City of Norfolk

WILLOUGHBY SPIT BEACH RESTORATION STUDY

FINAL ▪ DECEMBER 2011

moffatt & nichol

EXECUTIVE SUMMARY

The Willoughby Spit area of Ocean View Beach in Norfolk, VA, which extends from the terminal groin at the western end of Willoughby Spit approximately one (1) mile east to the 800 Block breakwater field, has been historically accreting, especially at the western end near the terminal groin and offshore breakwaters. The City has implemented numerous erosion control/mitigation and beach restoration projects along the Ocean View shoreline in the past. Such projects in the Willoughby Spit area have included construction of a groin field and terminal groin, beach nourishment and dune restoration projects, and the construction of two (2) offshore breakwaters. These efforts have helped to stabilize the Willoughby Spit shoreline. However, in recent years, the eastern portion of the Willoughby Spit shoreline has become a concern as the beach width in this area, especially in front of Toler Place and Fish Eye Condos, is significantly narrower than neighboring areas to the west near the terminal groin and offshore breakwaters. As a result, the performance of the existing groin field is an issue, given its current dilapidated condition. In addition to performance, the dilapidated condition of the existing groin field is also of concern from both a recreational safety and aesthetic viewpoint. Recent accretion of the west facing beach, downdrift of the terminal groin, has also become a concern.

On behalf of the City of Norfolk, Moffatt & Nichol has performed a comprehensive study of the historical and present conditions in the vicinity of Willoughby Spit to determine the cause and lessen the issue of accretion of the west facing beach, downdrift of the terminal groin, develop potential alternatives to mitigate erosion at areas of concern, and stabilize the shoreline, creating equivalent protection along the beach. This study involved review and analysis of historical shoreline position information, available beach transect surveys, past engineering works, wave data, and numerical modeling.

An extensive review of historical data and engineering activities along the Ocean View shoreline and the Willoughby Spit region was conducted. Historical aerial photography, digitized shorelines, beach transect surveys, available sediment sampling data, and measured wave data were examined to aid in the determination of the existing littoral transport patterns in the area and in modeling of potential alternatives. Extensive shoreline change modeling was performed using GENESIS-T for the existing conditions and to investigate potential alternatives to mitigate erosion at areas of concern and stabilize the shoreline, creating equivalent protection along the beach. Cross-shore profile behavior under storm conditions was assessed for both the existing conditions and for any nourishment projects incorporated into the final preferred alternative (selected from GENESIS-T modeling) using SBEACH. The final preferred alternative was also modeled using DELFT3D, a three-dimensional hydrodynamic, sediment transport and morphological model to confirm the littoral behavior as seen in the GENESIS-T results as well as provide insight into the cause and possible solutions to alleviate the problem of accretion on the downdrift, west facing side of the terminal groin.

Analysis of the historical and recent shoreline change indicates that in the past, the groin field has performed well, producing a strong groin signature and stabilizing the shoreline along Willoughby Spit. As expected, the terminal groin and existing offshore breakwaters have been successful in trapping sand and causing accretion at the western end of Willoughby Spit. However, in more recent years, it appears that the timber groin field which exists along the

remainder of the Willoughby Spit shoreline has not performed as well, especially during storm events, most likely due to its dilapidated condition. This is an issue in areas like Toler Place and Fish Eye Condos where the seaward position of existing infrastructure relative to adjacent structures already lends itself to a narrow beach. Consequently, equivalent protection along the Willoughby Spit shoreline is an issue with some portions of the beach being less that 100 ft wide while other portions are greater than 200 ft wide. In addition, it appears that littoral transport around the terminal groin to the west facing beach is the main cause of accretion of the west facing beach, with some sediment transport over the terminal groin during storm conditions.

The basic alternatives examined were to keep the existing conditions, remove the existing groin field, remove just the offshore portion of the groins in conjunction with beach nourishment, and the addition of offshore breakwaters in combination with beach nourishment. Improvements to the terminal groin, such as raising the elevation, were included in each option. The GENESIS-T model configuration and runtime allows comparison of various cases simulating years of shoreline change, whereas, the DELFT3D model requires high computational times and is not suitable to testing a large number of scenarios. Therefore, numerous alternatives were modeled with GENESIS-T and the results compared based on the goals of improving the shoreline position at Fish Eye Condos and Toler Place, creating equivalent protection along the Willoughby Spit shoreline, incorporating a sand recycling plan for any potential nourishment which would make use of the abundant material around the terminal groin and existing breakwaters, and maintaining the shoreline aesthetic.

GENESIS-T model results indicate that an ideal shoreline which provides equivalent protection by improving the shoreline position at the current areas of concern and using excess material from near the terminal groin for nourishment can be achieved with the addition of an offshore breakwater field which connects the existing 800 Block breakwater field to the existing offshore breakwaters at the western end of Willoughby Spit. GENESIS-T model simulations show the existing shoreline retreating significantly in front of Toler Place in the next eight (8) years if no action were taken. Initial and periodic beach nourishment will be required as part of an ongoing solution to restore and maintain the beach in this area due to the curvature of the shoreline and influence of the 800 Block breakwater field end effects. The amount and frequency of this nourishment can be reduced by stabilizing the shoreline with offshore breakwaters, reducing the wave climate and associated sediment erosion. The breakwater field will also help to provide more equivalent protection along the Willoughby Spit shoreline. DELFT3D results further indicate that while a majority of the accretion on the downdrift side of the terminal groin is due to littoral transport around the groin from Willoughby Bank, some relief would be provided by elevating the groin, preventing material from overtopping the groin during storms.

Based on the historical shoreline analysis, and the modeling results, the recommended alternative for Willoughby Spit consists of a beach nourishment and dune construction project to mitigate the beach width issue in the current areas of concern and provide additional protection to areas from which sand will be borrowed in combination with the addition of an offshore breakwater field to stabilize the entire shoreline and reduce nourishment frequency. The existing dilapidated groin field would be completely removed. The proposed preferred alternative seeks to balance the need to protect shoreline in areas where existing infrastructure is located seaward of adjacent structures while creating equivalent protection for the remainder of the shoreline as well as

improving safety and aesthetics of the beach. The addition of seven (7) offshore breakwaters was chosen to connect the 800 Block breakwater field with the existing breakwaters at Willoughby Spit, eliminating the erosional end effect issue that often accompanies breakwater fields. The breakwaters were staggered offshore with respect to the existing shoreline position and designed with varying lengths, particularly the two nearest the 800 Block breakwater field. These two breakwaters were designed slightly shorter than the remainder of the field so as to avoid any impedance of sediment transport at the bend in the shoreline just west of the 800 Block breakwaters. In addition, this option allows for some sand recycling in which material can be taken from the historically accreting areas nearest the terminal groin (both updrift and downdrift) and placed at areas of concern. Due to littoral transport from east to west in this area, some of the material would eventually return to its initial position and could be used again. Modeling results showed that 28,000 cy of material placed from Leclaire St to Worth St, adding approximately 45 ft of berm width, would address the issues at Fish Eye Condos and Toler Place. In addition, a 7,000 cy dune construction project at Lea View Avenue would add protection to the area from which sand would be borrowed for the previously mentioned nourishment. Sand recycling from both the updrift and downdrift sides of the terminal groin in addition to raising the elevation should help mitigate the issue of accretion of the west facing beach by keeping the groin pocket from overfilling, preventing overtopping, and making beneficial use of any material that does accrete in this area. It is expected that this sand recycling will need to be completed once every eight (8) years on average (barring large storm events), and the City should monitor conditions (using the spring/fall periodic surveys) around the terminal groin and Fish Eye Condos/Toler Place to determine when the recycling should take place. The addition of a staggered offshore breakwater field, connecting the current 800 Block breakwaters with the existing Willoughby Spit breakwaters, in conjunction with beach nourishment and sand recycling showed an improved shoreline in the areas of concern, equivalent protection along the entire beach, improved aesthetic, and reduction in the frequency of future beach nourishment requirements.

A preliminary opinion of probable cost for initial construction is approximately $3.65M for removal of the existing groin field, 35,000 cubic yards of beach nourishment and dune construction, the construction of the seven (7) offshore breakwaters, and slight improvements to the terminal groin. Assuming renourishment would be required every eight (8) years, the total cost over 30 years (present worth) is approximately $4.69M, given 3% interest.

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I. PROJECT BACKGROUND & SCOPE OF WORK

A. PROJECT BACKGROUND

The City of Norfolk shoreline lies on the Chesapeake Bay and extends approximately 7.3 miles, from Little Creek Inlet to Willoughby Spit (**Figure I-1**). The Willoughby Spit area extends from the terminal groin at the western end of the Ocean View Beach to Worth Street, just before the westernmost breakwater of the 800 Block breakwater field. The Willoughby Spit area has historically seen accretion, particularly at the western end near the terminal groin and offshore breakwaters due to the natural littoral drift from east to west in this area. The past and current issues in the Willoughby Spit region involve some localized erosion at the eastern end of the study area, creating beach width issues at Toler Place subdivision and Fish Eye condos where some structures are slightly seaward of adjacent infrastructure. Poor condition of the groin field in this area is likely a contributor to these conditions as well as the curvature of the shoreline which may increase offshore losses. In addition, the accumulation of sand on the western facing beach, downdrift of the terminal groin, has been seen in recent years. Sediment transport from Willoughby Bank around the terminal groin and overtopping of the groin during storm events due to overfilling of the groin pocket is believed to be attributing to this. Previous efforts by the City of Norfolk to preserve the beach in this area include numerous beach nourishment projects (1962, 1984, 1990, 1995, and 2004), dune reconstruction projects (1988-1989, 2005), initial construction of a groin field, including the terminal groin (1920-1938), timber groin reconstruction (1981, 1983), terminal groin reconstruction (1990, 1997), and construction of offshore breakwaters (1990).

Figure I-1 Willoughby Spit Project Study Area Location at Ocean View Beach

The existing Willoughby Spit shoreline is characterized by a terminal groin at the western end, two offshore breakwaters, and a groin field containing seven timber groins extending from just east of Rallston St to 11th View. In general, the structures have performed well and allowed for accretion of the Willoughby Spit region (particularly the western portion) over the years. However, the current physical condition of the groin field shows severe dilapidation of the timber, likely causing the increased erosion at the eastern end of the study area in recent years, especially during storm events. The curvature of the shoreline west of the 800 Block breakwaters also interrupts the sediment transport, likely contributing to offshore losses. In addition, the dilapidated condition of the groin field affects the aesthetics of the beach and could be a safety hazard for recreational users. There is also an issue with sediment transport around the terminal groin from Willoughby Bank and overfilling of the groin pocket, allowing some sediment to be transported over the terminal groin to the west facing beach during storms. The location of these issues within the study area is presented in **Figure I-2**.

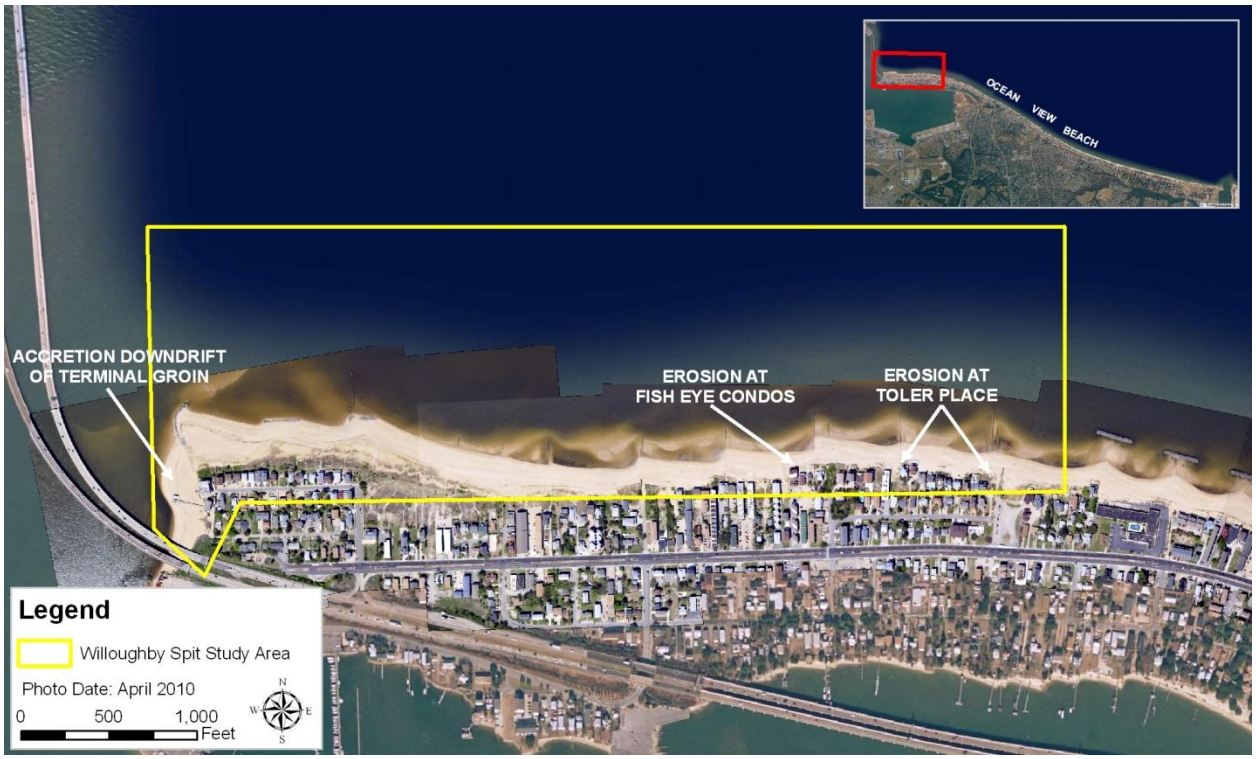

Figure I-2 Willoughby Spit Project Study Area

The City of Norfolk has requested a detailed study of shoreline at Willoughby Spit and development of recommended alternatives for beach restoration. Previous work done on the Ocean View area has provided extensive shoreline, survey, and sediment data for the area, which will be used to evaluate the existing system and predict future performance with various beach restoration alternatives through the use of a variety of models involving short-term storm induced cross-shore change, long-term shoreline change, and 3-dimensional morphological change.

B. SCOPE OF WORK

Moffatt & Nichol was tasked with the detailed study of shoreline erosion within the Willoughby Spit region of Ocean View Beach and development and recommendation of alternatives for beach restoration and stabilization at this location. The scope of work included 1) compilation of existing survey, shoreline, and sediment data, 2) review of historical shoreline trends, 3) analysis of existing wave data from the Norfolk wave gage, 4) modeling of the existing system within the Willoughby Spit region to determine the cause of localized erosion in the eastern portion of the study area and accretion downdrift of the terminal groin, 5) development of a list of alternatives for beach stabilization and restoration, and 6) modeling of the selected alternatives to determine the impact and effectiveness of each option, thus yielding the recommended alternative. As modeling constitutes a major portion of this study, the scope of modeling to be completed is as follows:

1. The SBEACH (Storm-induced BEAch CHange) model will be used to evaluate short-term cross-shore storm induced impacts and sediment transport patterns for the existing system and the impact of any beach nourishment alternatives to be considered. The SBEACH model will be evaluated at selected cross-sections within the Willoughby Spit study area, taking into account the location of problem areas, extents of available data, and structures which may impact cross-shore transport. The model will be run for recent storm events, using measured wave data from the Norfolk wave gage which has been deployed in the Chesapeake Bay since March 2006 in conjunction with water level data from Sewells Point. Survey data from the ongoing periodic surveying evaluation project along Ocean View Beach, which began in 2005, will be used for pre- and post-storm profiles. The SBEACH model will be calibrated and then subsequently verified using different storm events which have impacted the shoreline in this area. Once calibration and verification is complete, the model will be run to evaluate expected future response of the existing beach profile if no mitigation of the current erosion problem were to take place. An additional model will then be run to test the response of the beach profile to any restoration and stabilization alternatives developed involving beach fill. Model results will be used to evaluate the effectiveness of beach fill for beach restoration of the Willoughby Spit study area.

2. The GENESIS-T (Generalized Model for Simulating Shoreline Change) long-term shoreline evolution model will be used to model the existing system (from the Willoughby Spit terminal groin to Worth St) to further evaluate the historical shoreline change rate and associated erosion and to estimate future shoreline change. The GENESIS-T model will be calibrated using measured wave data from the Norfolk wave gage, existing structure positions, and historical shoreline position data developed from the periodic surveying evaluation project. The period of calibration will be chosen carefully to coincide with the presence or absence of activities which may have influenced the rate of change along the shoreline. Once the model is adequately calibrated, a verification model will be run to confirm the chosen calibration parameters. Upon completion of calibration and verification, a new model will be developed using the calibrated parameters and the current shoreline position to evaluate future shoreline response if no mitigation of the current erosion problem were to take place. An additional model will also be run to evaluate a variety of alternatives for beach

stabilization and restoration along the Willoughby Spit study area on a macro scale. The model will be run using multiple cycles of the existing wave gage data to simulate the shoreline impact and predict the design life of each alternative. The model results will be used to evaluate the effectiveness of each alternative for beach restoration.

3. In addition to the larger scale GENESIS-T modeling for the project, the DELFT3D modeling system will be used to provide insight into hydrodynamic circulation/sediment transport patterns and morphological changes in the immediate vicinity of the Willoughby Spit study area. The proposed model extent would extend from Worth street westward around the terminal groin to the west facing beach, encompassing the Fish Eye Condos and Toler Place areas of concern as well as the terminal groin itself. The model will include a detailed implementation of the existing structures and bathymetry. DELFT3D allows for simulation of multi-dimensional sediment transport patterns which cannot be simulated using GENESIS-T. The local DELFT3D hydrodynamic model will use hydrodynamic boundary conditions from a regional Chesapeake Bay model previously developed by Moffatt & Nichol. A local, high-resolution wave model will be driven with the finalized nearshore wave climate. Hydrodynamic and wave results will then be used as input to a detailed, two-dimensional, sediment transport model over the same grid. The model will be used to investigate hydrodynamic circulation/sediment transport patterns (including long-shore transport distributed across the profile) and morphological changes for a number of fair weather and storm wave conditions. Assessment of the model will be based on realistic flow, sediment transport, and morphological change patterns, not on specific comparisons with any available shoreline or bathymetry data. The DELFT3D modeling system will then be used to provide insight into hydrodynamic circulation/sediment transport patterns and morphological changes in the immediate vicinity of the terminal groin as well as the beach response of the remainder of the Willoughby Spit study area for the selected alternative.

Moffatt & Nichol will use the results of the SBEACH cross-shore modeling, GENESIS-T shoreline evolution modeling, the DELFT3D sediment transport and morphological modeling, and consultation with City staff, to determine the preferred alternative for beach restoration at the Willoughby Spit study area. Other factors to be considered include associated costs of construction and management, potential environmental impacts, potential impacts to adjacent shoreline, and aesthetic impacts on the shoreline.

II. DATA COLLECTION

The Willoughby Spit shoreline was modeled to determine the cause of erosion in the vicinity of Fish Eye Condos and Toler Place, accretion downdrift of the terminal groin, and provide various alternatives for restoration and stabilization of this area. The modeling effort considered both the cross-shore loss of sand from storm impacts and the overall long-term shoreline erosion. In order to develop such models, an intensive data collection of coastal conditions present around the Willoughby Spit study area was necessary. Beach and bathymetric survey data were collected for developing the cross-shore model input profiles. Shoreline position data obtained from aerial photos and historical maps were used to assess historical shoreline change rates and the impact of various engineering activities as well as develop long-term shoreline evolution model inputs. Additionally, sediment data from a 2004 analysis was acquired and used for determination of grain sizes to be used in the modeling efforts. Finally, wave data from a gage deployed in March 2006 off the Ocean View shoreline was compiled, reviewed, and assessed for use in the modeling efforts. It was supplemented with water level data from Sewells Point when necessary.

Furthermore, an engineering activities log of erosion control projects and surveys along the entire Ocean View shoreline was developed during previous studies by Moffatt & Nichol. This log was updated to include recent engineering activities such as nourishment projects, breakwater construction, and surveys that have taken place since the last revision during the 2007 study of the Bay Oaks hotspot by Moffatt & Nichol.

A. SURVEY DATA

Relevant historical and recent beach and bathymetric survey data obtained by the City of Norfolk, Waterway Surveys & Engineering, McKim & Creed, and Geodynamics were compiled in a GIS. The dates and sources of all relevant survey data for the Willoughby Spit study area were compiled and are shown in **Table II-1**. **Appendix A** presents a series of maps showing the coverage and extent of these surveys within the Willoughby Spit study area.

Table II-1 Beach & Bathymetric Survey Data Summary

Date	Source	Coverage
October 1998	City Survey	Entire Ocean View Shoreline
October 1999	City Survey	Entire Ocean View Shoreline
October 2000	City Survey	12th View St to Little Creek Inlet
October 2001	City Survey	Entire Ocean View Shoreline
July 2002	City Survey	Entire Ocean View Shoreline (excluding Sherwood Pl to Warwick Ave)
October 2002	City Survey	Entire Ocean View Shoreline (no beach or bathymetric survey data)
February-April 2004	Waterway Surveys & Engineering	Willoughby Spit to 17th Bay St
January-March 2005	Waterway Surveys & Engineering Post-Fill Survey	Willoughby Spit to Warwick Ave
September 2005	McKim & Creed Periodic Survey	Entire Ocean View Shoreline
March 2006	McKim & Creed Periodic Survey	Entire Ocean View Shoreline
October 2006	McKim & Creed Periodic Survey	Entire Ocean View Shoreline
March 2007	McKim & Creed Periodic Survey	Entire Ocean View Shoreline
October 2007	McKim & Creed Periodic Survey	Entire Ocean View Shoreline
March 2008	McKim & Creed Periodic Survey	Entire Ocean View Shoreline
October 2008	McKim & Creed Periodic Survey	Entire Ocean View Shoreline
April 2009	McKim & Creed Periodic Survey	Entire Ocean View Shoreline
October 2009	Geodynamics Periodic Survey	Entire Ocean View Shoreline
November 2009	Geodynamics Post-Storm Survey	Entire Ocean View Shoreline
March 2010	Geodynamics Periodic Survey	Entire Ocean View Shoreline

Recent survey data was used for developing inputs for the SBEACH model to determine impacts from Tropical Storm Ernesto and a November 2009 nor'easter on cross-shore beach profiles.

The use of these survey data sets in specific modeling applications will be discussed further in the SBEACH modeling section of this report (**Section VI**).

B. SHORELINE DATA

In addition to the beach and bathymetric survey data, digitized shorelines were obtained for a number of historical and recent dates. A majority of the older shoreline data was obtained from a study completed by Dr. David Basco of Beach Consultants, Inc, as part of a comprehensive shoreline analysis for Ocean View Beach completed in January 2004. This study involved the collection and analysis of historical and recent shoreline positions dating back to 1852. The process involved determining the shoreline positions from historical NOAA NOS "T-sheets" (topographic maps) and aerial photographs. Moffatt & Nichol provided additional shorelines for more recent dates by digitizing the wet/dry line from available aerial photographs. Furthermore, as part of an ongoing periodic surveying contract with the City of Norfolk, VIMS provided additional aerial photographs and digitized shorelines for periodic surveys between March 2006 and April 2010. **Table II-2** lists the dates and sources of the shoreline data collected in the Willoughby Spit area. **Appendix B** presents each of the shorelines overlain on aerial photographs.

Table II-2 Shoreline Data Summary

Shoreline Date	Source
October 1916	Basco (NOAA T-Sheet T-3647 1:20,000)
September 1956	Basco (VIMS Aerial Photography Archive)
1963	Basco (NOAA T-Sheet T-11704 1:20,000)
February 1976	Basco (VIMS Aerial Photography Archive)
March 1994	Moffatt & Nichol (DOQQ)
October 1995	Moffatt & Nichol (VIMS Aerial Photography Archive)
March 1999	Moffatt & Nichol (City of Norfolk Aerial Photographs)
October 1999	Moffatt & Nichol (VIMS Aerial Photography Archive)
Fall 2000	Moffatt & Nichol (AirPhotoUSA)
June 2002	Moffatt & Nichol (VIMS Aerial Photography Archive)
March 2006	VIMS (VIMS Aerial Photography Archive)
October 2006	VIMS (VIMS Aerial Photography Archive)
March 2007	VIMS (VIMS Aerial Photography Archive)
October 2007	VIMS (VIMS Aerial Photography Archive)
October 2008	VIMS (VIMS Aerial Photography Archive)
April 2009	VIMS (VIMS Aerial Photography Archive)
October 2009	VIMS (VIMS Aerial Photography Archive)
November 2009	Moffatt & Nichol (NOAA Aerial Photography)
April 2010	VIMS (VIMS Aerial Photography Archive)

The available shoreline data was used to analyze historical shoreline change rates and assess the impact of coastal structures and nourishment projects done in the Willoughby Spit area. The digitized shoreline data was also used, where applicable, in the GENESIS-T long-term shoreline evolution modeling. The use of shoreline data in specific applications of this study will be discussed further in GENESIS-T modeling section of this report (**Section V**).

C. SEDIMENT DATA

In April 2004, comprehensive sediment data was collected by Geotechnical Testing Environmental Solutions, Inc. for use in the Willoughby Spit to Central Ocean View restoration project. Sediment samples were obtained every 1000 ft along the Ocean View shoreline at the dune toe, mid beach, high waterline, and -6 ft. Sediment samples taken in the Willoughby Spit study area (samples OV1-OV6) were reviewed to determine existing sediment characteristics required for modeling efforts. **Table II-3** presents a summary of the d50 values for these sediment samples. **Appendix C** contains the sediment grain size distributions for the pre- 2004 nourishment of the Willoughby Spit study area. Based on this data and other studies that have been completed, a grain size of 0.4 mm was used for the study area.

