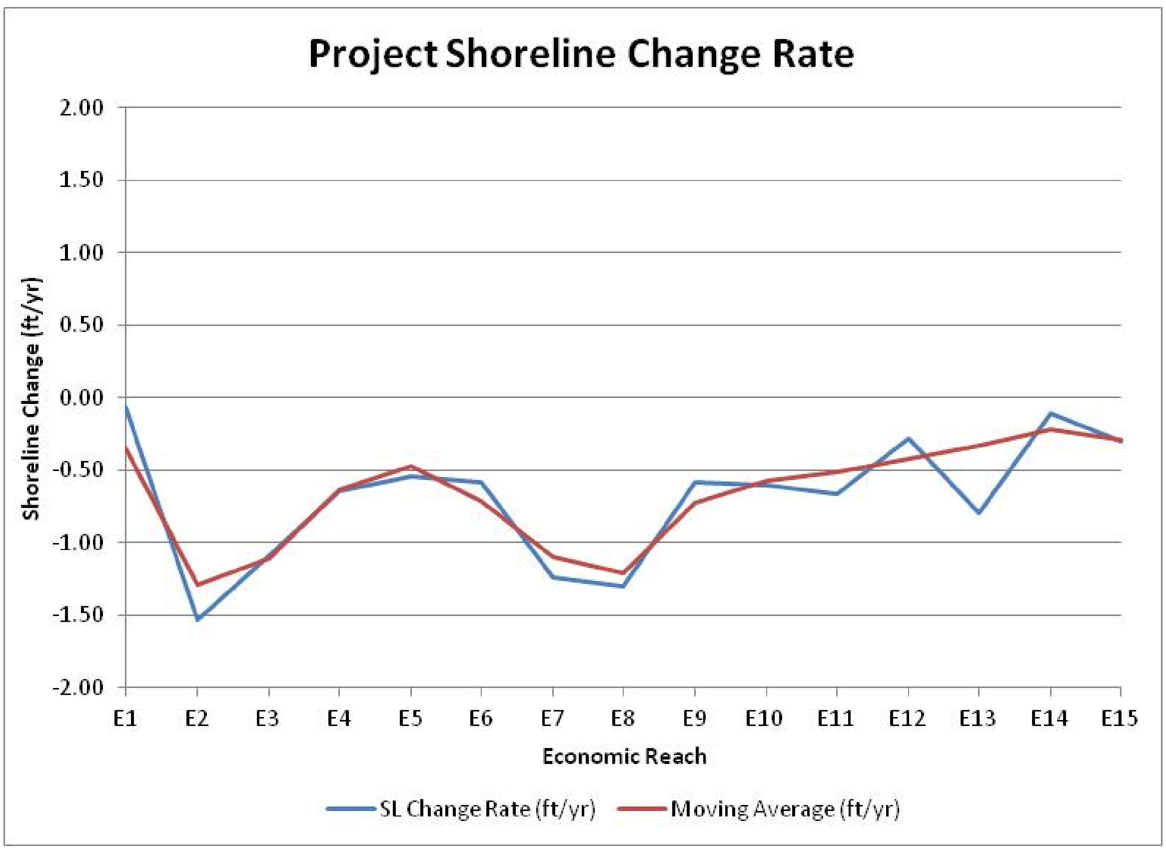

Figure 30: Project Change Rates (ft/yr)

6 Beach-fx Calibration

The calibration procedure for Beach-*fx* involves specification and tuning of a reach-level attribute known as the *applied erosion rate*. The applied erosion rate accounts for long-term shoreline change not attributed to storm-induced shoreline changes which are captured within the model by the random sampling of storm events as the model progresses through the lifecycle simulation. The concept is that there are two essentially separable components of beach evolution. The first is cross-shore transport dominated shoreline change due to storm events which is mostly recoverable due to post-storm berm width recovery. The second is longshore transport dominated shoreline change that is driven by longshore sediment transport gradients, underlying geological setting, and other factors such as relative sea level change. This second component of beach evolution is considered non-recoverable. The Beach-*fx* calibration concept is that the combination of these two drivers of beach evolution should, on average, over multiple simulated project lifecycles, return the long-term average rate of shoreline change. Because the Beach-*fx* simulated life cycle iteration employs a random sequence of storm events, the returned shoreline change rate differs for each lifecycle simulated. The Beach-*fx* calibration task is to determine an appropriate applied erosion rate for each reach such that the computed average rate of shoreline change on a reach-by-reach basis is equal to the estimated target historical shoreline change rate over multiple lifecycle simulations.