Table II-3 2004 Sediment Data Summary

Station	d50-dune toe (mm)	d50-mid beach (mm)	d50-high waterline (mm)	d50- -6 ft (mm)	d50-avg of dune toe, mid beach, high waterline, and -6 ft (mm)
OV1	0.68	0.56	0.89	NA	0.71
OV2	1.03	0.46	0.58	0.44	0.63
OV3	0.42	0.42	NA	0.23	0.36
OV4	0.43	0.50	0.33	0.28	0.39
OV5	0.36	0.36	0.37	0.33	0.35
OV6	0.47	0.49	0.62	0.22	0.45

D. WAVE DATA

Previous studies performed for East Ocean View (M&N 2004), 800 Block (M&N 2005), and Bay Oaks (M&N 2007) have utilized offshore wave data that was transformed to the site from the Duck FRF through numerical modeling. The resulting long-term wave time series used in these studies spanned 1991 to 2003. In March 2006, the City authorized Evans Hamilton Inc. to deploy a bottom mounted wave and current gage offshore of Ocean View to aid in engineering studies of the shoreline. The gage is serviced every 4 months during which new wave data is downloaded, compiled, and reviewed for accuracy. It has been determined that the amount of gage data collected to date (approximately 4 years) is now sufficient for use in modeling efforts. It will be used to model storm induced erosion in SBEACH for recent events, calibrate and run alternatives in the GENESIS-T model, and develop appropriate wave conditions to be used in Delft3D. Wave data review and analysis will be discussed further in this report (**Section IV**).

E. ENGINEERING ACTIVITIES LOG

Information related to engineering projects in the Ocean View area was compiled and was an essential reference for the review of historical data and numerical modeling completed in this study. It is important to consider these activities when examining historical erosional patterns, as shoreline change is significantly impacted by engineering interventions.

The engineering activities log was compiled from previous work and through discussions and verification with the City. **Appendix D** presents engineering activities including structure construction, beach nourishment projects, and surveys completed for the entire Ocean View shoreline between 1920 and 2010. Those activities impacting the Willoughby Spit study area are

highlighted in the table and are also presented in **Table II-4**. These activities are further discussed with respect to the shoreline change analysis in the following section **(Section III)**.

Table II-4 Willoughby Spit Engineering Activities

Date	Project Type	Location	Vol (cy)	Sand Source
1920-1937	Groin Construction	Willoughby Spit Shoreline		
1938	Groin Construction	Between Willoughby Spit and Chesapeake Blvd.		
1962	Beach Nourishment	Terminal Groin to 9th View St (Willoughby Spit)	176,000	
1981	Groin reconstruction	Willoughby Spit area		
1983	Groin Construction	Western end of Willoughby Spit		
Jan-Apr 1984	Beach Nourishment	Terminal Groin to 5th View St (Willoughby Spit)	537,500	Navy Piers
Spring 1988	Dune Repair	Willoughby Beach	10,000	Terminal Groin
June, 1989	Dune Repair	Willoughby Beach	25,000	Terminal Groin
1990	Breakwater Construction	Western end of Willoughby Spit-Lea View Ave.		
1990	Terminal Groin Reconstruction	Western end of Willoughby Spit-Lea View Ave.		
1990	Beach Nourishment	Willoughby Spit-Near Terminal Groin	100,000	West of Terminal Groin
1995	Beach Nourishment	Willoughby Spit	240,000	15th View
December, 1995	Beach Nourishment	13th View St to 12 View St (in 4 groin pockets)	4,000	15th View
March, 1997	Terminal Groin (trunk) Elevated	Willoughby Spit		
August, 2004	Beach Nourishment	13th View to 11th View, Behind Western 4 Breakwaters at 800 Block, 1200' East of dogleg	37,000	Truck Haul
January-March, 2005	Dune Restoration	Willoughby Spit to Central Ocean View (14th View St to Warwick Ave)	504,329	Thimble Shoal Channel

III. REVIEW & ANALYSIS OF HISTORICAL DATA

A review of historical shoreline data and engineering activities at the Willoughby Spit project study area was conducted to develop an initial understanding of the long-term shoreline change trends within the study area and the shoreline response to engineering activities.

A. SHORELINE CHANGE ANALYSIS

The available shorelines from 1852 to April 2010 were placed in ArcGIS. A baseline for measuring shoreline positions was digitized along the Willoughby Spit shoreline. Transects running perpendicular to the baseline were placed every 10 ft. **Figure III-1** shows the defined baseline and transects overlain on April 2010 aerial photography. Transects are only shown every 100 ft for visual purposes. The distance from the baseline to the shoreline was measured along each transect. Shoreline change rates were then computed by dividing the change in shoreline position by the amount of time between each data set. Shoreline change was calculated between specific sets of dates dependent on the presence or absence of engineering activities. The resulting plots are presented in **Figure III-2** through **Figure III-10** at the end of this section.

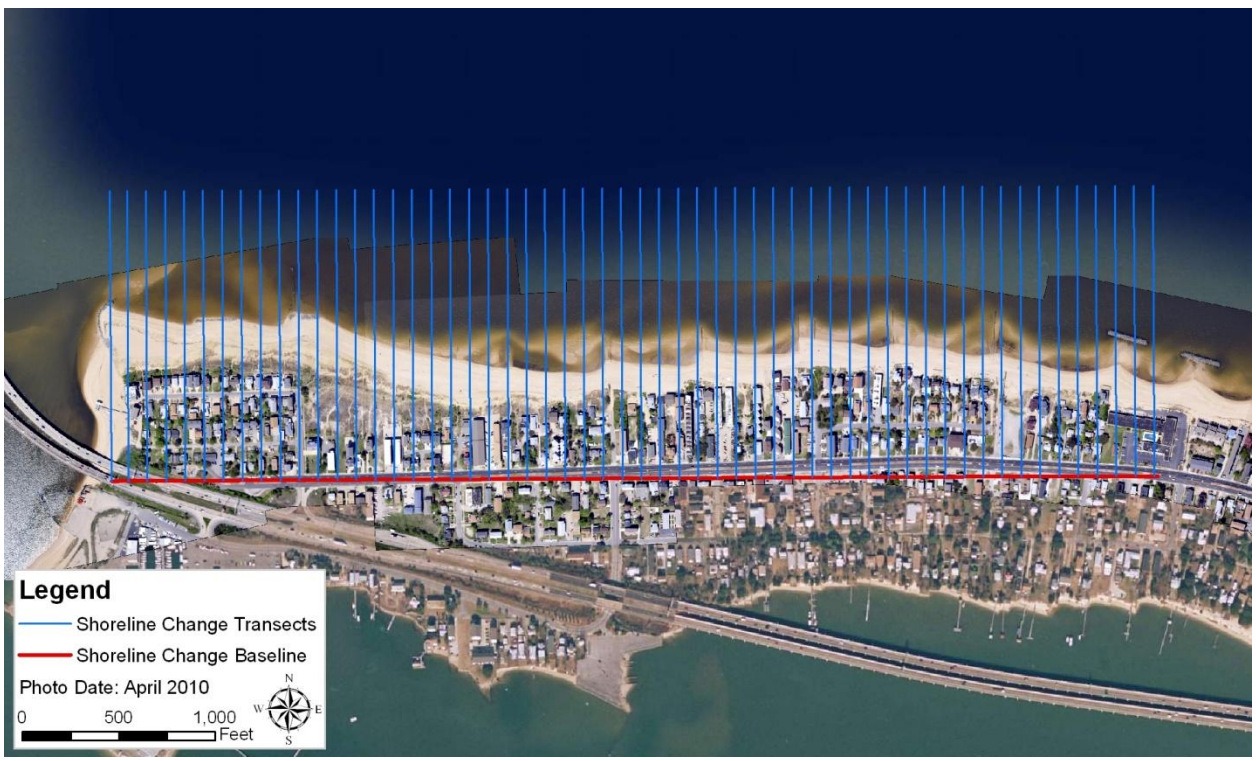

Figure III-1 Shoreline Change Baseline and Transects

Analysis of the shoreline change plots indicates the large influence that engineering activities, including coastal structures and beach nourishment, have had on the Ocean View shoreline over the years. The following sections will review the historical shoreline change analysis by presenting for each time period analyzed, the applicable data sources, relative shoreline positions, coincident engineering activities, and the computed shoreline rates of change across the study area extent. For ease in the presentation of results, all figures referenced in the following discussions are presented at the end of this section.

1. October 1916 – September 1956

The October 1916 shoreline and September 1956 shorelines were both obtained from the Basco study in which the 1916 shoreline was delineated from a NOAA T-sheet and the 1956 shoreline was digitized from an aerial photograph provided by VIMS. It should be noted that the 1956 shoreline only covers the eastern portion of the study area. The Willoughby Spit area was impacted during this time period by the construction of a large groin field extending from Willoughby Spit to Chesapeake Blvd. In all, 99 groins were constructed from 1920 to 1938, including the original timber terminal groin. **Figure III-2** presents a comparison of the relative shoreline positions overlain on the aerial photo from 1956 and the computed shoreline change rate across the study area transects. The natural shoreline had an erosional trend with an average shoreline change rate of -4.3 ft/yr over the eastern portion of study area (where data was available).

2. September 1956 – 1963

The September 1956 shoreline and 1963 (month unknown) shorelines were both obtained from the Basco study in which the 1956 shoreline was digitized from an aerial photograph provided by VIMS and the 1963 shoreline was delineated from a NOAA T-sheet. As previously mentioned, the 1956 shoreline only covers the eastern portion of the study area. During the time period from 1956 to 1963, the Willoughby Spit region was impacted by a beach nourishment project in 1962 which extended from the terminal groin to 9th View, placing 176,000 cy of material on the beach. The impact of the nourishment project is apparent in **Figure III-3** where the two shoreline positions are shown overlain on 1956 aerial photography along with the computed shoreline change rate across the study area transects. The trend across the region shows a large amount of accretion with an average shoreline change rate for the time period from 1956 to 1963 of 19.0 ft/yr over the eastern portion of study area (where data was available).

3. 1963 – February 1976

The 1963 (month unknown) shoreline and February 1976 shorelines were both obtained from the Basco study in which the 1963 shoreline was delineated from a NOAA T-sheet and the 1976 shoreline was digitized from an aerial photograph provided by VIMS. There were no engineering projects during this time period. **Figure III-4** shows the two shoreline positions overlain on aerial photography from 1976 and the computed shoreline change rate across the study area transects. The average shoreline change for the project area during this time period was -4.5 ft/yr, similar to the historical erosion rate prior to the 1962 nourishment project.

4. February 1976 – March 1994

The February 1976 shoreline was obtained from the Basco study in which it was digitized from aerial photography provided by VIMS. The March 1994 shoreline was digitized by Moffatt & Nichol using the USGS DOQQ which covers the study area. During the time period from 1976 to 1994, there were numerous engineering activities which took place. A few groins were reconstructed in 1981 followed by the addition of 5 new groins in 1983. A large beach nourishment project took place in January through April of 1984 in which 537,500 cy of material from Navy Piers was placed between the terminal groin and 5th View. In 1988 and 1989, dune repair projects took place in which 10,000 and 25,000 cy of material, respectively, was taken from accretion of the terminal groin and used on Willoughby Beach. In 1990, a series of projects took place including construction of two offshore breakwaters, reconstruction of the original

terminal groin which involved raising the groin and extending it using rock, and a beach nourishment project near the terminal groin using 100,000 cy of material from accretion west of the terminal groin. Accretion of the area closest to Willoughby Spit due to the reconstruction of the terminal groin, addition of offshore breakwaters, and the beach nourishment project is apparent in **Figure III-5** where the two shorelines are overlain on aerial photography from 1994 and the computed shoreline change rate across the study area transects is shown. The remainder of the area also shows slight accretion, most likely as a result of the other beach nourishment and dune repair projects and new structures. The average shoreline change rate for the entire study area was 5.6 ft/yr from 1976 to 1994.

5. March 1994 – October 1995

As previously mentioned, the March 1994 shoreline was digitized by Moffatt & Nichol from USGS DOQQs. The October 1995 shoreline was also digitized by Moffatt & Nichol from VIMS aerial photography. There was one beach nourishment project during the time period in 1995 (prior to October) where 240,000 cy of material was taken from 15th View and placed near the terminal groin. The effect of this on the shoreline can be seen in **Figure III-6,** where the two shorelines are overlain on 1995 aerial photography and computed shoreline change rate across the study area transects is shown**.** The shoreline nearest Willoughby Spit shows accretion from the nourishment project while the remainder of the shoreline shows an erosional trend. The average shoreline change rate during this time period was -8.5 ft/yr for the entire study area.

6. October 1995 – March 1999

The October 1995 and March 1999 shorelines were digitized by Moffatt & Nichol from VIMS aerial photography and City of Norfolk aerial photography, respectively. The study area underwent one beach nourishment project in December 1995 where 4,000 cy of material was taken from 15th View ad placed in 4 groin pockets between 13th View and 12th View. This is evident in **Figure III-7** which shows the two shorelines overlain on 1999 aerial photography and the shoreline change rate across the study area transects. In addition, the terminal groin trunk was elevated to +4 ft in 1997. The average shoreline change rate for the study area during this time was 1.9 ft/yr. However, during this time period the breakwater field to the east was also constructed and the accretion behind and erosion downdrift of these structures is also apparent.

7. March 1999 – June 2002

The March 1999 and June 2002 shorelines were digitized by Moffatt & Nichol from City of Norfolk aerial photography and VIMS aerial photography, respectively. During this time period, there were no engineering activities. **Figure III-8** shows the two shorelines overlain on 2002 aerial photography and the shoreline change rate across the study area transects. Accretion at Willoughby Spit and erosion over the remainder of the study area is apparent. The average shoreline change rate for the entire study area was -3.2 ft/yr, which is slightly lower than previous time periods where no engineering activities took place. There is also still a noticeable erosion signal immediately downdrift of the eastern breakwaters, where a bend in the shoreline also takes place.

8. June 2002 – March 2006

The June 2002 shoreline was digitized by Moffatt & Nichol using VIMS aerial photography. The March 2006 shoreline was digitized by VIMS using aerial photography they flew as part of

the ongoing periodic surveying of the Ocean View shoreline. In August 2004 the area from 13th View to 11th View, along with the 800 Block breakwater region, received 37,000 cy of material that was hauled in by truck from another location. A large dune restoration project took place in January to March 2005, extending from 14th View to Warwick Ave in which 504,329 cy of material from Thimble Shoal Channel was placed on the beach. These nourishment projects are evident in **Figure III-9** where the two shorelines are overlain on 2006 aerial photography and the computed shoreline change rate across the study area transects is presented. The average shoreline change rate during this time period was 7.5 ft/yr over the entire study area.

9. March 2006 – April 2010

The March 2006 and April 2010 shorelines were digitized by VIMS from their aerial photography as part of the ongoing periodic surveying of Ocean View Beach. There were no engineering activities which took place during this time period. However, a large nor'easter damaged much of the shoreline in November 2009. **Figure III-10** presents the shorelines overlain on 2010 aerial photography and computed shoreline change rate across the study area transects. The trend across the region is erosional with an average rate of -2.9 ft/yr. Please note the erosional area downdrift of the easternmost breakwaters is still apparent.

B. IMPACT OF EXISTING STRUCTURES AND BEACH FILL

It appears that the western end of the study area has greatly benefitted from the terminal groin and offshore breakwaters. During recent periods void of engineering activities (beach nourishment), the shoreline near the terminal groin has shown a stable, and sometimes, accretional trend. The combination of structures and littoral transport direction has greatly benefitted this area. The remainder of the shoreline in the eastern portion of the study area often shows a slight erosional trend during periods of inactivity. This is likely due to the poor condition of the groins not being able to hold the shoreline as needed. In addition, there could be some end effect of the 800 block breakwater field interfering with the sediment transport in the eastern portion of the study area as well as the natural curvature of the shoreline which would tend to have increased losses offshore with longshore transport.

Based on aerial photography, it appears that the terminal groin pocket completely filled sometime between June 2002 and March 2006. It also appears that the accretion of the western facing beach downdrift of the terminal groin began sometime between March 2006 and October 2006, just after the groin pocket was filled. Therefore, it is likely that the filling of the groin pocket triggered a change in littoral transport in the area, causing accretion of the west facing beach to begin. With a full groin pocket, it is likely that Tropical storm Ernesto, which occurred in early September 2006, caused some overtopping of the groin, also transporting sediment to the west facing beach.

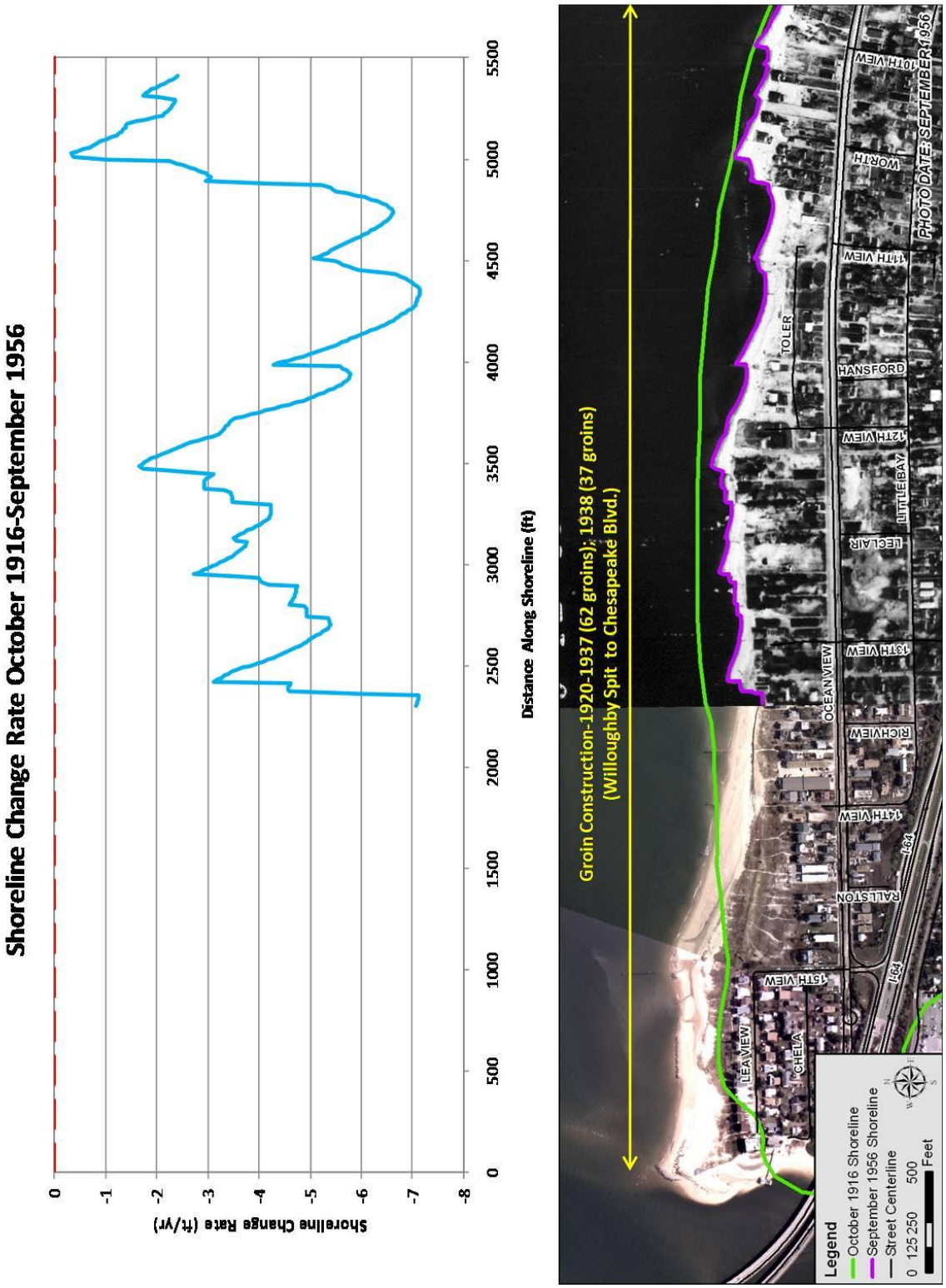

Figure III-2 Shoreline Change Rate (October 1916 – September 1956)

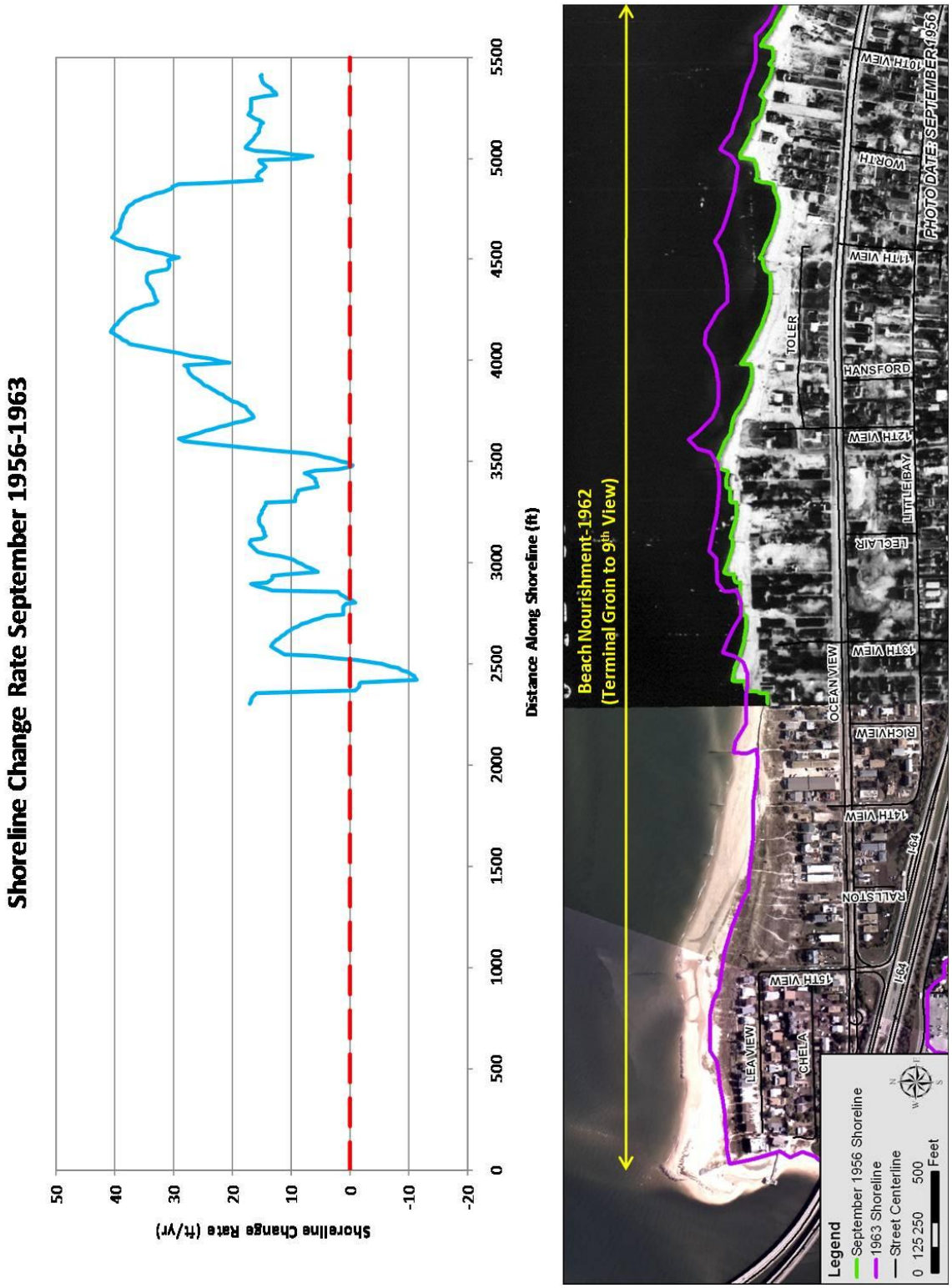

Figure III-3 Shoreline Change Rate (September 1956 – 1963)

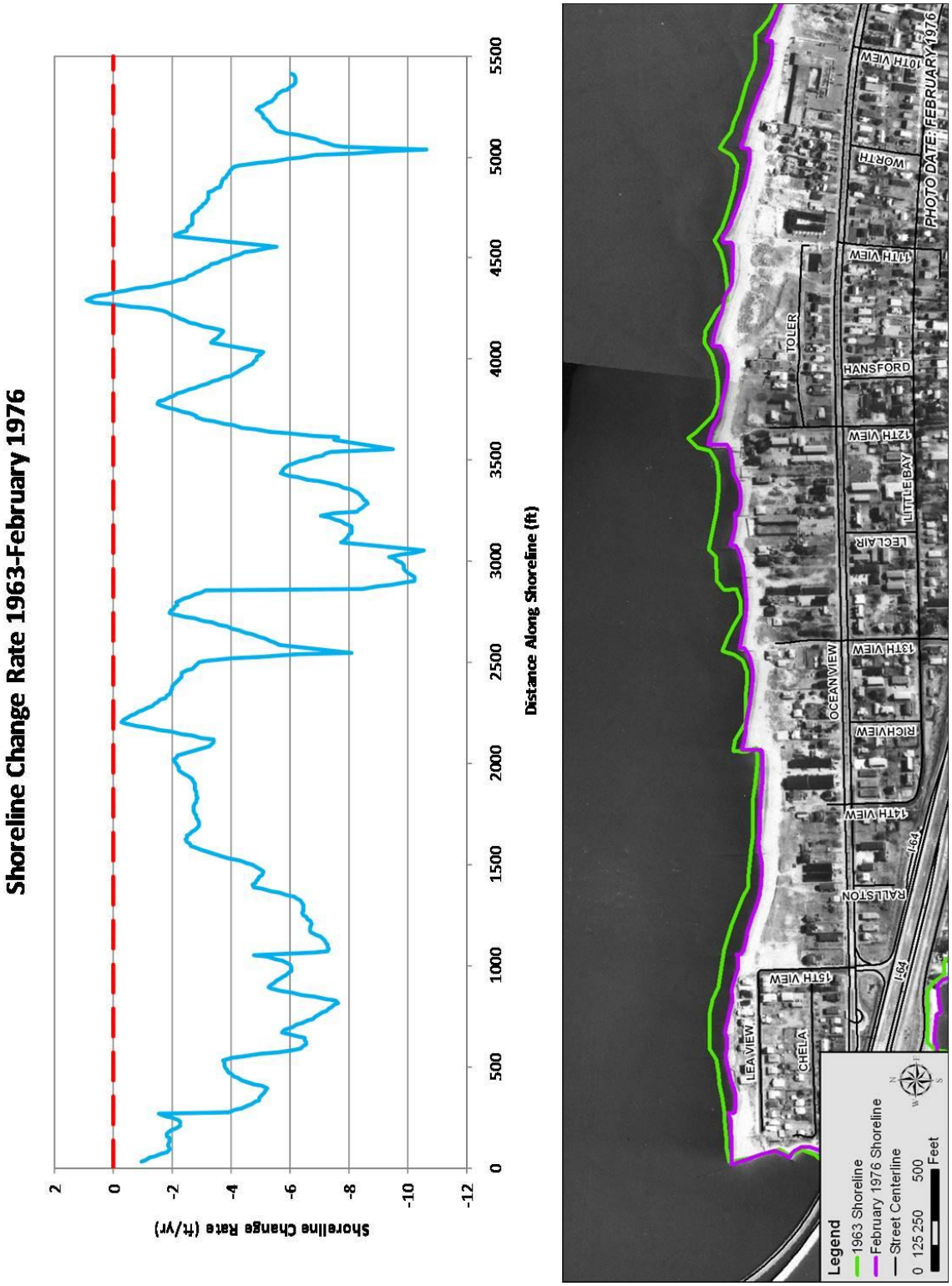

Figure III-4 Shoreline Change Rate (1963 – February 1976)

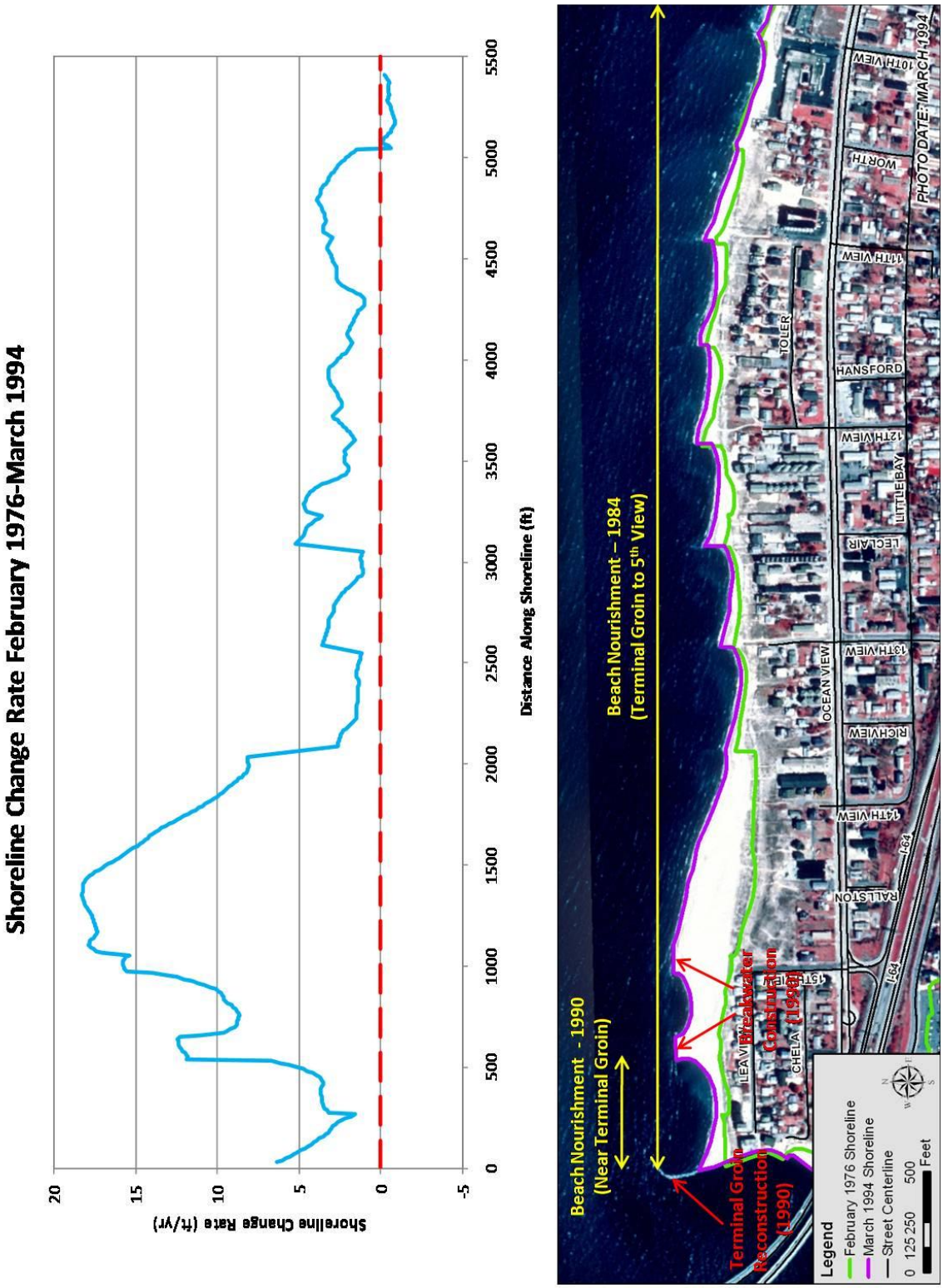

Figure III-5 Shoreline Change Rate (February 1976 – March 1994)

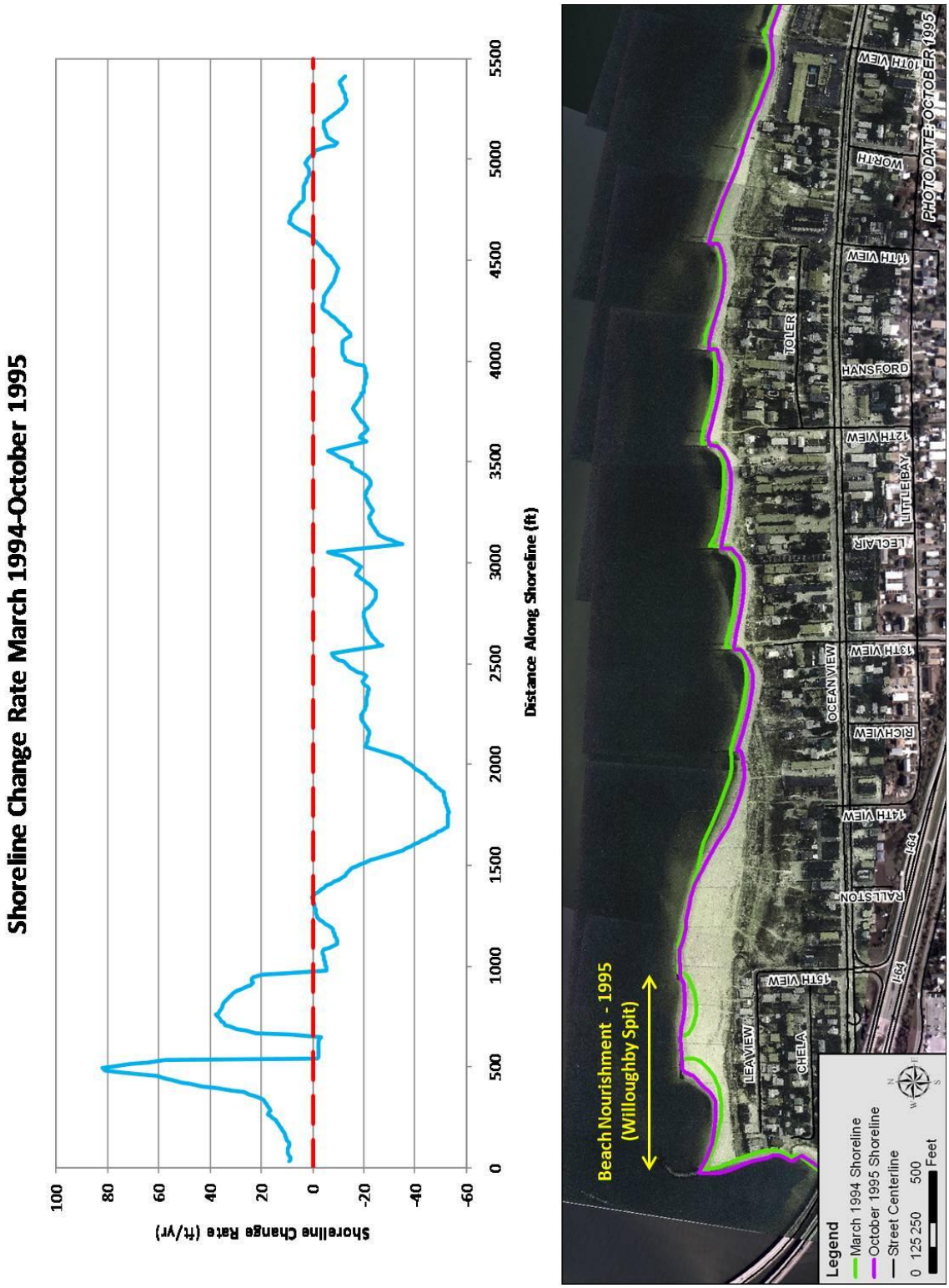

Figure III-6 Shoreline Change Rate (March 1994 – October 1995)

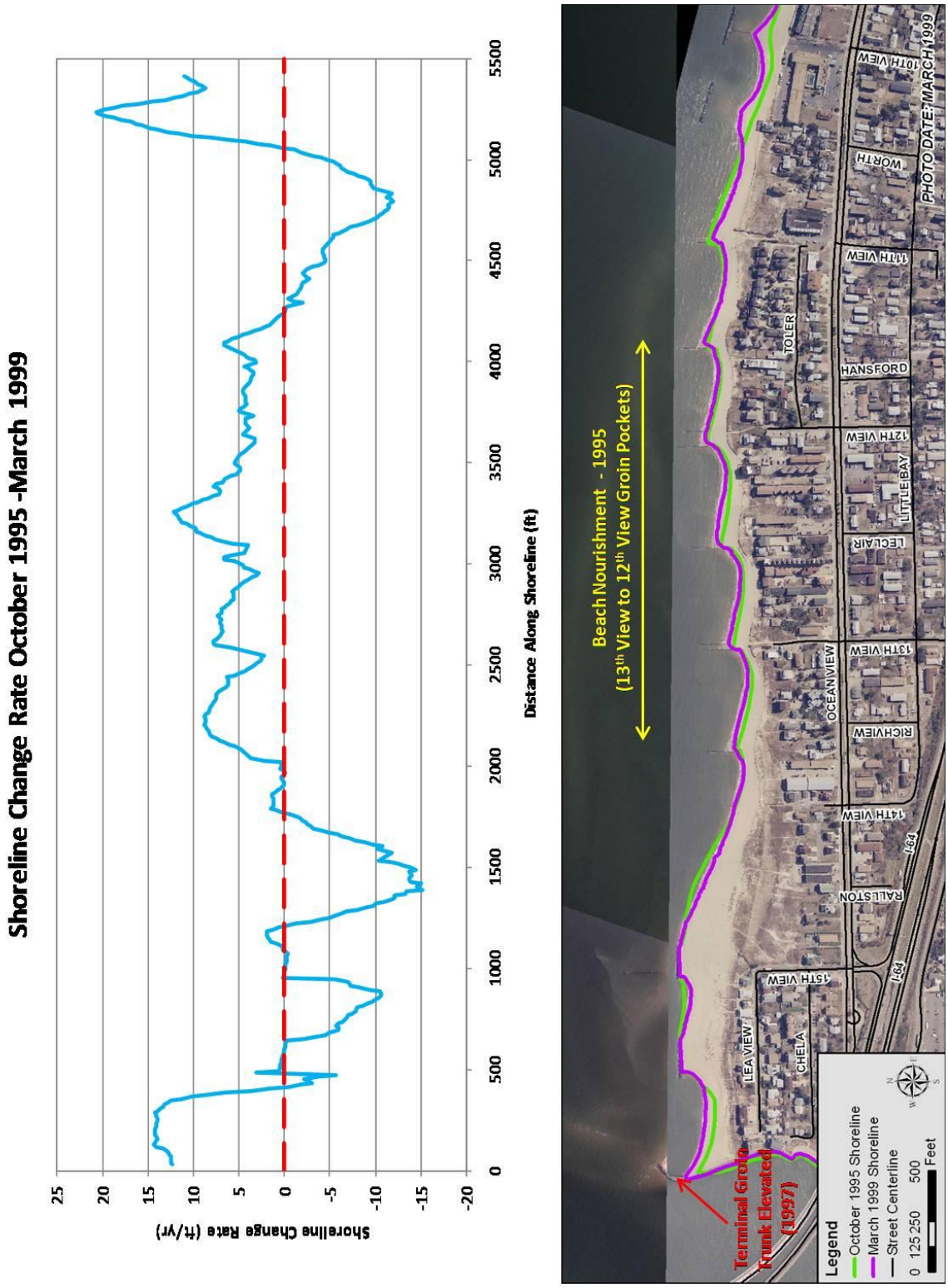

Figure III-7 Shoreline Change Rate (October 1995 – March 1999)

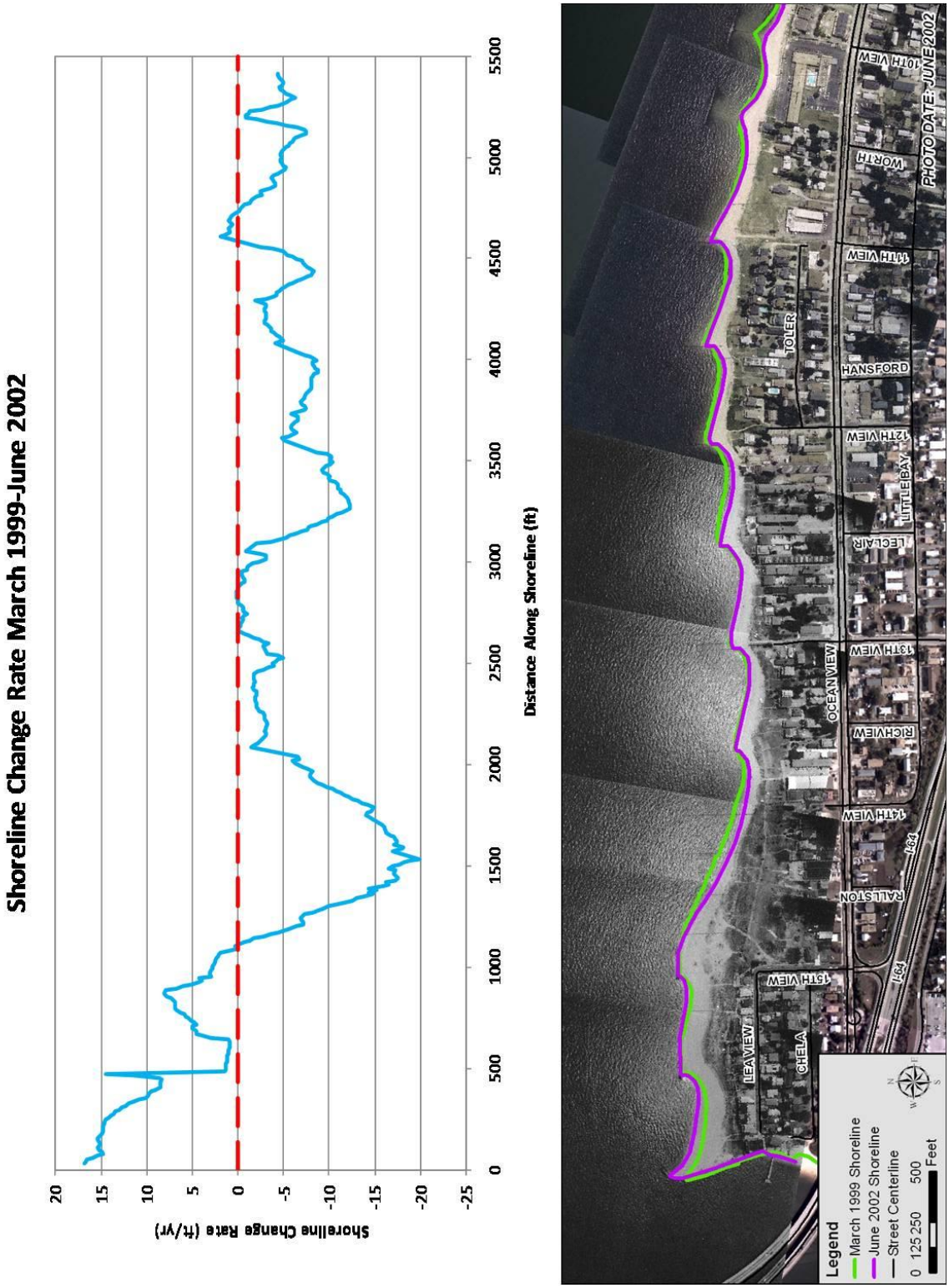

Figure III-8 Shoreline Change Rate (March 1999 – June 2002)

Figure III-9 Shoreline Change Rate (June 2002 – March 2006)

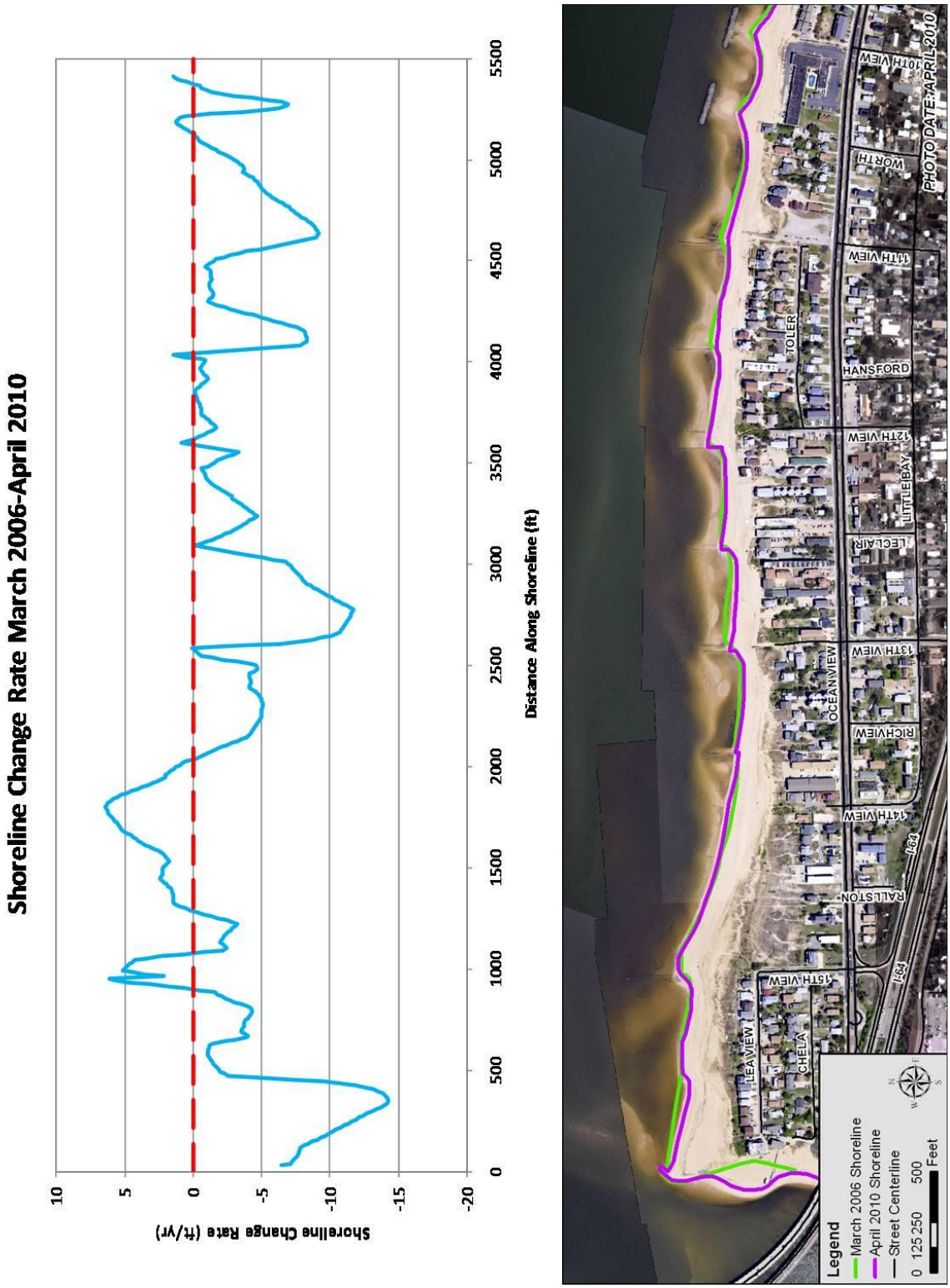

Figure III-10 Shoreline Change Rate (March 2006 – April 2010)

IV. WAVE DATA REVIEW AND ANALYSIS

In order to develop an efficient design and estimate the expected design life of a proposed project, a reasonable estimate of the wave climate at the site is crucial. Previous studies performed for the East Ocean View, 800 Block, and Bay Oaks regions of Ocean View have utilized offshore wave data that was transformed to the site through numerical modeling. The resulting long-term wave time series used in these studies spanned 1991 through 2003. In March 2006, the City authorized Evans Hamilton, Inc. (EHI) to deploy a bottom-mounted wave and current gage offshore of Ocean View to aid in engineering studies of the shoreline. The gage is serviced every 4 months during which new wave data is downloaded, compiled, and reviewed for accuracy. With multiple years of data now collected, the gage data was found to be sufficient for modeling input. This new wave data was reviewed, analyzed, and evaluated to develop multiple short-term and long-term time series for various periods between March 2006 and April 2010 to be utilized in SBEACH (short-term storm induced erosion) and GENESIS-T (long-term shoreline change) for both calibration and alternative testing. Wave characteristics determined during the gage wave data analysis were also used in DELFT3D (morphological modeling) to characterize the wave climate. In some instances, water levels from Sewells Point were used in conjunction with the wave gage data where necessary (SBEACH).

A. NORFOLK MEASURED NEARSHORE WAVE DATA

Understanding of the wave climate immediately offshore of the Norfolk shoreline is vital for the design, monitoring, and understanding of projects along the shoreline and the behavior of the beach from both a real life and modeling perspective. In March 2006, a bottom-mounted wave gage (**Figure IV-1**) was deployed by Evans Hamilton Inc. for the City to measure the wave climate offshore of Ocean View to aid in improving knowledge of the nearshore wave climate. The Nortek AWAC-AST wave gage was placed on the sea floor and looks upward measuring currents through the water column and tracks the water surface elevation above it. The AWAC (Acoustic Wave And Current) gage is a combination acoustic Doppler current profiler and directional wave gage employing a unique Acoustic Surface Tracking (AST) vertical beam to measure the surface waves from a subsurface location. The data is collected at regular intervals (every 20 minutes for currents and hourly for waves) and stored in the instrument for later retrieval during quarterly servicing when the data collected is downloaded and analyzed. The wave gage is centrally located along the Norfolk Ocean View shoreline, in 23 feet of water, and far enough offshore to not be shielded by the spit (see **Figure IV-2**). Further details of the instrumentation, sampling scheme, and the measured wave data are documented by deployment period (quarterly during the first year) in reports submitted to the City of Norfolk. These wave measurements are still ongoing and will provide an important basis for future analysis and coastal engineering works along the shoreline.