For the Hashamomuck Cove project, Beach-*fx* was calibrated across 300 iterations of a 55-year lifecycle using an assigned depth of closure specification of -21 ft NAVD. The depth of closure estimate was developed based on an analysis of the available beach profile data from the recent 2014 survey, the 1969 survey report, and local knowledge. The 55-year lifecycle duration stems from the use of the December 2014 beach profile survey to define the initial condition leading to a start year specification of 2015 and the specification of year 2019 as the base year for calculating the economics and an economic analysis horizon corresponding to a 50-year project life. The use of 300 iterations was selected to obtain a stabilization of the model results.

After a number of iterations, Beach-*fx* was calibrated to precisely reproduce the target historical SRC on average over 300 55-year lifecycles. Figure 31 shows the result of the calibration by displaying the target historical SRC (blue line) and the Beach-*fx* calculated average rate of shoreline change over 300 iterations (red stars).

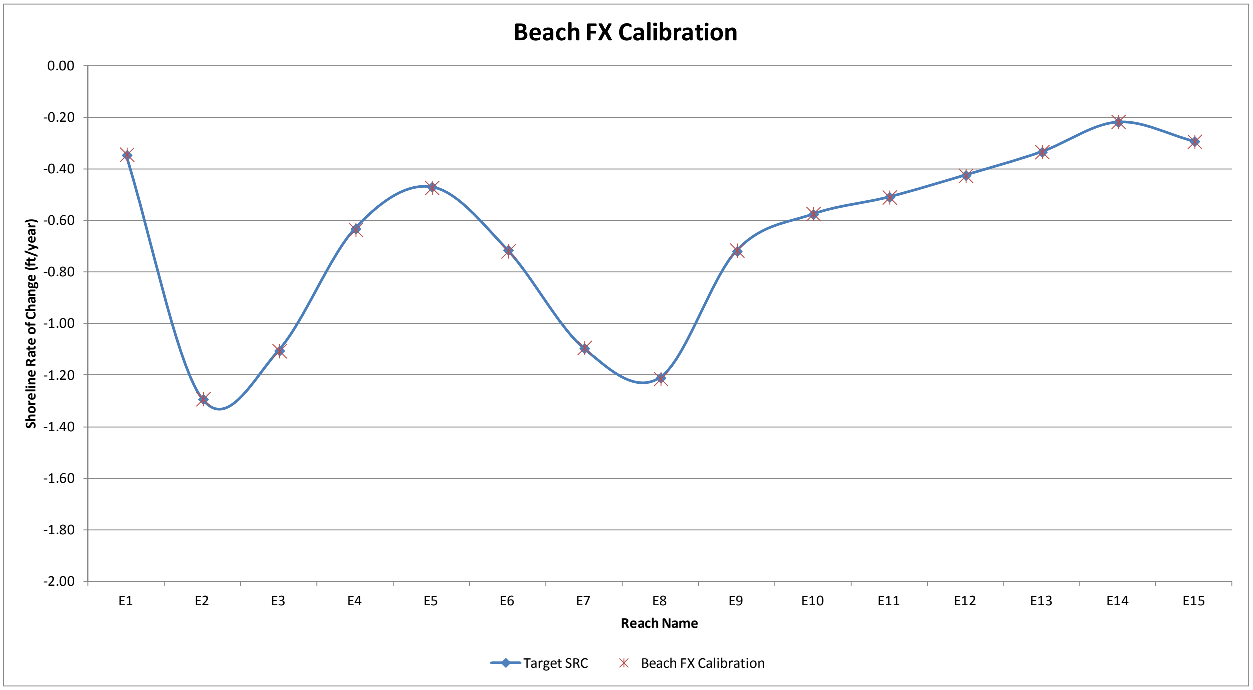

Figure 31: Beach-fx calibration results

7 Future Sea Level Change

In accordance with EC 1165-2-212, the direct and indirect effects of future sea level change on the identified Tentatively Selected Plan (beach nourishment alternative) will be evaluated using the Beach-fx model. Relative sea level change at Hashamomuck Cove is one of rising sea levels. The historical rate of sea level rise was determined to be 0.00961 ft/year (http://corpsclimate.us/ccaceslcurves.cfm). The future low rate of sea level change was taken as a linear projection of this historical rate of change. The future intermediate rate of sea level change was computed using modified NRC Curve I and equation 2 and 3 in EC 1165-2-212. The future high rate of sea level change was computed using modified NRC Curve III and equations 2 and 3 in EC 1185-2-212. These relationships for future sea level change as defined in EC 1165-2-212 are coded within Beach-fx and sea level change is internally computed continuously throughout the simulated project lifecycle. Figure 3 provides a plot of the Beach-fx computed sea level rise for each of the three sea level change scenarios. This figure shows that incremental sea level rise across the simulation period (2014 to 2069) was computed at 0.53 ft, 1.01 ft, and 2.55 ft, for the low, intermediate, and high rates of sea level change, respectively.

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