Figure IV-1 Wave Gage and Bottom Mount

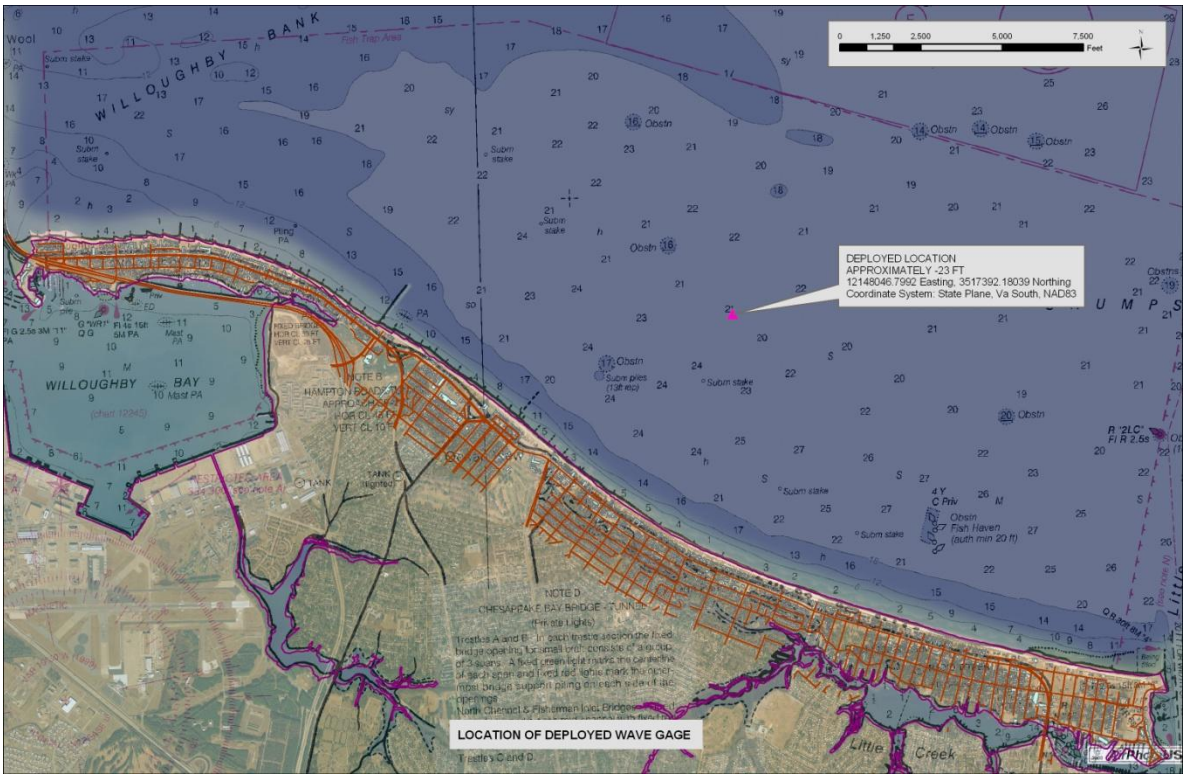

Figure IV-2 Wave Gage Deployment Location

B. WAVE DATA DISCUSSION

The understanding of coastal processes and the design of coastal projects requires a reasonable estimate of the wave climate. Along a beach, water level variations and waves drive the hydrodynamics of the sand movement. Properly assessing the wave climate is essential to developing suitable solutions to beach erosion and evaluating the potential design life of a project. Both storm (short-term) and long-term wave data is required for use in the SBEACH, GENESIS-T and DELFT3D models to accurately predict beach changes due to storms and shoreline evolution over time.

The wave data from the gage at Norfolk provides the best available wave information since the data is directly measured and site-specific. For the purposes of this study, the measured wave data has been determined to be of sufficient length for use in modeling efforts which require both short-term and long-term time series. Wave data over the first thirteen deployments covers a time period from March 2006 to May 2010. This data, together with survey profiles and digitized shoreline data from within this time period, was used to calibrate and verify the numerical modeling in SBEACH and GENESIS-T. The data was also used to run various alternatives for future shoreline and profile response. The data appears to represent both high energy periods of wave activity (storms) as well as quiescent periods of time, creating a reasonable estimate of future wave activity. As a note, two fairly significant storms which impacted the Ocean View shoreline, Tropical Storm Ernesto (September 2006) and the November 2009 nor'easter, are contained within the recent measurements and were used directly in SBEACH modeling of storm-induced cross-shore change as well as included within the longer term time series used in GENESIS-T modeling. DELFT3D modeling also used characteristic wave data determined from analysis of the four year time period over which the gage data has been collected.

The measured wave gage data over the first four years of deployment exhibit some clear overall trends. The wave climate is divided between waves traveling from the Atlantic Ocean through the mouth of Chesapeake Bay (swell) and waves generated within Chesapeake Bay by winds (sea). The swell waves tend to exist throughout the year and are of longer period. The second component of the wave climate is generated by winds blowing over the waters of Chesapeake Bay. These locally-generated sea waves within the Bay tend to have shorter wave periods. During storm events, especially those with a northerly wind blowing across the longest fetch of the Bay toward the Norfolk shore (extratropical nor'easters common to the area), these sea waves have the largest wave heights impacting the beach. It is these storm waves that drive the largest motion of sand both along and across (on and offshore) the shoreline.

The measured directional spectra (**Figure IV-3**) illustrate the division in the wave energy between local wind generated sea (higher frequency/shorter period waves generally generated within Chesapeake Bay coming from northerly directions) and the transformed swell entering form the Atlantic Ocean (lower frequency/longer period waves generally coming from easterly directions). **Figure IV-4** shows the percent occurrence of important wave characteristics (wave direction, wave period, and wave height) for the four years of wave gage deployment. **Figure IV-5** shows the seasonality of wave characteristics by displaying percent exceedance of wave heights on a quarterly basis. The fall and winter months exhibit much larger waves, as expected, due to the occurrence of hurricanes and nor'easters. The average wave characteristics

determined during this analysis (wave direction, wave height, and wave period) was used to develop the wave environment during DELFT 3D modeling as well as aid in understanding SBEACH and GENESIS-T modeling results.

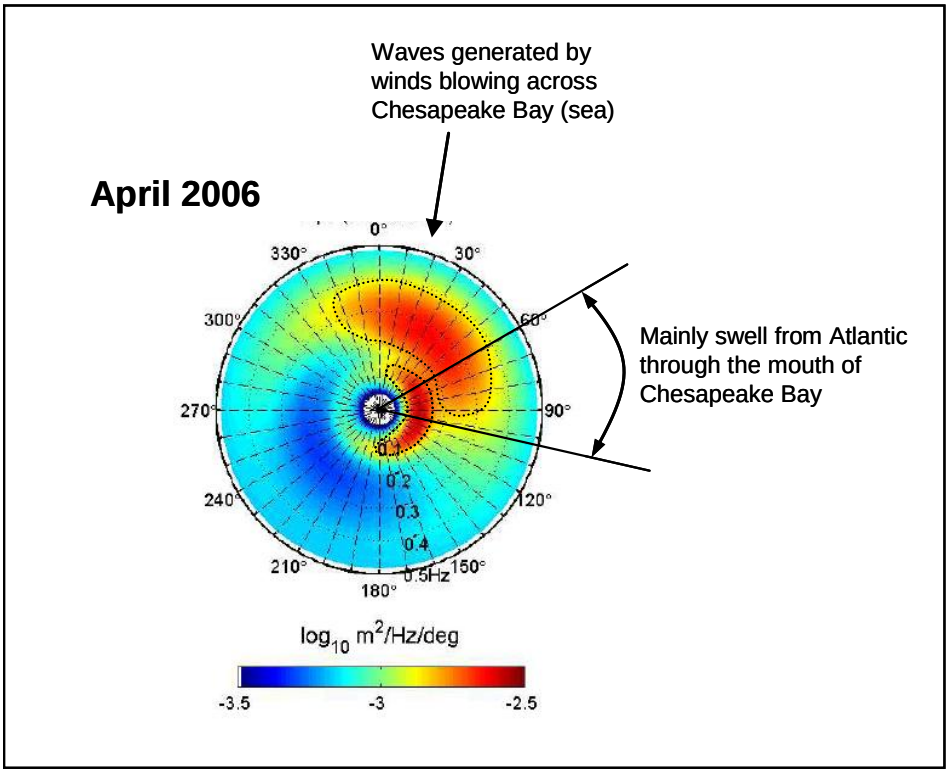

Figure IV-3 Example of Measured Directional Wave Spectrum

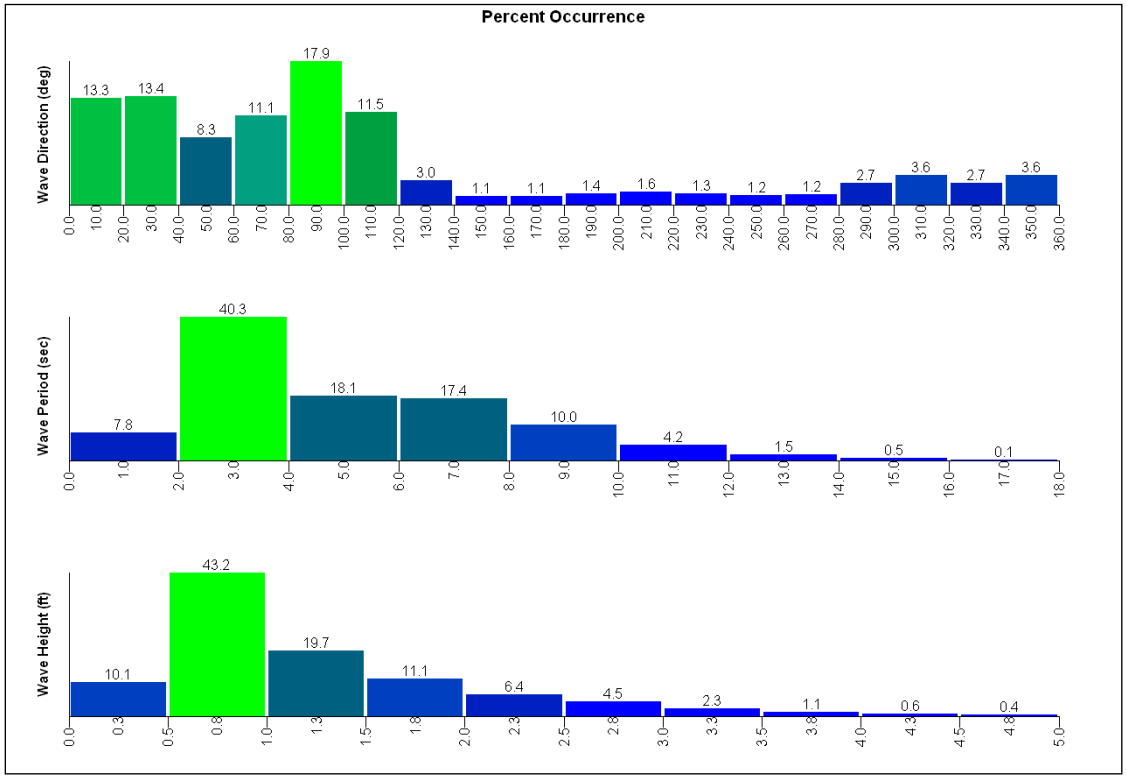

Figure IV-4 Measured Wave Conditions (March 2006 - May 2010)

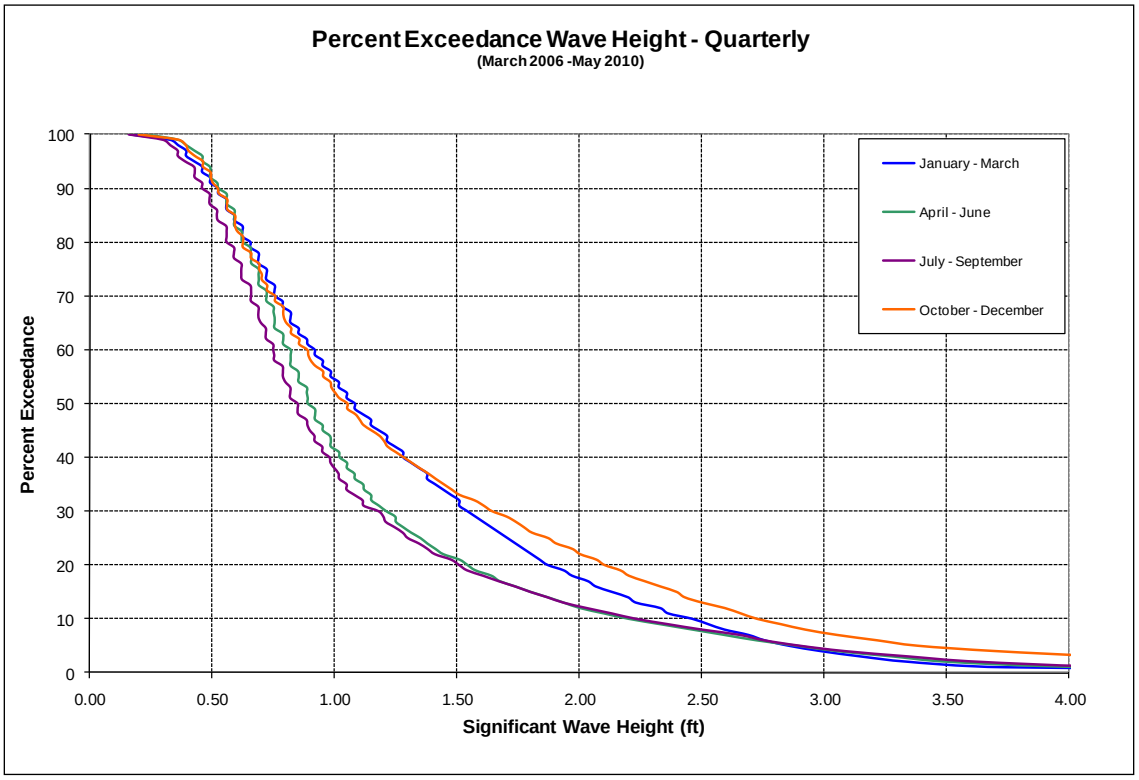

Figure IV-5 Quarterly Percent Exceedance of Wave Heights (March 2006 - May 2010)

V. MODELING OF LONG-SHORE CHANGE WITH GENESIS-T

GENESIS (Generalized Model for Simulating Shoreline Change) is designed to simulate long-term shoreline change based on spatial and temporal differences in longshore sediment transport induced primarily by wave action. The GENESIS modeling system allows for a number of user-specified inputs including wave inputs, initial shoreline positions, coastal structures and their characteristics, and beach fills; all of which aid in the calculation of sediment transport and shoreline change. This model was developed at the U.S. Army Corps of Engineers (USACE), Engineer Research and Development Center (ERDC), Coastal & Hydraulics Laboratory (CHL). For a more detailed description of the GENESIS model, the reader is referred to the User's Manual and Technical Reference published on the model (Hanson and Krauss, 1989, Gravens et al, 1991).

GENESIS-T is a recent release that expands on the modeling capabilities of GENESIS, allowing for the formation of tombolos at detached breakwaters and/or T-groins. After a comparison of GENESIS and GENESIS-T, it was decided to use GENESIS-T for this study, due to the capability of tombolo formation, which is a distinct possibility given the behavior of the shoreline in response to the existing breakwaters. It was determined in a previous study by M&N (Bay Oaks, 2007) that GENESIS and GENESIS-T results yield almost identical predicted shorelines in the absence of tombolo formation.

GENESIS-T operates within the Coastal Engineering Design and Analysis System (CEDAS), a suite of tools developed by Veri-Tech, based on various numerical models and codes developed at CHL. GENESIS and GENESIS-T run through NEMOS, which is designed to ease in the preparation of data inputs, analysis, and manipulation for a number of related coastal models.

The GENESIS-T model has potential for many applications in the coastal environment, including evaluation of longshore sediment transport, analysis of beach fill performance, or the analysis of the impact of coastal structures on shoreline change.

The main inputs to the GENESIS-T model include:

- Shoreline Position Data – one-dimensional description of the shoreline position relative to a straight baseline position,
- Wave Data – long-term time dependent description of wave heights, periods, and directions applicable to the study area,
- Coastal Structures – position and characteristics of coastal structures (breakwaters, groins, jetties, or seawalls) acting along the study area,
- Beach Fill – starting and ending dates and location of beach fill defined by an added berm width,
- Sediment and Beach Characteristics – effective grain size, average berm height, and closure depth for the study area,
- Sediment Transport Parameters – used to characterize longshore sediment transport and calibrate the model, and
- Boundary Conditions – seaward boundary conditions for the input wave data and lateral boundary conditions for the shoreline (left and right).

A. MODELING SCOPE

The GENESIS-T model serves as the basis for developing an understanding of the historical longshore sediment transport and erosional patterns along the Willoughby Spit study area and for evaluating numerous shoreline stabilization and restoration alternatives. The GENESIS-T modeling task involved evaluating the long-term change in shoreline position based on a long-term period of wave action (2006-2010).

To establish the appropriate model parameters, the GENESIS-T model was calibrated for a March 2006 to April 2010 time period using historical shoreline positions from periodic survey evaluations and coinciding wave data from the Norfolk wave gage. GENESIS-T is primarily calibrated by adjusting the longshore sand transport coefficients (K_1 and K_2). Additionally, the model may be calibrated by adjusting the characteristic transmissivity or permeability of offshore breakwaters, groins or jetties.

Once a calibrated model was developed, the model was run for a shorter verification time period from October 2009-April 2010. This verification time period included the November 2009 nor'easter and ensured that the model performed correctly under storm conditions. Shoreline positions from the periodic survey evaluations were used in conjunction with data from the Norfolk wave gage.

Following calibration and verification, an existing conditions model was developed and run for a future eight (8) year time period to determine the impacts with no mitigation of the existing erosion problem. The April 2010 shoreline from the periodic survey was used as the initial condition and the four years of wave data from the Norfolk wave gage was run twice to simulate eight (8) years into the future. Then, the calibrated model was used to simulate future long-term shoreline change with numerous erosion control/beach nourishment alternative improvements in place. The selected alternatives were evaluated based on comparisons against the predicted existing conditions shoreline case.

B. STUDY AREA

The GENESIS-T model extent extended from the terminal groin eastward to the first breakwater in the 800 Block breakwater field. Since GENESIS-T does not have the capability to model around the corner of the terminal groin, this analysis was later performed using DELFT3D. **Figure V-1** shows the GENESIS-T model extent and existing structure locations.

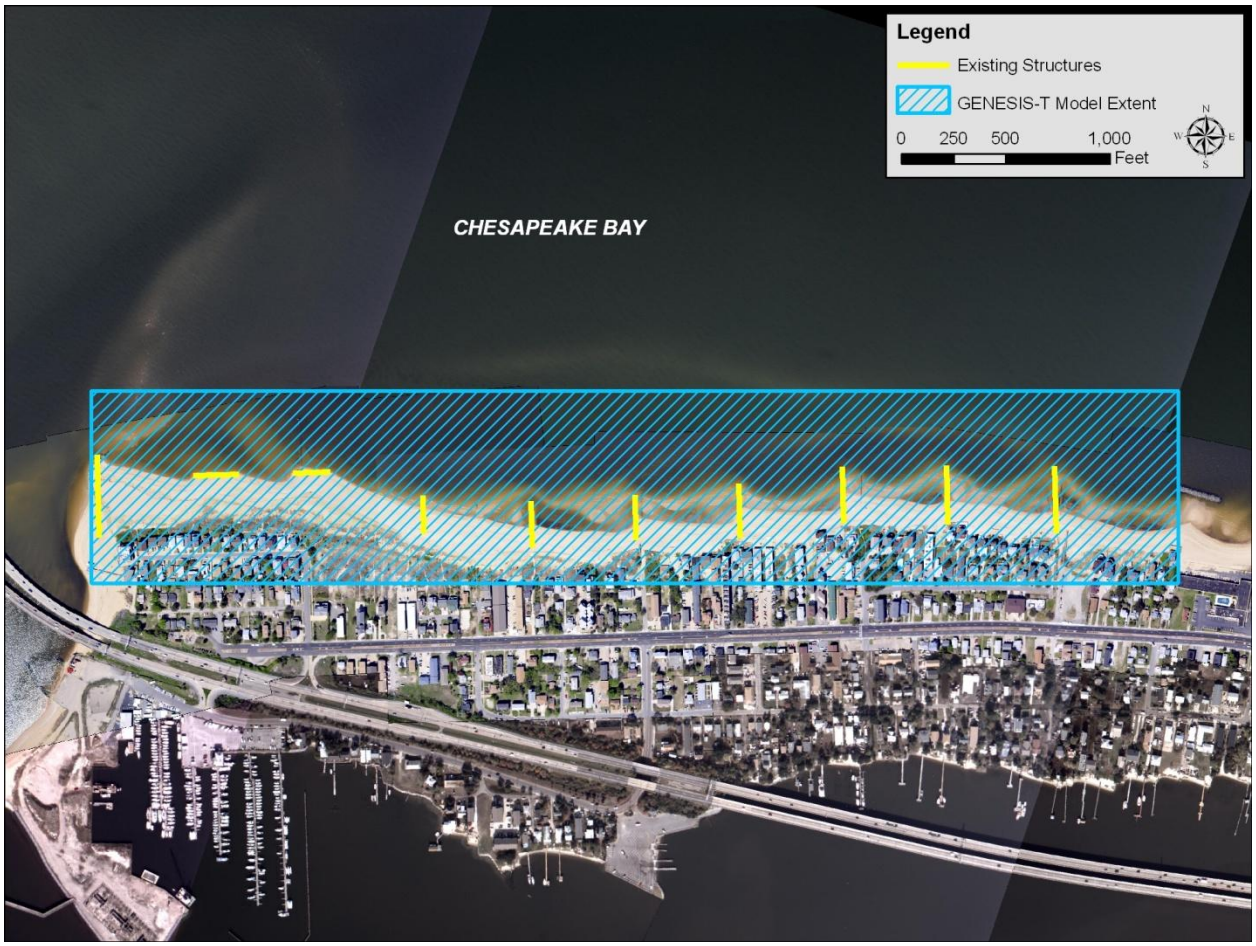

Figure V-1 GENESIS-T Model Extent and Existing Structure Locations

C. CALIBRATION AND VERIFICATION MODELS

The GENESIS-T model was calibrated to reflect the historical trends of longshore sediment transport and the resulting shoreline change over the study area. The overall calibration time period was based on the availability of quality measured shoreline data and measured wave gage data. An overall calibration time period was selected where no engineering activities took place, allowing for structural conditions on the beach to remain consistent. This was necessary as GENESIS-T does not allow for time-varying structural configurations in an individual model (i.e. structures are either present or absent throughout the entire simulation period).

As stated previously, GENESIS-T is typically calibrated by adjusting the sediment transport parameters, K_1 and K_2, which characterize longshore sediment transport across the region. If structures are present, the calibration process may also involve adjustment of the transmission coefficients for breakwaters, and the permeability coefficients for groins until an accurate shoreline response is achieved. Several other boundary condition parameters (e.g. smoothing, wave input adjustments) may be altered to achieve a particular shoreline response, or to test the model sensitivity. For this study, the general calibration procedure involved:

1. establishing known model inputs including shoreline position, waves, locations of structures, sediment and beach characteristics, and boundary conditions

2. establishing initial sediment transport parameters and adjusting these parameters until the relative shoreline response (erosion/accretion) matched historical trends, and
3. working in the direction of sediment transport (east to west), adjusting the groin permeability and breakwater transmissivity coefficients until the shoreline response (e.g. updrift/downdrift, and salient/embayment formations) matched historical trends.

This calibration sequence was followed using known inputs and initial parameters based on the neighboring 800 Block study (M&N, 2005). Then, particular input parameters (sediment transport parameters, smoothing, wave input adjustments etc.) were revisited and the sensitivity of the model response to changes in these parameters was tested. In many cases, a given parameter was adjusted to yield a more accurate shoreline response. The final determined input data for the calibration model will be presented in the following sections, in the order that this information is input to the GENESIS-T model (e.g. not the true calibration sequence).

The calibration period was selected based on availability of survey data, wave data, and the presence or absence of engineering activities in the Willoughby Spit region. The period of time over which the wave gage had been deployed at the time of the study (March 2006 to May 2010) was absent of any engineering activities that may have had a large influence on shoreline change and also had available shoreline data from the ongoing periodic surveying effort. Therefore, it was decided to use March 2006 through April 2010 as the time period for calibration.

1. Shoreline Position Data (Calibration Model)

For shoreline input, GENESIS-T requires the shoreline be specified in a station-offset formulation whereby the station represents a position along a landward baseline and the offset is the perpendicular distance from this baseline to the shoreline. The initial shoreline used in the GENESIS-T model was the March 2006 shoreline, digitized by VIMS from aerial photos of the study area. The final reference shoreline to which the model was calibrated was the April 2010 shoreline, which was digitized by VIMS from aerial photography. **Figure V-2** shows the shorelines, initial and reference, used in the GENESIS-T model calibration runs overlain on the April 2010 aerial photograph.

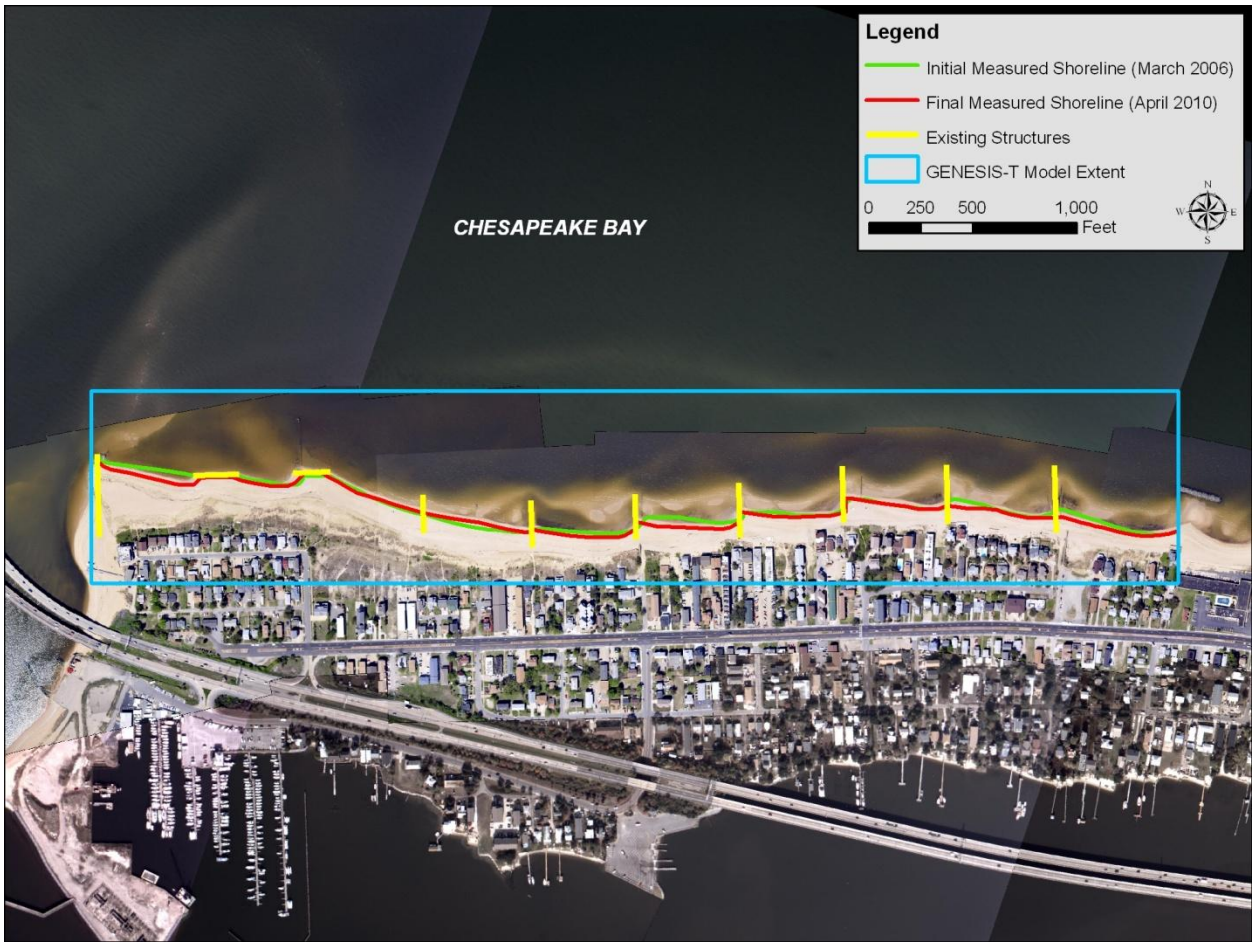

Figure V-2 GENESIS-T Calibration Model Setup

2. Wave Data (Calibration Model)

The wave data used in the GENESIS-T calibration was measured data from the Norfolk wave gage located off of the Ocean View shoreline. Data was available for the time period from March 6, 2006 to April 11, 2010, coinciding with the dates of the shoreline positions from the periodic survey evaluation. The gage data was transformed into the appropriate format for use in GENESIS-T. Significant wave height (ft), peak wave period (seconds), peak wave direction (degrees), and water level (ft NAVD88) were specified as model inputs for the four year time series.

The GENESIS-T model used the defined gage data as a lookup table to transform a given wave condition from the offshore to the nearshore. Then, an internal wave model was applied in GENESIS-T to bring the nearshore waves to the breaking point.

3. Coastal Structures (Calibration Model)

GENESIS-T requires the locations and characteristics of nearshore structures as input. The coastal structures are incorporated in the GENESIS-T model by a station-offset formulation, similar to the shoreline position. Allowable structures include non-diffracting groins/jetties, diffracting groins/jetties, seawalls, and/or detached breakwaters. Each structure is modeled

uniquely with respect to longshore transport and shoreline change. In general, structures exert two direct effects on the shoreline change modeling:

1. Structures extending into the surf zone block a portion, or all, of the longshore transport from their updrift sides and may reduce the transport of sand towards the downdrift side. This effect may be induced by a groin or jetty.

2. Structures which have seaward ends extending well beyond the surf zone, including jetties or detached breakwaters, induce wave diffraction which causes the local wave height and direction to change.

Wave transmission through and over breakwaters is controlled by the user-specified transmission coefficient (K_t). The transmission coefficient is defined as the ratio of wave heights on the shoreward side of the breakwater to the incident wave heights on the seaward side of the breakwater and may range from 0 (no transmission) to 1 (complete transmission). Transmission coefficients applied in the Willoughby Spit model were determined through numerous model iterations, in which the K_t value for each detached breakwater was adjusted for a given set of longshore transport rate coefficients until the observed shoreline response matched closely with historical trends. The breakwaters incorporated in the calibration models are known to be moderately to highly porous with low crest elevations (+2 ft NAVD88), yielding transmission coefficients ranging from 0.7 to 0.8.

Similar to detached breakwaters, a non-diffracting or diffracting groin implemented in GENESIS-T must have a defined permeability which controls the transmission of sand over and through the structure. The permeability can range from 0, implying an impermeable structure to 1, implying a completely transparent structure. The permeability of the existing terminal groin was set at 0.2 since it traps a majority of the sediment being transported from the east. The permeability of the groins within the existing groin field were set between 0.5 and 0.6 due to the more dilapidated condition in comparison to the terminal groin.

4. Sediment and Beach Characteristics (Calibration Model)

The selected effective grain size assumed in the GENESIS-T model was 0.4 mm. This grain size was determined based on analysis of measured sediment data collected near the study area in April 2004 as detailed in **Section II.C**.

The average berm height was defined as +3 ft NAVD88 and the closure depth was set to -10 ft NAVD88. These values were determined based on observations of measured survey data during the calibration time period from the ongoing periodic surveys.

5. Sediment Transport Parameters (Calibration Model)

Longshore sediment transport is characterized by the transport parameters K_1 and K_2 in GENESIS-T. The transport rate coefficient, K_1, is used to control the time-scale and magnitude of the simulated shoreline change, while K_2 is used to control shoreline change and longshore sand transport in the vicinity of structures. Although the values of K_1 and K_2 have been empirically estimated, these coefficients are treated as calibration parameters in GENESIS-T.

The calibration models were initially run with the K_1 and K_2 coefficients used in the 800 Block study (M&N, 2005), where $K_1 = 0.1$ and $K_2 = 0.3$. The resulting April 2010 model shoreline was compared with the measured April 2010 shoreline and the coefficients were adjusted to achieve the closest match in the model results and the measured shoreline position. Through this procedure, it was determined that slightly reducing the K_1 value and reducing the K_2 value significantly resulted in shoreline response which was most indicative of historical patterns. The final calibration coefficient values were $K_1 = 0.09$ and $K_2 = 0.09$. The larger K_2 value used in the 800 Block analysis created exaggerated shoreline changes near the structures and was therefore considerably reduced.

6. Boundary Conditions (Calibration Model)

The required boundary condition inputs for GENESIS-T include the seaward wave data boundary conditions and the lateral boundary conditions at the left (west) and right (east) ends of the shoreline.

a) Seaward Boundary Conditions

As stated, wave height, wave period, wave direction, and water level from the Norfolk Wave Gage were implemented in the GENESIS-T model. Within the seaward boundary conditions, the user may modify the input wave conditions (wave height and direction) to analyze the impact modeled wave conditions have on the resulting shoreline response. Since the wave data utilized in this study were derived from measured wave conditions at the offshore gage, the wave heights were not modified. However, during calibration it was determined that the angle with which waves are applied across the boundary of the model needed to be modified. To better represent diffraction around the groin structures, an angle offset of -5 degrees was used.

The smoothing factor applied with the seaward boundary conditions is an indication of how the offshore contour moves relative to the shoreline and is used to prevent unrealistic wave transformation that may occur if the shoreline changes relatively abruptly (e.g. at a groin). The smoothing value may range from 0 to 50, with a lower value indicating the offshore contour follows the shoreline position and a higher value implying that the contour is straighter than the shoreline. After numerous trials, a smoothing factor of 25 was applied in the GENESIS-T model based on the effect that this parameter was observed to have on the resulting shorelines.

b) Lateral Boundary Conditions

The left (west) boundary of the model was located just west of the terminal groin structure, in order to allow for sediment transmission through the terminal groin. It was determined that due to the recent accretion of material downdrift of the terminal groin, an accretional moving boundary would be appropriate. The right (east) boundary of the model was established at the first 800 Block breakwater where shoreline change is very minimal. Therefore, a pinned boundary condition was used there.

7. Calibration Model Results

Figure V-3 shows the final shoreline resulting from the GENESIS-T calibration modeling against the initial shoreline position (March 2006) and the comparable measured shoreline position (April 2010).

As shown, the model output produces a standard groin signature with an accurate magnitude of shoreline displacement between the updrift and downdrift side of the groins. Based on these results, all future model runs utilized the defined parameters for coastal structures (breakwater transmission and groin permeability), sediment transport (K_1 and K_2), and boundary conditions (wave angle offset and smoothing factor) which were set during the calibration modeling.

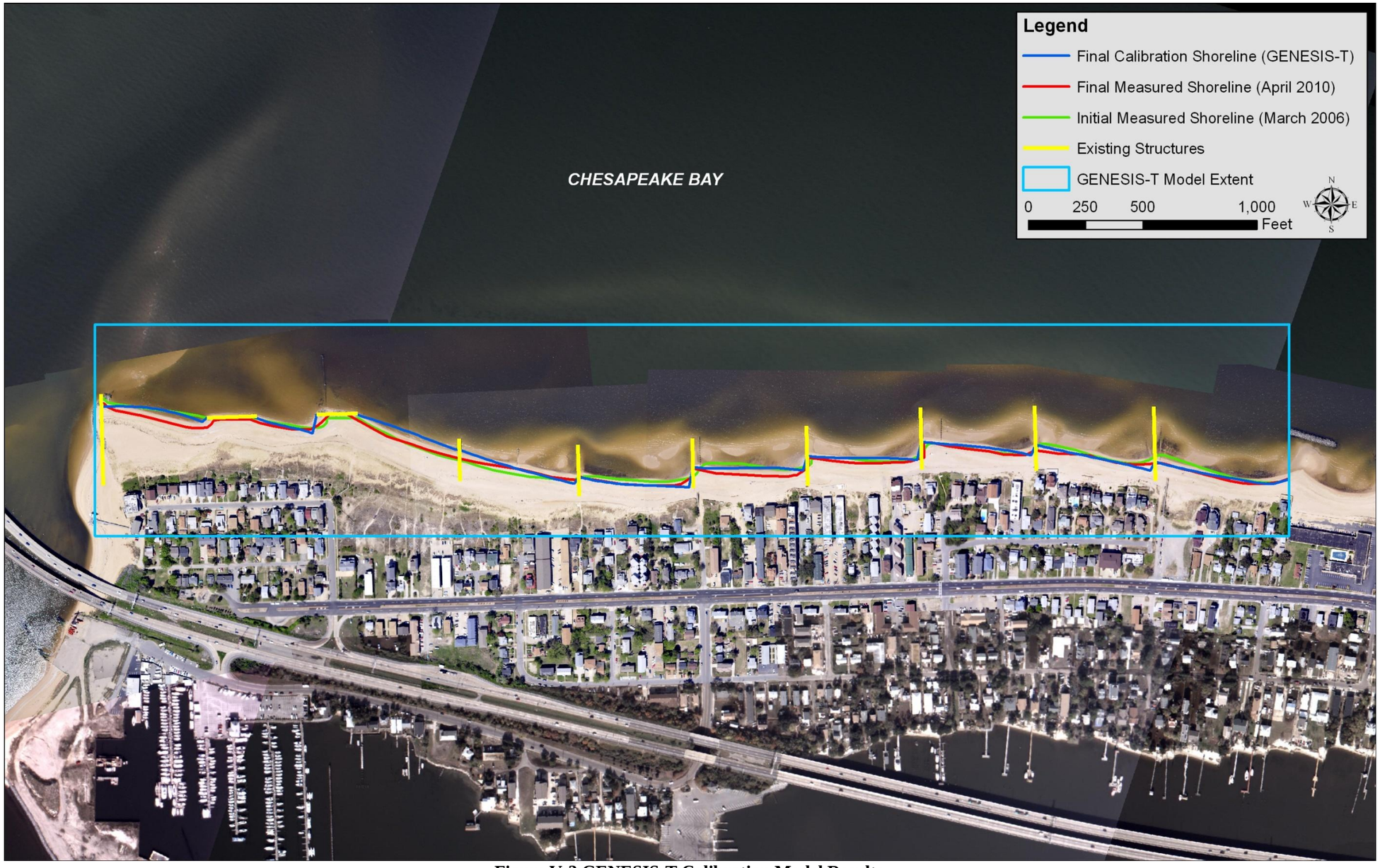

Figure V-3 GENESIS-T Calibration Model Results

D. VERIFICATION MODEL

To validate the shoreline response in GENESIS-T based on the calibration coefficients chosen during the calibration process, a verification model was set up for a shorter time period which included stormy conditions from October 2009 through April 2010. Only input shorelines and wave data were varied from the calibration model. All structures, beach characteristics, sediment transport parameters, and boundary conditions were held consistent with those used in the calibration model.

1. Shoreline Position Data (Verification Model)

The initial shoreline used in the GENESIS-T verification model was the October 2009 shoreline, digitized by VIMS from aerial photos of the study area. The final reference shoreline to which the model was calibrated was the April 2010 shoreline, which was digitized by VIMS from aerial photography. **Figure V-4** shows the shorelines, initial and reference, used in the GENESIS-T model calibration runs overlain on the April 2010 aerial photograph.

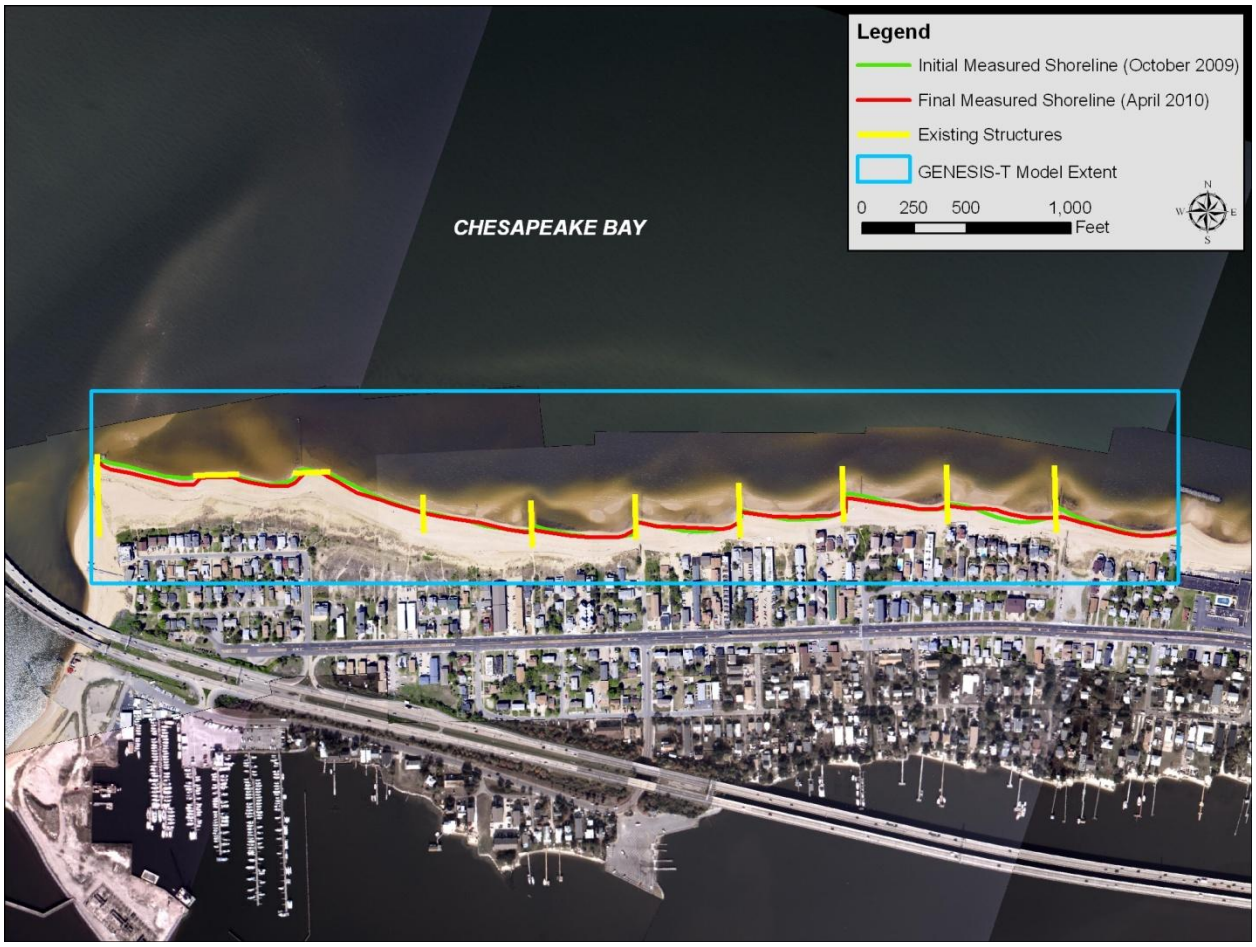

Figure V-4 GENESIS-T Verification Model Setup

2. Wave Data (Verification Model)

The wave data used in the GENESIS-T calibration was measured data from the Norfolk wave gage located off of the Ocean View shoreline. Data was available for the time period from

October 12, 2009 to April 11, 2010, coinciding with the dates of the shoreline positions from the periodic survey evaluation. This time period includes the November 2009 nor'easter and allows for some recovery afterward. The gage data was transformed into the appropriate format for use in GENESIS-T. Significant wave height (ft), peak wave period (seconds), peak wave direction (degrees), and water level (ft NAVD88) were specified as model inputs for the six month time series.

The GENESIS-T model used the defined gage data as a lookup table to transform a given wave condition from the offshore to the nearshore. Then, an internal wave model was applied in GENESIS-T to bring the nearshore waves to the breaking point.

3. Verification Model Results

Figure V-5 shows the final shoreline resulting from the GENESIS-T verification modeling against the initial shoreline position (October 2009) and the comparable final measured shoreline position (April 2010).

As shown, the model output produces a standard groin signature with an accurate magnitude of shoreline displacement between the updrift and downdrift side of the groins. Based on these results, all future model runs utilized the defined parameters for coastal structures (breakwater transmission and groin permeability), sediment transport (K_1 and K_2), and boundary conditions (wave angle offset and smoothing factor) which were set during the calibration modeling.

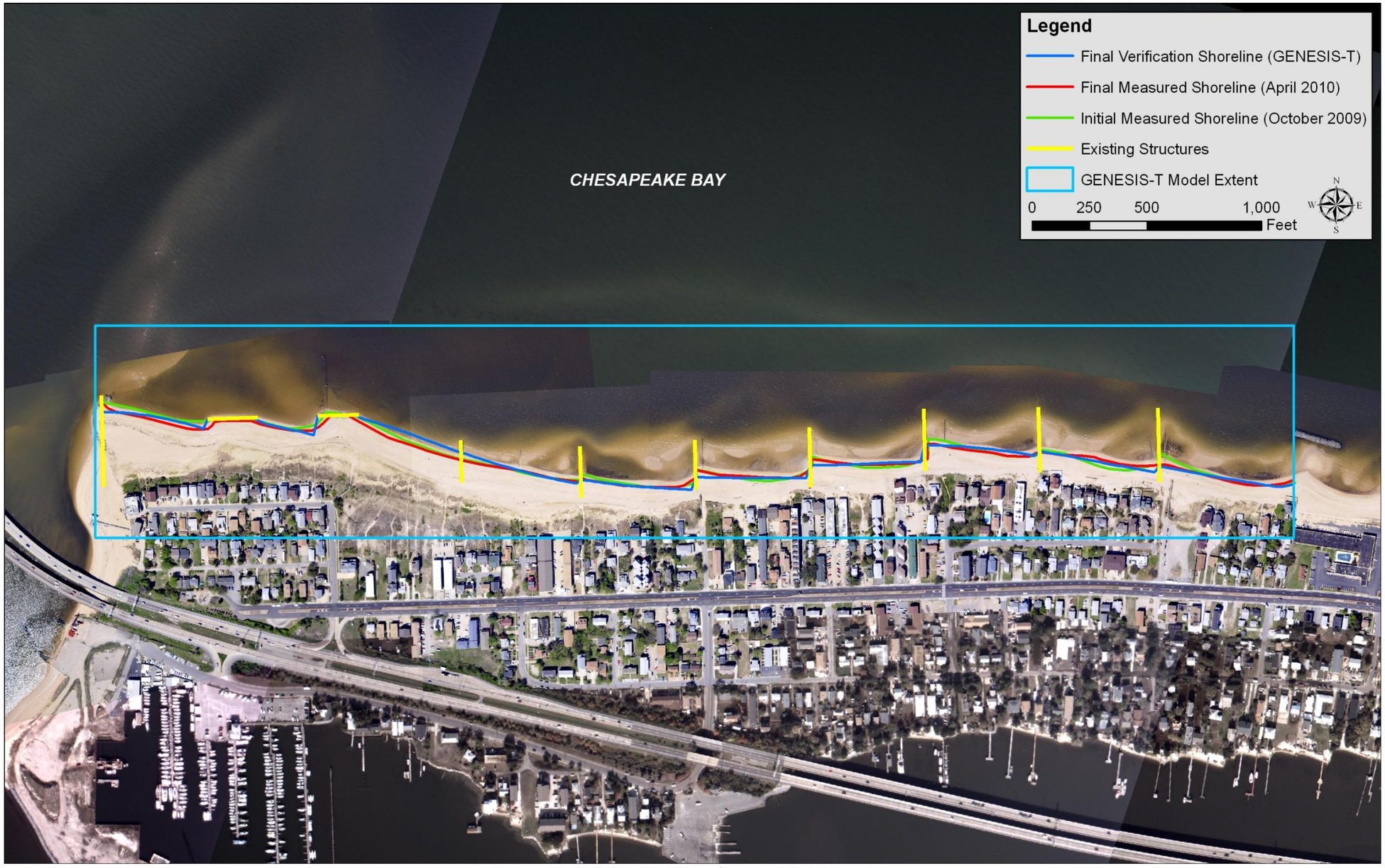

Figure V-5 GENESIS-T Verification Model Results

E. EXISTING CONDITIONS MODEL

An existing conditions model was run to determine the changes in the study area which would take place with no mitigation of the existing erosion problem. This model also served as the basis for decision making and comparison of proposed erosion control alternatives. The existing conditions model run involved an eight (8) year simulation representing the predicted future response of the shoreline under long-term typical wave action, using two cycles of the four (4) year time series of data developed for the calibration model from the Norfolk wave gage. The initial shoreline in the existing conditions model was the measured April 2010 shoreline. All other parameters in the GENESIS-T model were the same as defined for the calibration model including the structural characteristics, sediment and beach characteristics, sediment transport coefficients, and boundary conditions.

Figure V-6 shows the structural configuration implemented in this model run and the predicted shoreline position after an eight (8) year time period. The resulting shoreline is compared against the initial shoreline position. As shown, the model predicts significant erosion at the eastern end of the existing groin field in front of Toler Place. It also predicts erosion near the western end of the groin field at 13th View St.

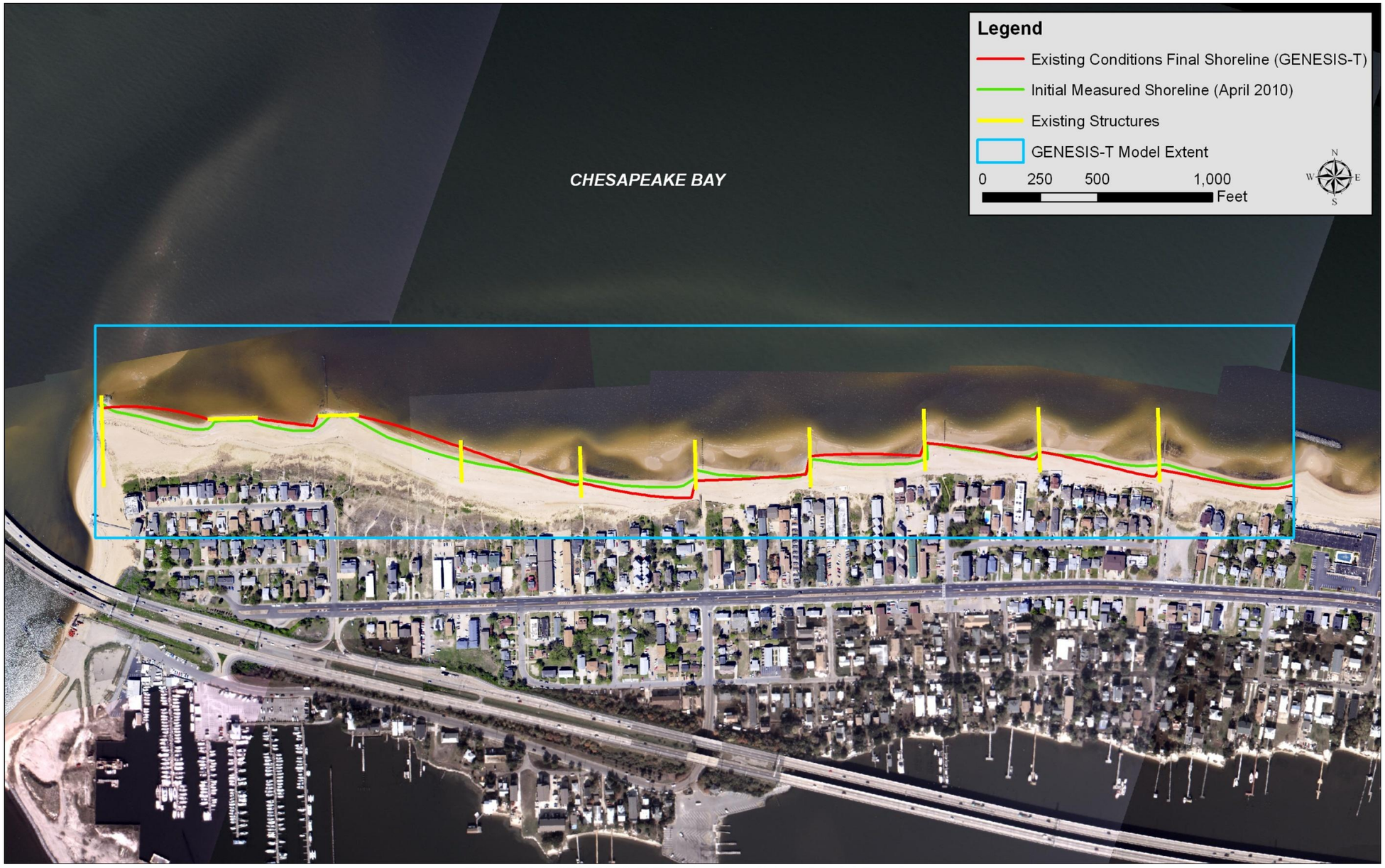

Figure V-6 GENESIS-T Existing Conditions Model Results

F. DEVELOPMENT OF EROSION CONTROL ALTERNATIVES

While the Willoughby Spit area is historically a stable and sometimes accretional area, there are portions of shoreline where beach width is becoming a concern (i.e. Toler Place, Fish Eye Condos). The current groin field configuration is very dilapidated and may not provide adequate protection for those areas with the narrowest beach width if a storm were to impact the area in the future. It also creates a recreational hazard as well as an unpleasing aesthetic to the beach. In addition, recent years have seen accretion of the western facing beach on the downdrift side of the groin.

Given these concerns, the goal of the proposed beach stabilization and restoration effort is twofold. **First, providing equivalent protection to all structures along the Willoughby Spit shoreline is of primary significance.** This will require the build out of the eastern portion of the study area, with any potential end effect being moved toward Willoughby Spit, just east of the existing breakwaters, where the shoreline is currently almost 500 ft from existing structures. A breakwater field configuration to replace the existing dilapidated groins and protect the shoreline behind it, allowing accretion of the beach in this area, would be ideal. **Second, addressing the issue of accretion on the downdrift side of the terminal groin is of major importance.** This will require a look into sand recycling from both the updrift and downdrift sides of the groin as well as increasing the amount of sediment being trapped currently by the terminal groin.

In March 2011, a meeting was held with the City and M&N to present the preliminary results of the historical data review and analysis and to discuss initial proposed alternatives for erosion control. Proposed options for improving the beach involved multiple ideas and approaches. The preliminary erosion control alternatives, which were presented by M&N, included the following structural modifications, improvements, and additions, to be implemented individually or in combination, where practicable:

- Partial removal of the existing groin field (seaward portion of the groins)
- Beach nourishment with sand recycling from Willoughby Spit near the terminal groin and the westward facing beach
- Lengthening of the existing terminal groin to trap more sediment for beach nourishment and prevent travel around the groin
- Addition of a breakwater field between 800 Block and the existing Willoughby Spit breakwaters to protect the shoreline and provide equivalent protection

In response to the above alternatives and the evidence presented as part of the review of historical data, the City made additional requests for modeling which included:

- Full removal of the existing groin field
- Removal of the existing Willoughby Spit breakwaters in conjunction with the lengthening of the terminal groin to trap more sediment
- Use of additional sand from the City owned portion of the beach just to the east of the existing Willoughby Spit breakwaters for beach nourishment and sand recycling

With these options in mind, multiple alternatives were run using combinations of the above mentioned structural modifications, improvements, and additions in GENESIS-T to solve the various issues of concern in the Willoughby Spit area.

G. MODELING OF ALTERNATIVES IN GENESIS-T

The calibrated GENESIS-T model was used to simulate future long-term shoreline change with numerous erosion control/beach restoration alternative improvements in place. Each proposed structural configuration was modeled in GENESIS-T for a future eight (8) year time period utilizing two cycles of the four year wave time series developed for calibration. The initial shoreline was the April 2010 shoreline, with modifications to the western end in the form of beach material excavation for nourishment where appropriate. The characteristic transmissivity and permeability of existing structures were set based on the defined values determined in the calibration model. The estimation of these parameters for new, proposed structures will be discussed for the applicable options presented herein. All other parameters in the GENESIS-T model were the same as defined for the calibration model including the sediment and beach characteristics, sediment transport coefficients, and boundary conditions.

A number of selected alternatives will be presented herein, providing an overview of the range of alternatives analyzed and to present the process of optimization used to determine the final proposed alternative. Each selected alternative was evaluated through comparison of the predicted future eight (8) year shoreline position determined from the existing conditions model and the predicted eight (8) year shoreline position with comparable alternatives in place. The final alternative was selected and recommended for additional hydrodynamic modeling using SBEACH and DELFT3D. For ease in the presentation of results, all figures referenced in the following discussions are included at the end of this section.

It should be noted that while the issue of accretion on the downdrift side of the terminal groin is a significant concern, the limitations of GENESIS-T do not allow for modeling of improvements such as a change in elevation. Therefore, DELFT3D was used to model this concept in further detail. However, sand recycling, as a way to decrease potential sediment transport over the groin, was modeled in GENESIS-T for various alternatives.

1. Option 1

Option 1 involves complete removal of the existing groin field. **Figure V-7** shows the structural configuration and initial shoreline position implemented in this model run. The resulting shoreline is compared against the existing conditions model shoreline position after an eight (8) year time period.

Based on the model results, this option has a large effect on the shoreline in the eastern portion of the study area. Shoreline erosion far beyond what the existing conditions would be is present just west of the 800 Block breakwater field, in front of Toler Place and Fish Eye Condos. The western portion of the study area shows some accretion seaward of the existing conditions due to the now unimpeded sediment transport from the eastern portion of the study area. While this solution improves the aesthetic and safety of the beach, it worsens the problem in front of Toler Place and Fish Eye Condos and moves further away from equivalent protection along the shoreline. In addition, it could worsen the overfilling of the groin pocket and sediment transport

around and over the terminal groin due to increased accretion at the western end of the study area.

2. Option 2

Option 2 involves removing the offshore portion of the existing groin field, keeping the onshore portion as extra protection in case of severe erosion, and completing a beach nourishment project in front of Toler Place and just east of the 800 Block breakwater field to mitigate any erosional end effects. The nourishment would be approximately 45,000 cy, some of which could be taken from the Willoughby Spit area near the terminal groin and from behind the existing breakwaters. **Figure V-8** shows the structural configuration and initial shoreline position, using Willoughby Spit as a sediment source, implemented in this model run. The resulting shoreline is compared against the existing conditions model shoreline position after an eight (8) year time period.

Option 2 shows that the nourishment material quickly travels west, leaving the portion of the shoreline that is most in need close to the existing conditions shoreline, worse than the initial conditions. In order to keep the beach width at least 100 ft from any existing structures, renourishment would need to occur approximately every four (4) years. Unfortunately, there would not be enough excess material near Willoughby Spit to allow for sand recycling of the entire amount every four (4) yrs. **Figure V-9** shows intermediate yearly model results which support a nourishment frequency of four (4) years in order to maintain adequate beach width in front of structures and also indicates that the spit does not completely fill back in after four (4) years, which would results in less than the required amount of material needed for future nourishments. In addition this option does not provide equal protection for the beach. As will be seen in the following section (**Section VI**), the cost of such frequent nourishment can exceed that of building structures to protect and stabilize the shoreline, lessening the nourishment frequency.

3. Option 3

Option 3 consists of removing the existing groin field and adding three offshore breakwaters to the eastern portion of the study area to protect Toler Place and Fish Eye Condos. The breakwaters are located fairly far offshore (approximately 375 ft) and are relatively short (120 ft) to avoid interruption of sediment transport around the bend in the shoreline at the western end of the 800 Block breakwater field. The shoreline behind the breakwater field would be nourished with approximately 45,000 cy of material taken from the Willoughby Spit area near the terminal groin and from the vacant City land just east of the corner of Lea View Avenue and 15th View Street. **Figure V-10** shows the structural configuration and initial shoreline position, using Willoughby Spit as a sediment source, implemented in this model run. The resulting shoreline is compared against the existing conditions model shoreline position after an eight (8) year time period.

Option 3 shows that breakwaters in front of the area of concern merely moves the erosional end effect of a breakwater field westward, creating a large erosional hotspot in the shoreline. Therefore, a small breakwater field does not appear to be a feasible option in this area. Analysis of this alternative shows that the only options are to attempt to mitigate the end effect (see Option 4a, 4b, and 4c), move the erosional end effect to an area not of concern (see Option 5) or connect the breakwater field between the 800 Block and the existing Willoughby Spit breakwaters near the terminal groin (Option 6) to eliminate the end effect. This option does

however, allow for recovery of the beach from which sediment was taken for the nourishment. This would allow for sand recycling to meet nourishment needs. However, the amount and frequency of nourishment may increase due to creating a new hotspot west of the existing area of concern.

4. Option 4a, 4b, and 4c

Based on the results seen in Option 3, various configurations of additional breakwaters were modeled in conjunction with the existing groin field in an attempt to mitigate the end effect of a shorter breakwater field located offshore of the current areas of concern.

Option 4a consists of adding three offshore breakwaters to the eastern portion of the study area to protect Toler Place and Fish Eye Condos, removing the three existing groins behind the new breakwaters, and keeping the remaining four groins from the existing groin field. The breakwaters are located fairly far offshore (approximately 375 ft) and are relatively short (120 ft) to avoid interruption of sediment transport around the bend in the shoreline at the western end of the 800 Block breakwater field. The shoreline behind the breakwater field would be nourished with approximately 45,000 cy of material taken from the Willoughby Spit area near the terminal groin and from the vacant City land just east of the corner of Lea View Avenue and 15th View Street. **Figure V-11** shows the structural configuration and initial shoreline position, using Willoughby Spit as a sediment source, implemented in this model run. The resulting shoreline is compared against the existing conditions model shoreline position after an eight (8) year time period. Option 4a shows that while keeping the remainder of the existing groin field does improve the final shoreline position from Option 3, the end effect of the breakwater field is still very large.

Option 4b consists of adding four offshore breakwaters to the eastern portion of the study area to protect Toler Place and Fish Eye Condos, removing the four existing groins behind the new breakwaters, and keeping the remaining three groins from the existing groin field. The breakwaters are located fairly far offshore (approximately 375 ft) and are relatively short (120 ft) to avoid interruption of sediment transport around the bend in the shoreline at the western end of the 800 Block breakwater field. The shoreline behind the breakwater field would be nourished with approximately 45,000 cy of material taken from the Willoughby Spit area near the terminal groin and from the vacant City land just east of the corner of Lea View Avenue and 15th View Street. **Figure V-12** shows the structural configuration and initial shoreline position, using Willoughby Spit as a sediment source, implemented in this model run. The resulting shoreline is compared against the existing conditions model shoreline position after an eight (8) year time period. Option 4b shows that adding another breakwater to Option 4a simply moves the erosional hotspot further westward and the remaining groins are not effective enough to mitigate the hotspot.

Option 4c consists of adding five offshore breakwaters to the eastern portion of the study area to protect Toler Place and Fish Eye Condos, removing the five existing groins behind the new breakwaters, and keeping the remaining two groins from the existing groin field. The breakwaters are located fairly far offshore (approximately 375 ft) and are relatively short (120 ft) to avoid interruption of sediment transport around the bend in the shoreline at the western end of the 800 Block breakwater field. The shoreline behind the breakwater field would be nourished

with approximately 45,000 cy of material taken from the Willoughby Spit area near the terminal groin and from the vacant City land just east of the corner of Lea View Avenue and 15th View Street. **Figure V-13** shows the structural configuration and initial shoreline position, using Willoughby Spit as a sediment source, implemented in this model run. The resulting shoreline is compared against the existing conditions model shoreline position after an eight (8) year time period. Option 4c shows that, once again, adding another breakwater to Option 4b simply moves the erosional hotspot further westward and the remaining groins are not effective enough to mitigate the hotspot.

5. Option 5

In Option 5, the existing groin field is removed and the breakwater field is extended to the west with six 180 ft breakwaters, approximately 300 ft offshore. Analytical analysis showed these dimensions to be within an appropriate design range with respect to their effect on the shoreline. The shoreline in front of the current problem areas would be nourished with approximately 45,000 cy of material taken from the Willoughby Spit area near the terminal groin and from the vacant City land just east of the corner of Lea View Avenue and 15th View Street. **Figure V-14** shows the structural configuration and initial shoreline position, using Willoughby Spit as a sediment source, implemented in this model run. The resulting shoreline is compared against the existing conditions model shoreline position after an eight (8) year time period.

Based on the model results, Option 5 provides substantial protection for the areas of concern (Toler Place and Fish Eye Condos) and moves the erosional end effect to an area of vacant City land. It also substantially increases the amount of time between nourishments from the nourishment only option (Option 2) to approximately every eight (8) years. However, this option does not allow for the recovery of the beach in the area from which sediment was taken due to the erosional end effect of the breakwater field. Therefore, sand recycling would not be an option for future upkeep of the beach. **Figure V-15** shows intermediate yearly model results which support a nourishment frequency of eight (8) years in order to maintain adequate beach width in front of structures and also indicates that the City land from which a majority of the material was borrowed does not fill back in after eight (8) years, which eliminates the possibility of sand recycling.

6. Option 6

Option 6 removes the existing groin field and completely connects the 800 Block breakwater field with the existing Willoughby Spit breakwaters by adding a 7th breakwater to the new field. The breakwaters remain approximately 300 ft offshore and vary in length from 120 ft to 180 ft with two shorter ones (120 ft and 140 ft) existing at the eastern end (just west of the 800 block breakwater field) to avoid impeding the sediment transport around the bend in the shoreline. The remaining five breakwaters would all be 180 ft in length. The shoreline in front of the current problem areas would be nourished with approximately 28,000 cy of material taken from the Willoughby Spit area near the terminal groin and from the vacant City land just east of the corner of Lea View Avenue and 15th View Street. In addition, approximately 7,000 cy of material would be available for a dune construction project in front of the houses on Lea View Avenue, providing extra protection since sediment from in front of those houses would be removed and used for nourishment. **Figure V-16** shows the structural configuration and initial shoreline position, using Willoughby Spit as a sediment source, implemented in this model run. The

resulting shoreline is compared against the existing conditions model shoreline position after an eight (8) year time period.

Based on the model results, Option 6 provides substantial protection for the current areas of concern (Toler Place and Fish Eye Condos) as well as the remainder of the Willoughby Spit shoreline, creating equivalent protection. In addition, it allows for some recovery of the beach from which sediment was taken for the initial nourishment, allowing sand recycling to still be an option for future nourishment needs. It also substantially increases the amount of time between nourishments from the nourishment only option (Option 2) to approximately every eight (8) years. **Figure V-17** shows that nourishment would not be needed more frequently than every eight (8) years and that a portion of the City land from which material was borrowed will be filled in by year eight (8), allowing for some sand recycling. In addition, Option 6 provides added protection (with dune creation) to the houses on Lea View Avenue to mitigate loss of sand from Willoughby Spit for use in renourishment of the eastern portions of the study area in the future.

H. PREFERRED ALTERNATIVE BASED ON GENESIS-T RESULTS

Based on GENESIS-T model results, Option 6 did the best to address the two major issues of concern previously discussed (equivalent protection for the entire shoreline and accretion downdrift of the terminal groin). First, the model results showed that the structural configuration of Option 6 provided the best solution to equivalent protection of all structures along the Willoughby Spit shoreline. This option increased the beach width in areas where it is currently the narrowest, while using sand from areas where the beach width is currently the widest. Second, while elevation improvements to the terminal groin were not able to be modeled, sand recycling was addressed in an effort to keep excess material from building up around the terminal groin and possibly be washed over during a storm event.

Therefore, it was determined that Option 6 should be further modeled in SBEACH to address the impact of cross-shore transport on the proposed dune and nourishment projects. In addition, DELFT3D modeling of Option 6 will be used to further capture issues and model potential solutions in the vicinity of the terminal groin as well as verify the sediment transport patterns shown by GENESIS-T.

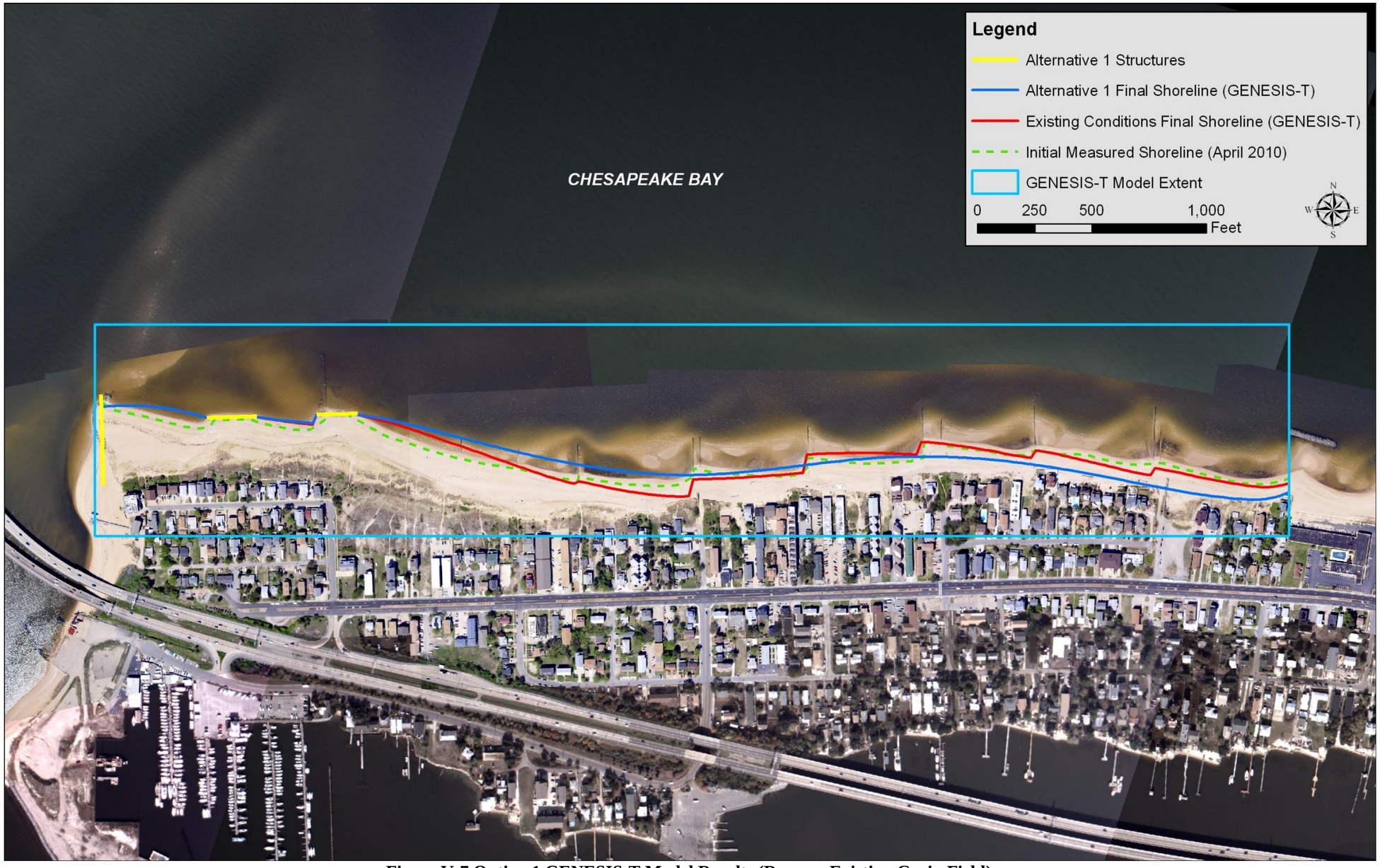

Figure V-7 Option 1 GENESIS-T Model Results (Remove Existing Groin Field)

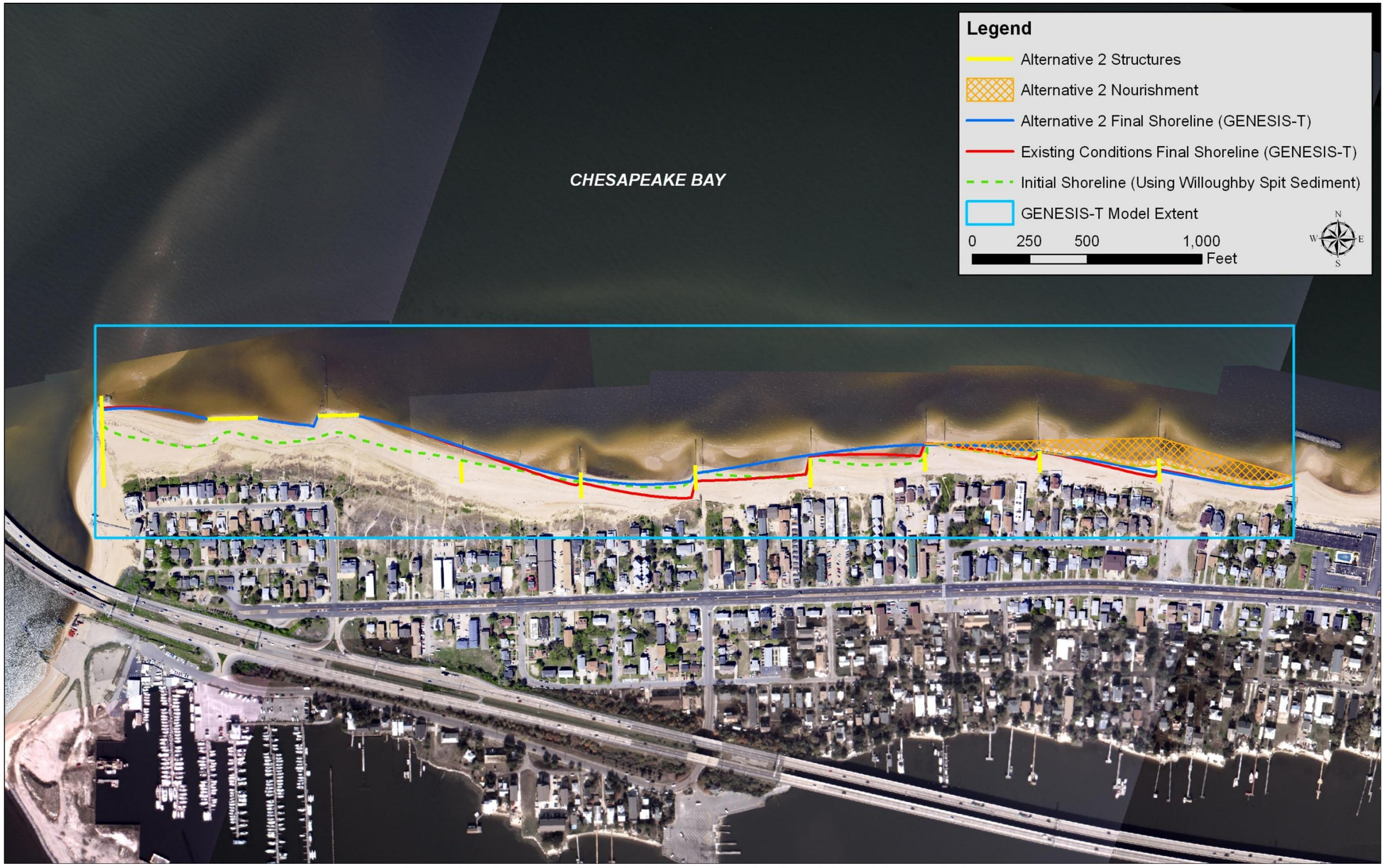

Figure V-8 Option 2 GENESIS-T Model Results (Beach Nourishment Only)

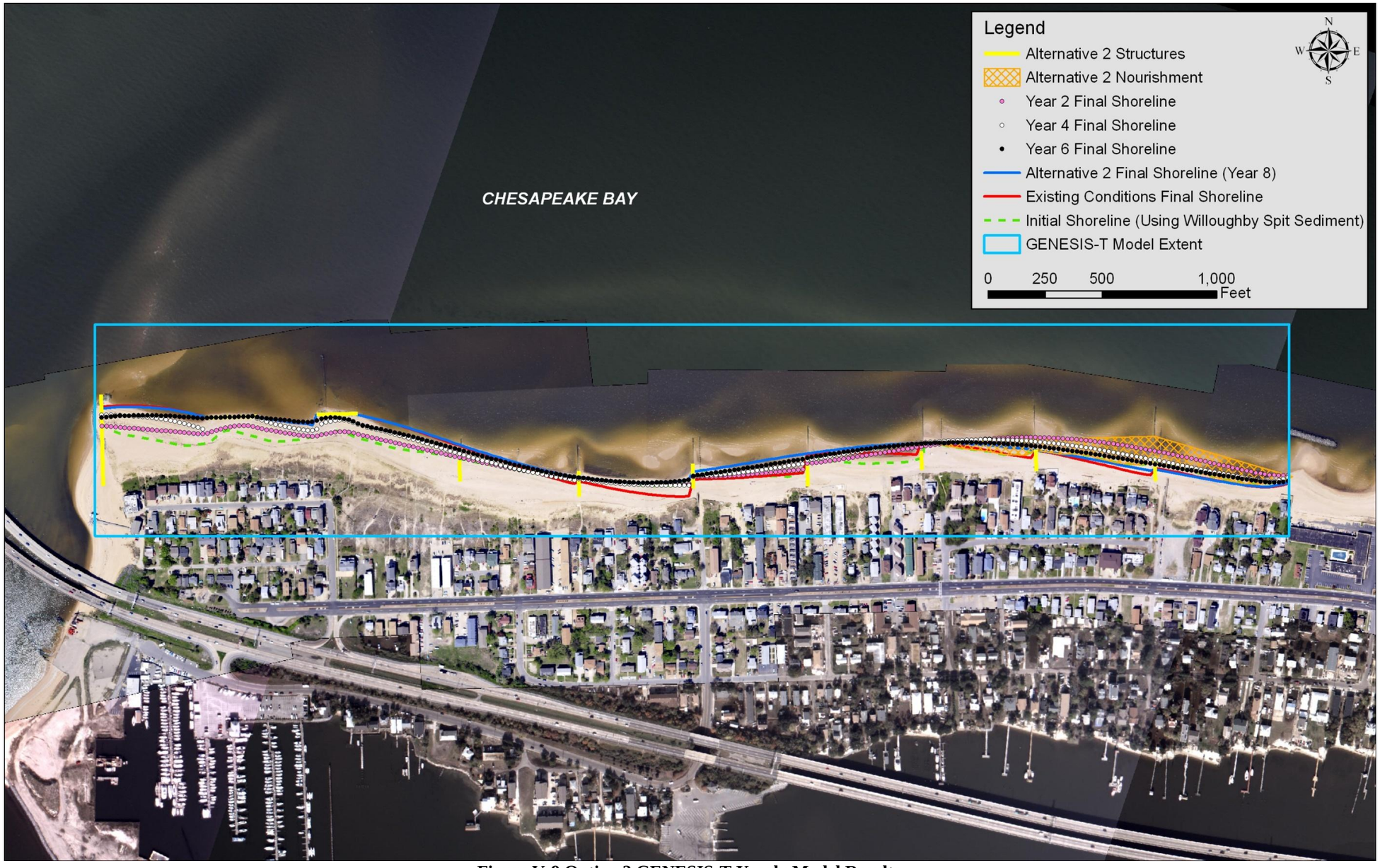

Figure V-9 Option 2 GENESIS-T Yearly Model Results

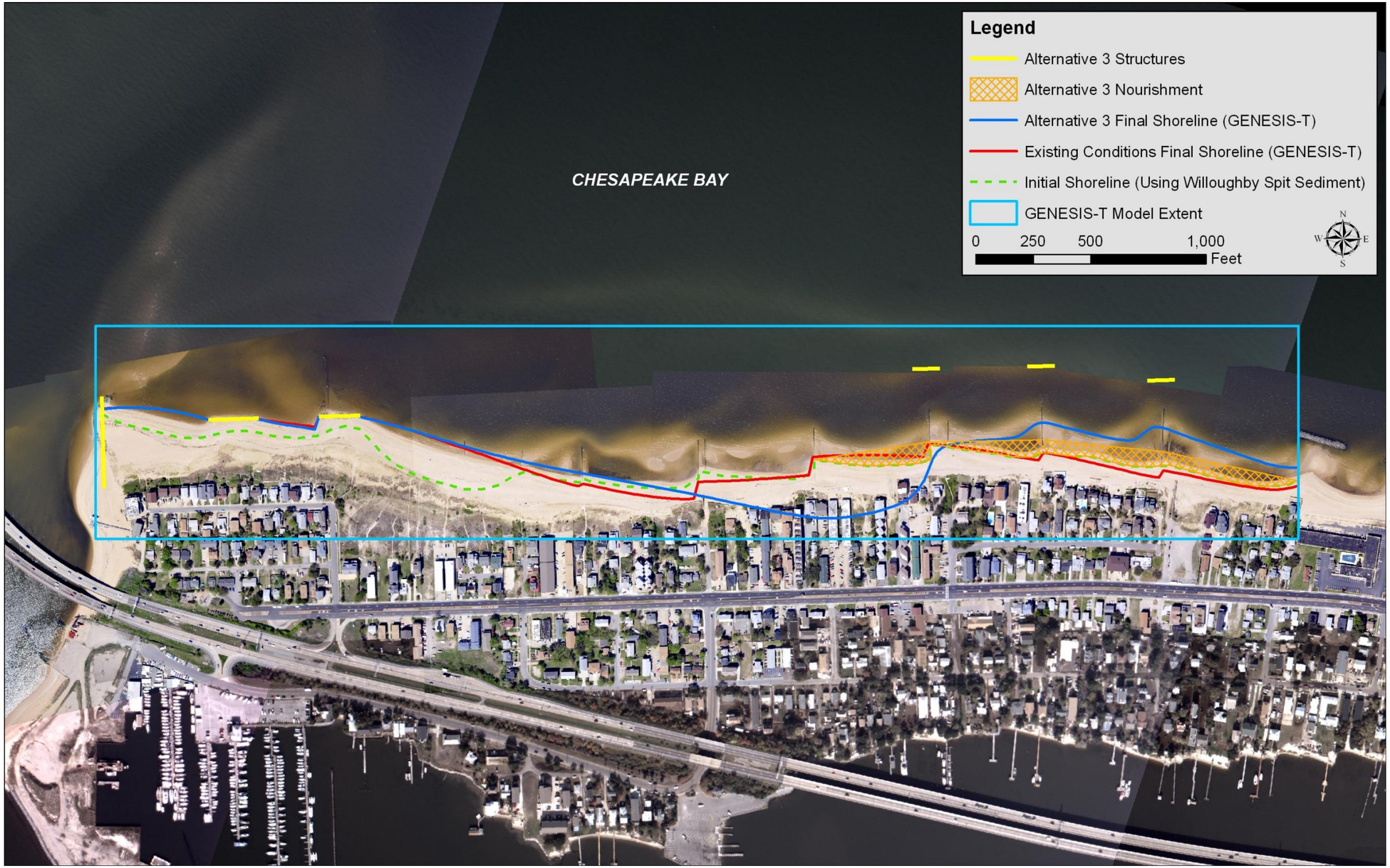

Figure V-10 Option 3 GENESIS-T Model Results (3 Offshore Breakwaters With Beach Nourishment)

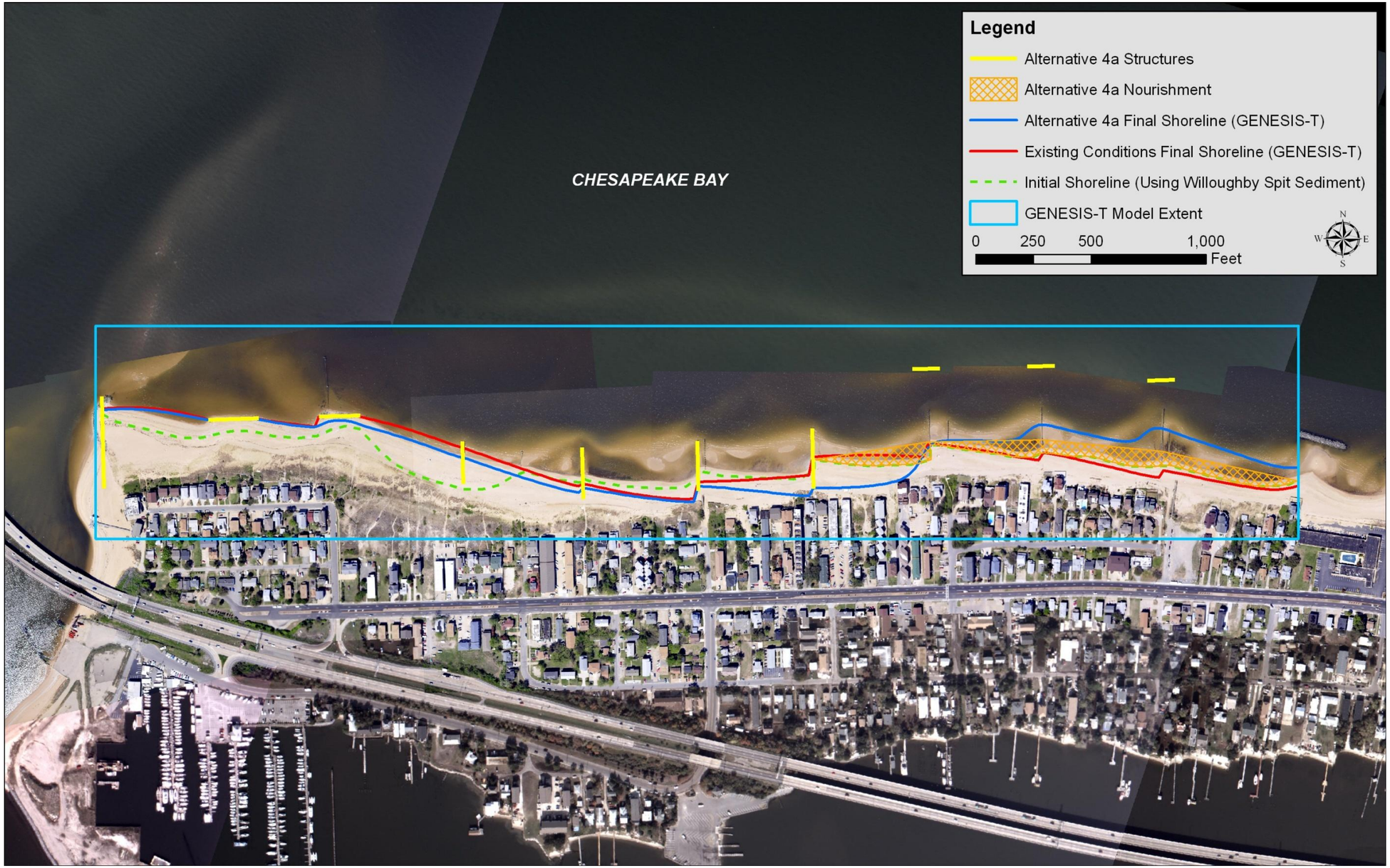

Figure V-11 Option 4a GENESIS-T Model Results (3 Offshore Breakwaters With 4 Existing Groins and Beach Nourishment)

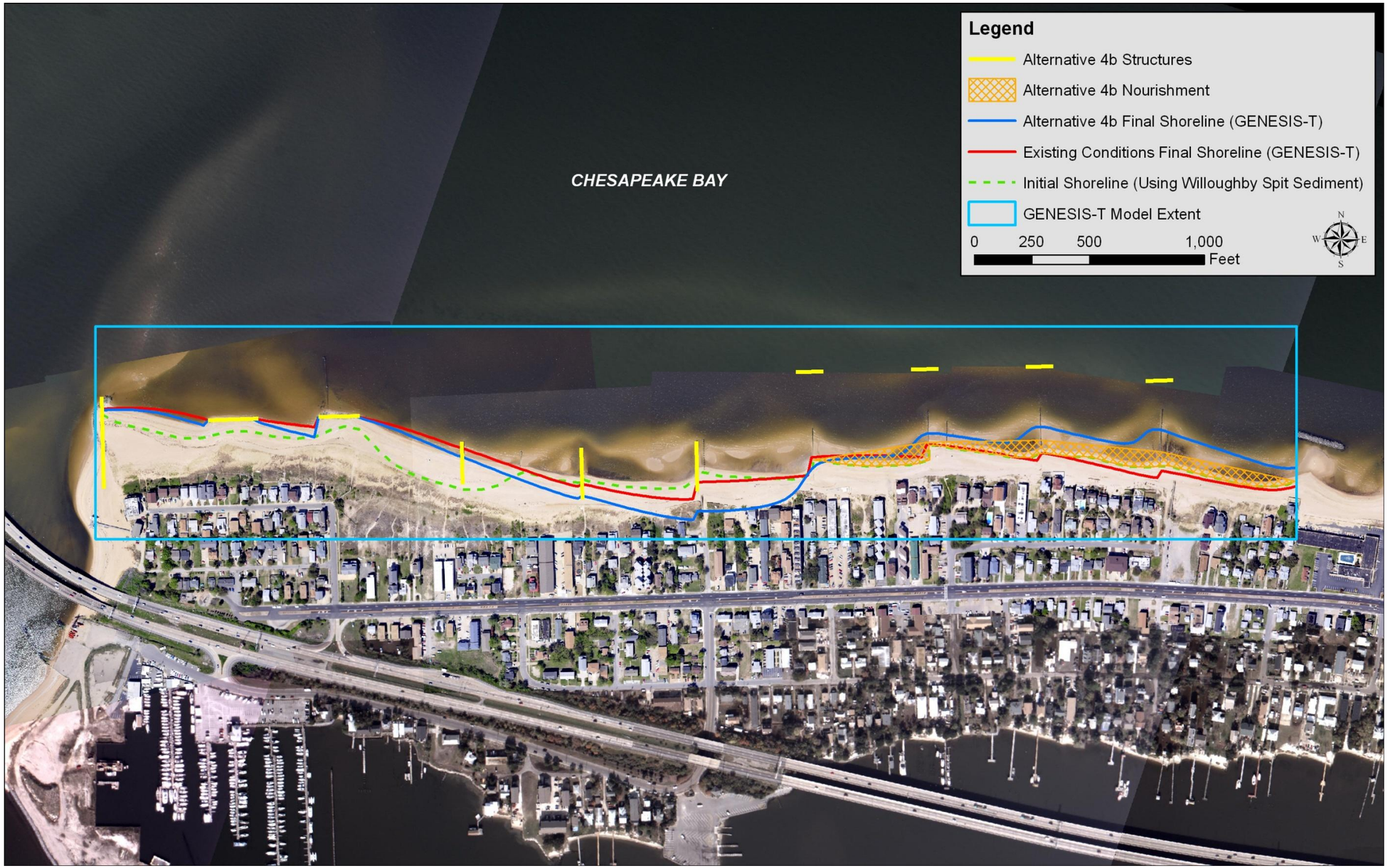

Figure V-12 Option 4b GENESIS-T Model Results (4 Offshore Breakwaters With 3 Existing Groins and Beach Nourishment)

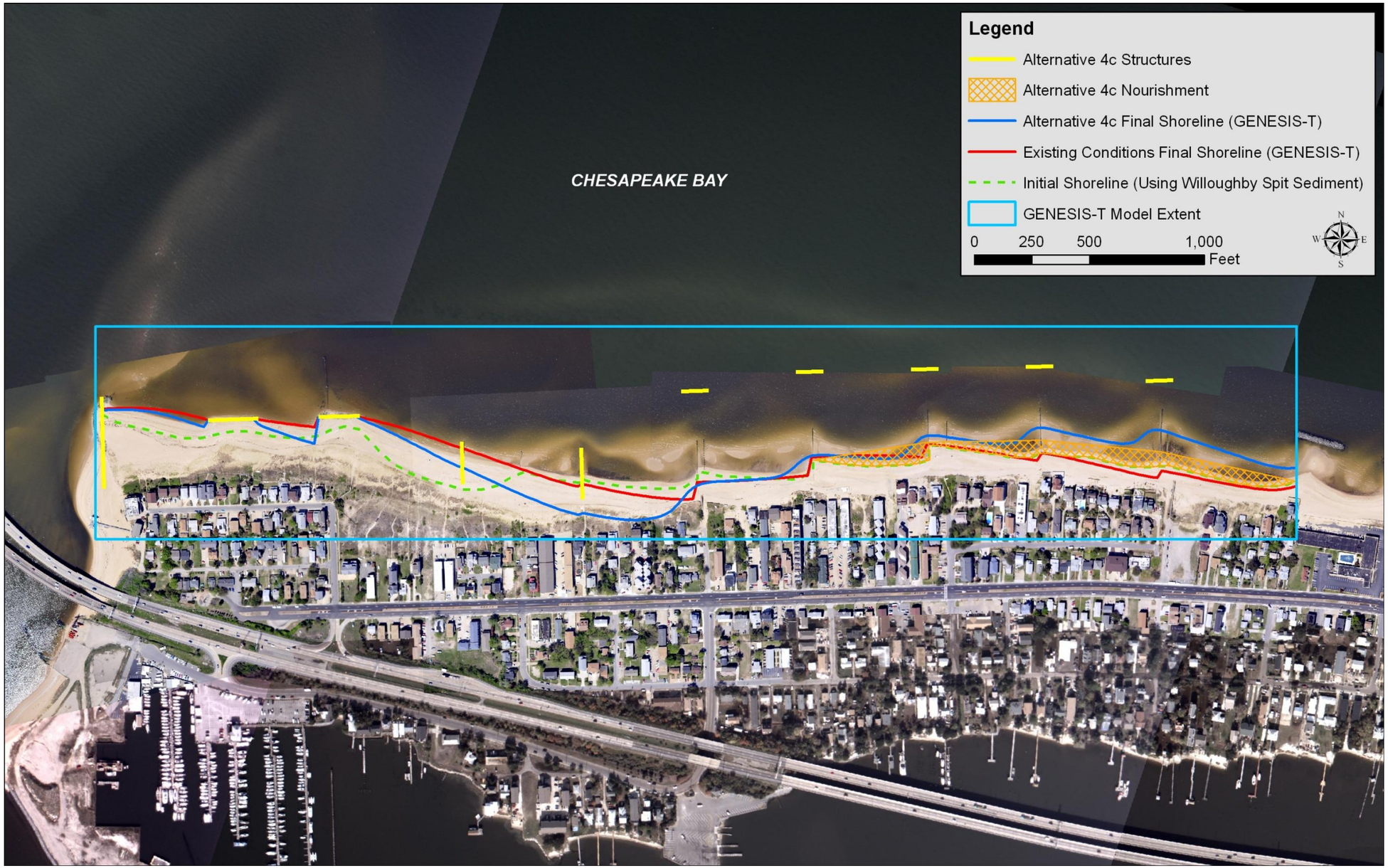

Figure V-13 Option 4c GENESIS-T Model Results (5 Offshore Breakwaters With 2 Existing Groins and Beach Nourishment)

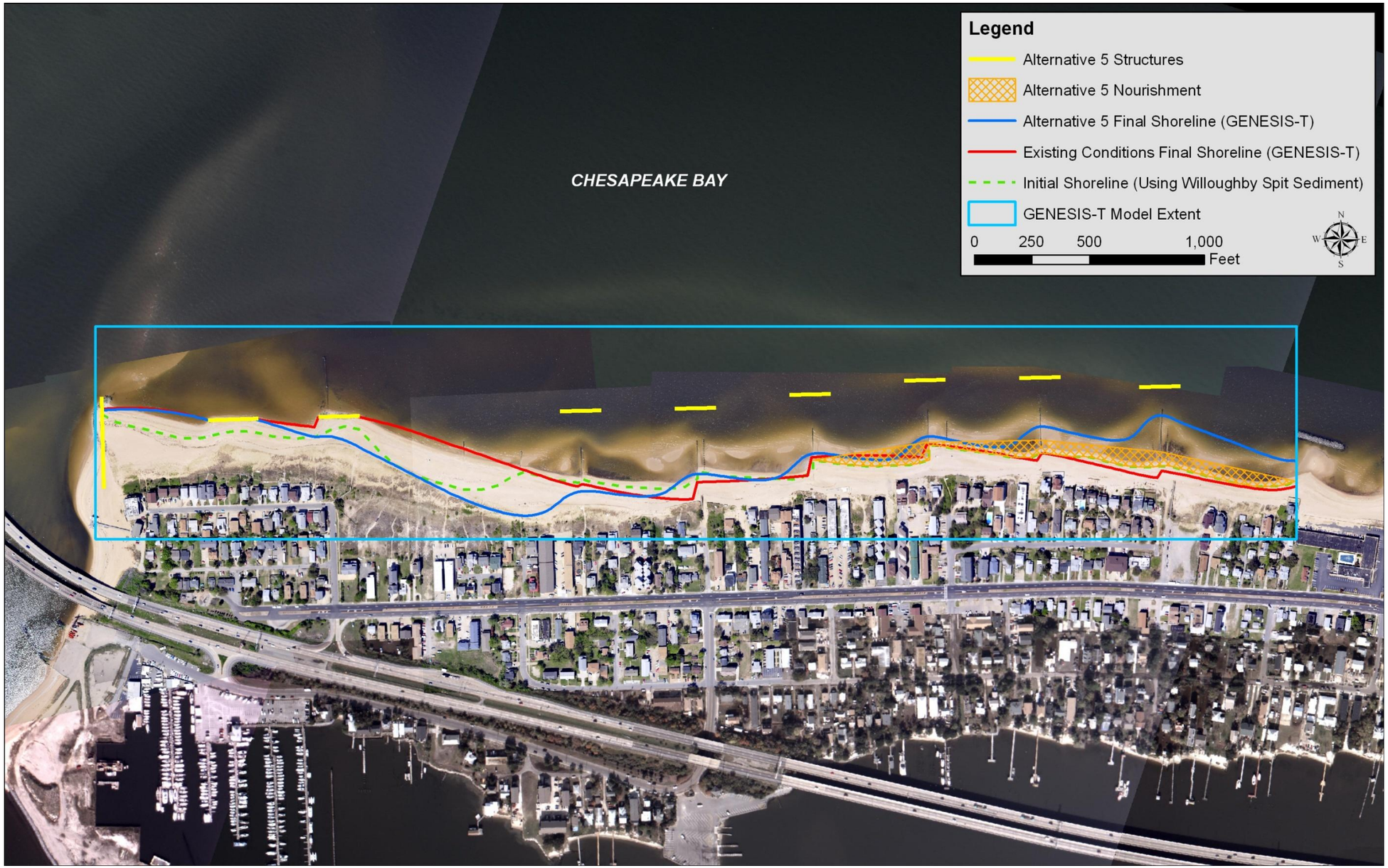

Figure V-14 Option 5 GENESIS-T Model Results (6 Offshore Breakwaters With Beach Nourishment)

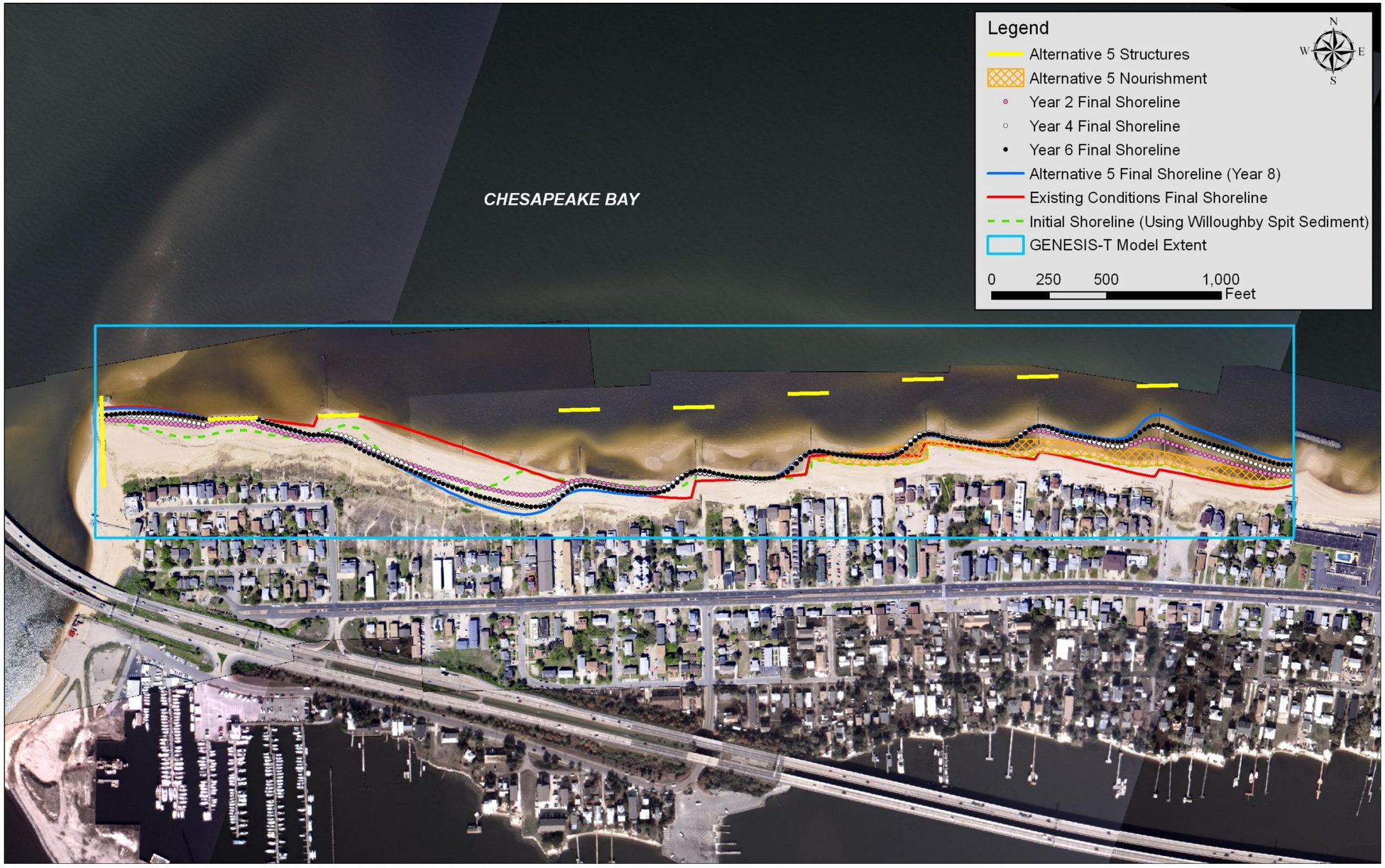

Figure V-15 Option 5 GENESIS-T Yearly Model Results

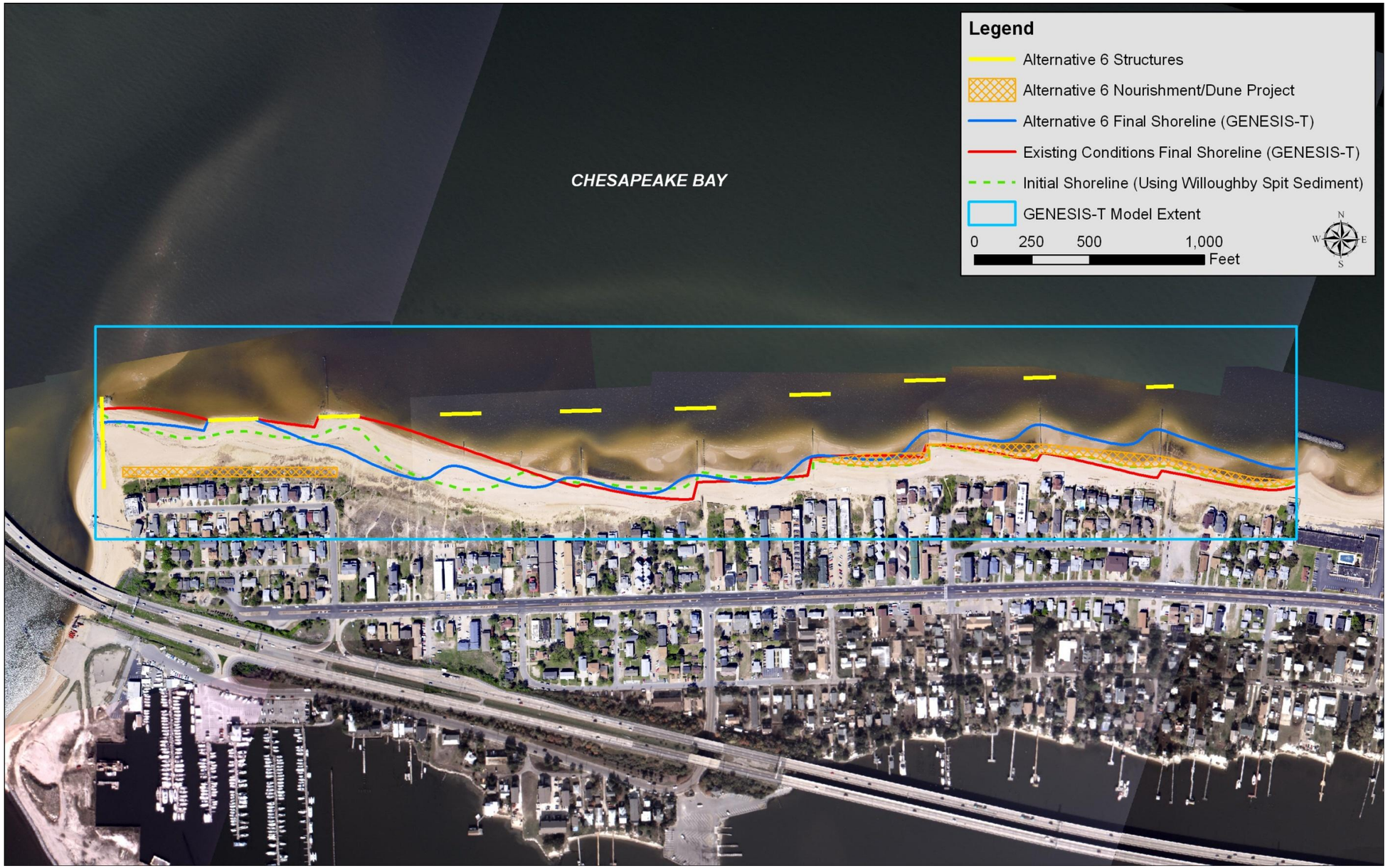

Figure V-16 Option 6 GENESIS-T Model Results (7 Offshore Breakwaters With Beach Nourishment)

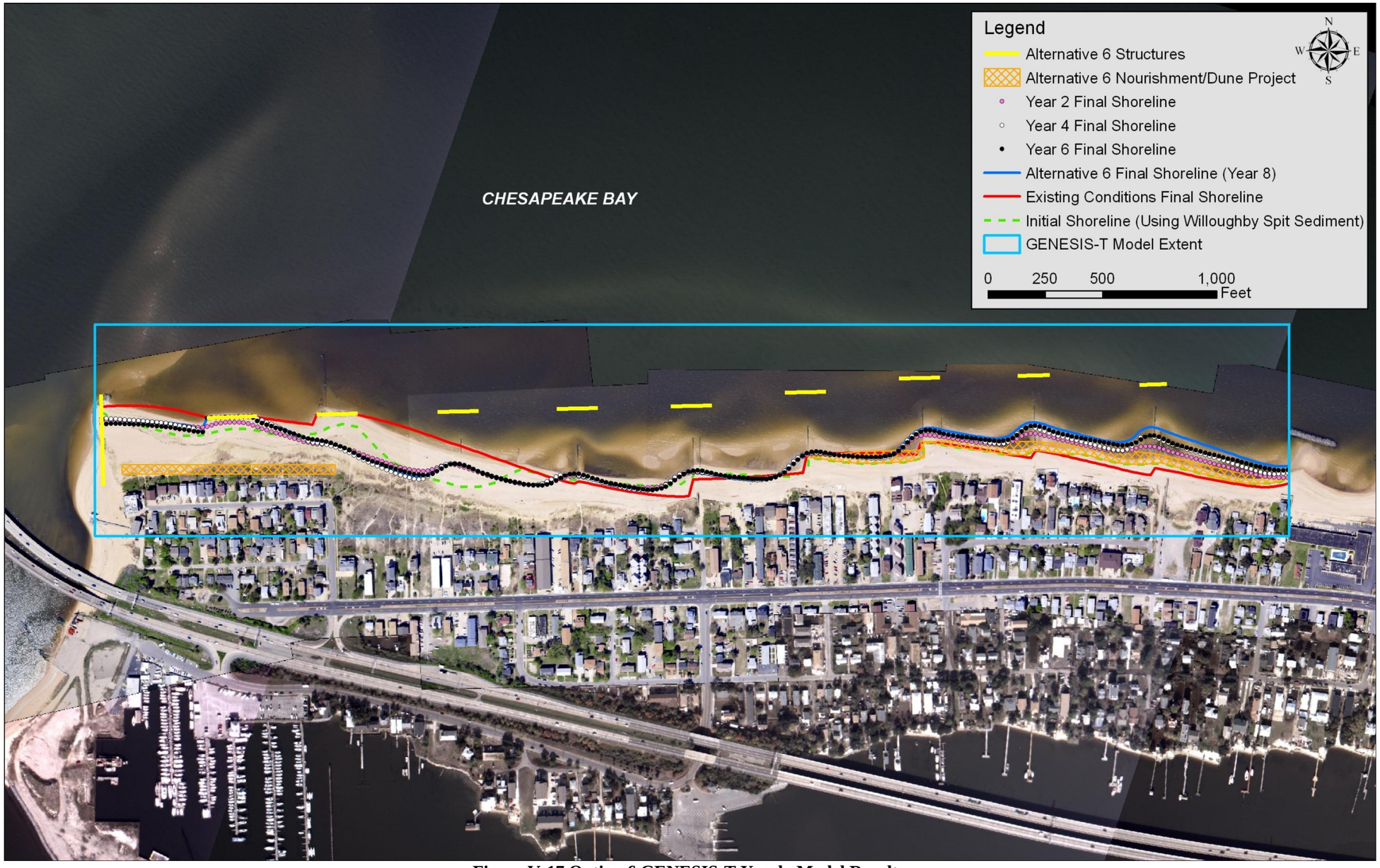

Figure V-17 Option 6 GENESIS-T Yearly Model Results

VI. MODELING OF CROSS-SHORE CHANGE WITH SBEACH

SBEACH (Storm-induced BEAch CHange) is an empirically based numerical simulation model which was developed at the U.S. Army Corps of Engineers (USACE) Waterways Experiment Station (WES) Coastal & Hydraulics Laboratory (CHL). The purpose of the model is to calculate two-dimensional, cross-shore beach, berm, and dune erosion under single-storm surge, wave, and wind action. The SBEACH model is based on a fundamental assumption that profile change is produced only by cross-shore processes. Therefore, longshore processes are considered uniform and neglected in calculating profile change. The cross-shore sediment transport processes are governed by empirical equations defined for four distinct zones in the nearshore: swash, broken wave, breaker transition, and prebreaking. For a more detailed description of the sediment transport mechanisms governing SBEACH, the reader is referred to a series of USACE reports published on the model (Larson and Krauss, 1989, Larson et al., 1990, Rosati et al., 1993).

The most recent version of SBEACH, released in 2010, operates under the Coastal Engineering Design and Analysis System (CEDAS), a suite of tools developed by Veri-Tech, based on various numerical models and codes developed at WES. The CEDAS suite also includes GENESIS/GENESIS-T (Generalized Model for Simulating Shoreline Change), which was also utilized in this study.

The SBEACH model has potential for many applications in the coastal environment, including evaluation of design beaches for erosion and/or flood protection, evaluation of short-term beach fill performance, and preliminary input for economic analyses of beach alternatives.

The main inputs to the SBEACH model include:

- Profile Data – two-dimensional description of the shoreline extending from offshore to a landward point of interest,
- Sediment Data - characterization of the average sediment size and,
- Storm Data – time dependent description of water elevation, waves, and winds (if available).
- Model Calibration Parameters-various beach characteristic and sediment transport parameters which influence beach profile change.

A. MODELING SCOPE

The SBEACH model serves as a basis for understanding cross-shore loss of sand in the berm and/or dune following storm activity. The November 2009 nor'easter was chosen as the calibration period for SBEACH modeling. Wave data from the Norfolk wave gage was used in conjunction with water level data from Sewells Point for the same time period. Beach profile data from the October 2009 periodic survey served as pre-storm conditions while survey data collected shortly after the storm (approximately 2-3 weeks post-storm) served as the post-storm conditions. Multiple iterations were performed before deciding on calibration coefficients that best matched the storm induced cross-shore change.

After model calibration was complete, model verification was performed using Tropical Storm Ernesto as the verification time period. Again, wave data from the Norfolk wave gage was used in conjunction with water level data from Sewells Point for the same time period. Beach profile data from the May 2006 periodic survey served as pre-storm conditions while survey data collected during the October 2006 periodic survey served as the post-storm conditions.

The calibrated SBEACH model was then used to evaluate the performance of nourishment incorporated into the final preferred alternative to be determined using GENESIS-T and DELFT3D modeling. The same measured waves and water levels from recent storm events (Tropical Storm Ernesto and November 2009 nor'easter) which were used for calibration were used to simulate expected short-term storm induced impacts on nourishment projects for similar wave conditions.

B. STUDY AREA

Within the Willoughby Spit project study area, specific transects were selected to evaluate cross-shore storm induced impacts. **Figure VI-1** shows the location of the selected beach profiles which were modeled in SBEACH for both the calibration and verification process as well as the existing conditions and project alternative evaluation process. The profile stationing is in accordance with the City surveys.

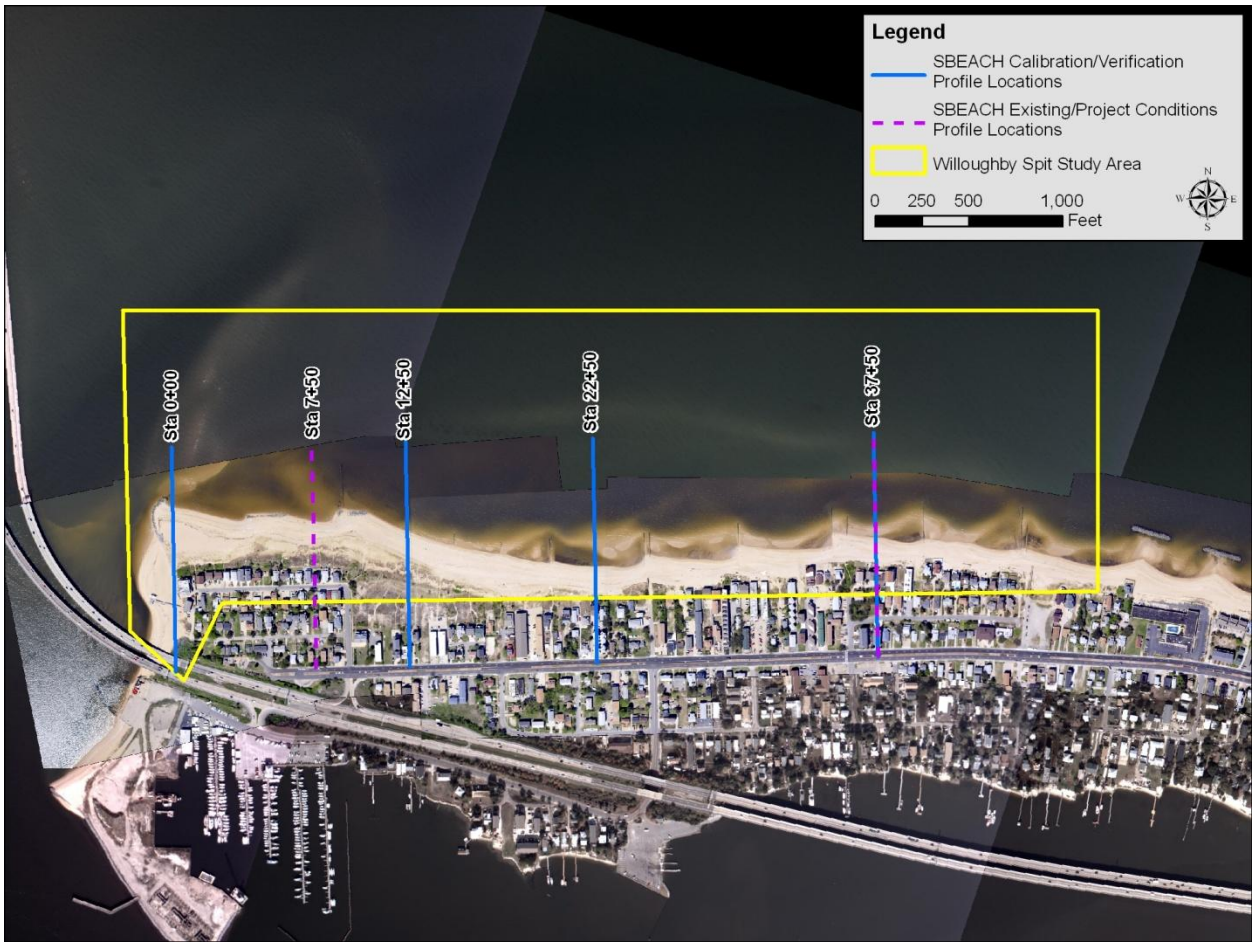

Figure VI-1 Location of Modeled SBEACH Profiles

Several factors were considered in selecting profile locations to be used in the calibration/verification modeling. First, profiles near the ends of the study area were selected. Second, intermediate locations were chosen outside the direct effects of coastal structures to minimize longshore transport influences and maximize cross-shore transport processes. Third, an effort was made to select transect that had both pre- and post-storm data for the November 2009 nor'easter and Tropical Storm Ernesto. Finally, the intermediate profiles were selected in areas of concern including the severe dune erosion that occurred at Sta 37+50 during the November 2009 nor'easter.

Profiles selected for existing conditions and future project alternative modeling were selected in areas where beach nourishment was incorporated into the final selected alternative (see **Figure V-16** for final alternative configuration). When possible, these profiles coincided with the profiles used for the calibration/verification process.

C. CALIBRATION MODEL

The SBEACH model was calibrated to reflect the storm induced impacts which occurred as a result of a nor'easter on November 13, 2009. Pre- and post-storm surveys for this event were taken fairly close to the event itself and therefore provide a good period for calibration, with minimal change due to non storm related activity.

SBEACH is typically calibrated by adjusting the model calibration parameters, which include a number of sediment transport characteristics and other beach characteristics that influence sediment transport. For this study, the general calibration procedure involved:

1. establishing known model inputs including profile data, storm data, and sediment data
2. establishing initial sediment transport parameters and adjusting these parameters until the predicted profiles best match the measured profiles
3. establishing initial beach characteristic parameters and adjusting these parameters until the predicted profiles best match the measured profiles

This calibration sequence was followed using known inputs and initial parameters based on the Bay Oaks study by Moffatt & Nichol in 2007. Then, particular input parameters (sediment transport parameters and beach characteristics) were revisited and the sensitivity of the model response to changes in these parameters was tested. In many cases, a given parameter was adjusted to yield a more accurate profile response. The final input data for the calibration model will be presented in the following sections.

1. Profile Data (Calibration Model)

The profile data was obtained from the City of Norfolk surveys done in October 2009 and November 2009. The October 2009 survey was part of the bi-annual monitoring for the period survey evaluation. The November 2009 survey was an additional survey requested by the City as part of the monitoring contract to be taken only after large storm events. Four profiles were selected for the calibration model based on their location relative to the areas of interest within the Willoughby Spit study area. **Figure VI-2** shows the location of the selected profiles. The measured October 2009 profile became the initial beach profile for the SBEACH model input.

The measured November 2009 profile was also loaded into the model to serve as a reference profile position for the model calibration.

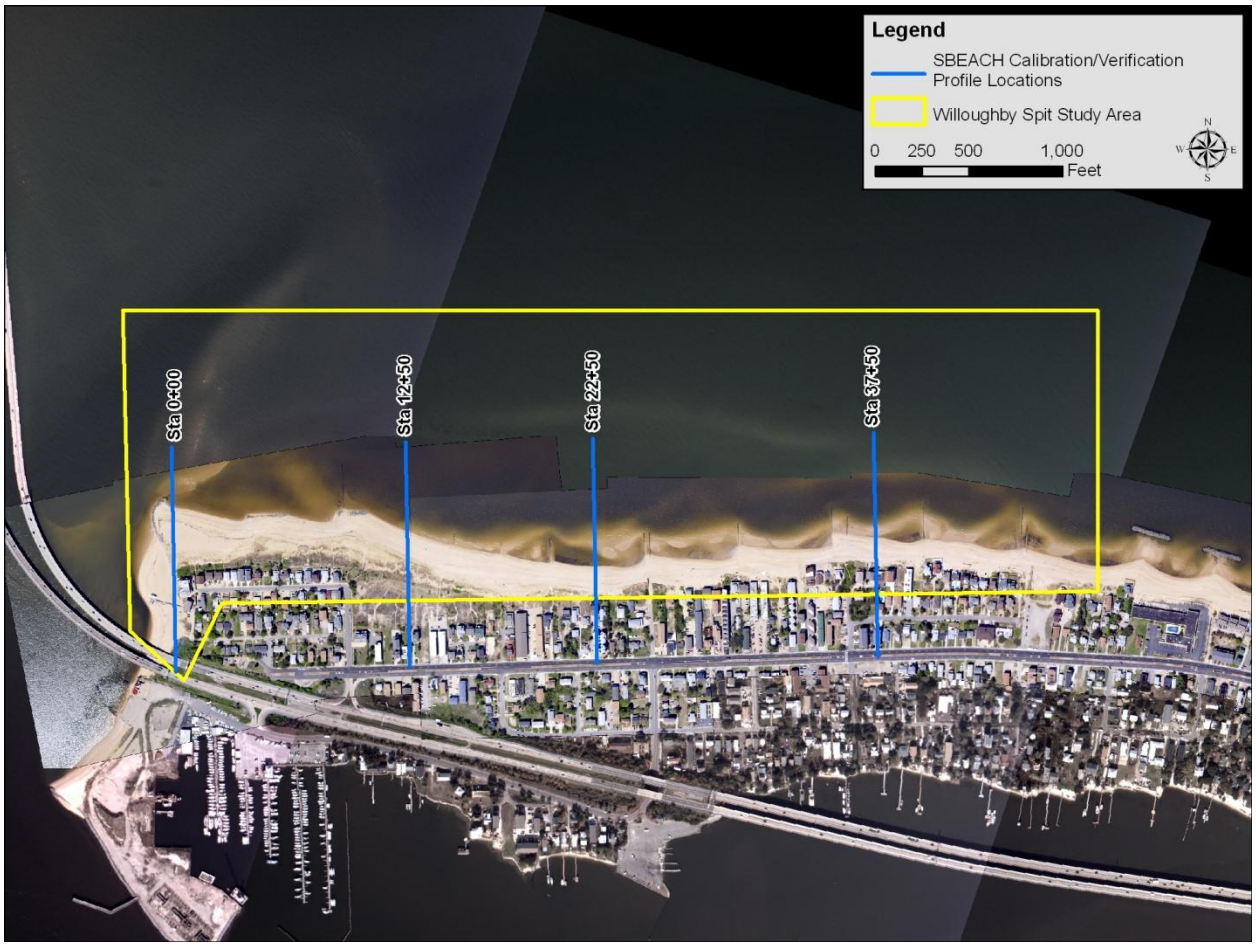

Figure VI-2 Selected Profiles for SBEACH Calibration

2. Storm Data (Calibration Model)

Typical storm data input for SBEACH includes storm hydrographs of total water elevation, wave conditions, and wind conditions. For this analysis, the simulation involved a 6 day time series of wave gage data spanning November 10, 2009 through November 16, 2009. The wave gage information used included significant wave height, peak wave period, wave angle, wind speed, and wind direction. Water elevation data was downloaded from Sewells Point for the same time period. While water level data is also collected at the wave gage, SBEACH is very sensitive to the elevation in terms of where erosion occurs on the profile. It was found during calibration that water level data from Sewells Point provided much better results, in terms of the elevation at which erosion occurred, than that collected from the gage. **Figure VI-3** shows the storm data used for the November 2009 nor'easter calibration (wave height, peak period, and water level).

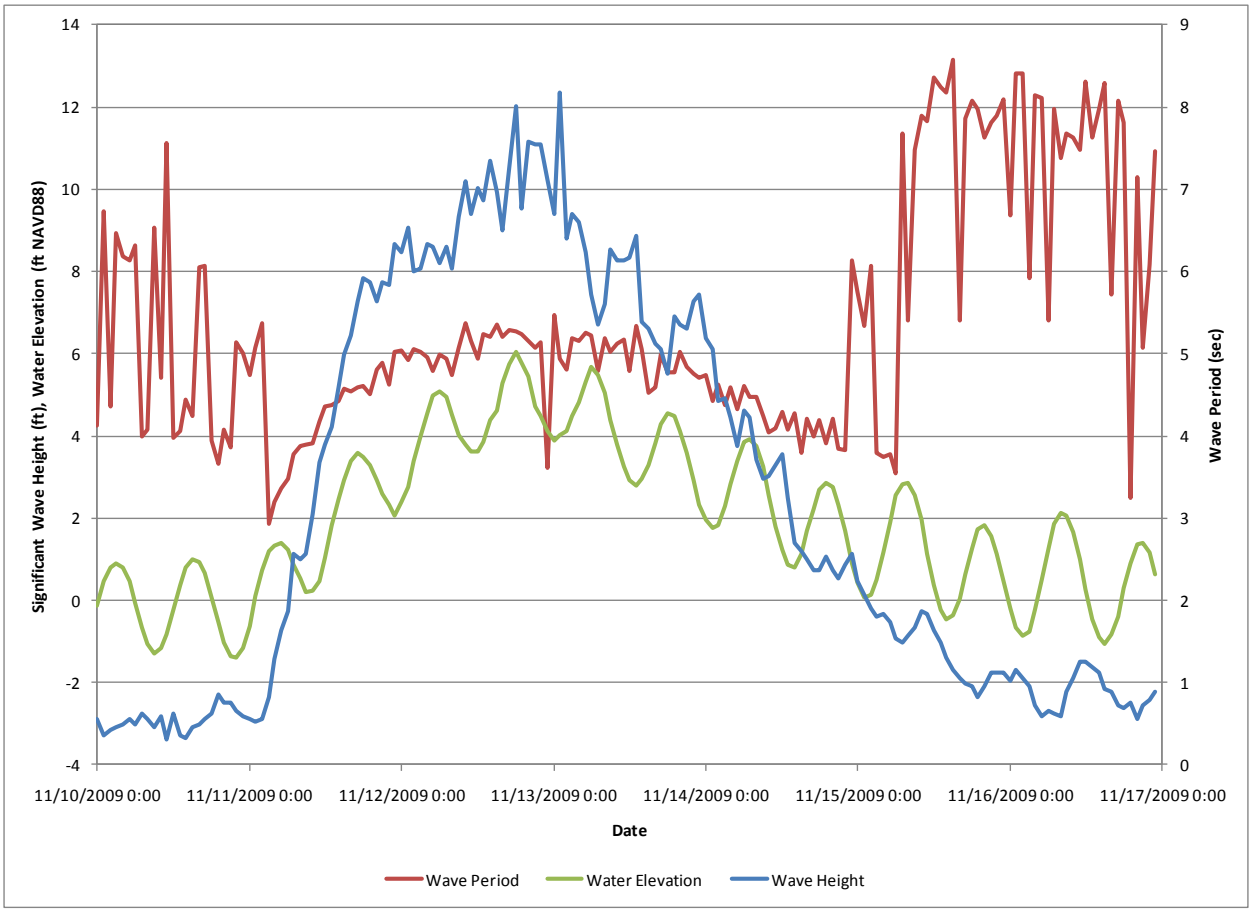

Figure VI-3 Storm Data For The November 2009 Nor'easter

3. Sediment Data (Calibration Model)

For this analysis, the effective grain size used for the model profile was 0.40 mm. As mentioned in **Section II.C**, this is an average grain size computed from a comprehensive April 2004 post nourishment sediment study.

4. Model Calibration Coefficients (Calibration Model)

SBEACH is typically calibrated by adjusting the sediment transport characteristics or beach characteristics. Sediment transport characteristics include Transport Rate Coefficient, K (m^4/N), Coefficient for Slope Dependent Term, Eps (m^2/s), Overwash Transport Parameter, Transport Rate Decay Coefficient Multiplier, and Water Temperature (°C). Beach characteristics include Landward Surf Zone Depth and Avalanche Angle (Deg). The initial model was run using the parameters established for the August 2007 Bay Oaks study. Then, each parameter was adjusted individually, within the recommended range, to determine its influence on model output. The appropriate model coefficients were determined by comparing the SBEACH final output profile with the corresponding measured November 2009 profile.

After running a number of model scenarios, it was determined that the following model parameters yielded the most accurate final profile.

- Transport Rate Coefficient, K (m^4/N) = 6.0 x 10^{-7},
- Coefficient for Slope-Dependent Term, Eps (m^2/s) = 0.005,
- Overwash Transport Parameter = 0.002,
- Transport Rate Decay Coefficient Multiplier = 0.5,
- Water Temperature=15º C,
- Landward Surf Zone Depth = 1.6, and
- Avalanche Angle = 35º

5. Model Output (Calibration Model)

A comparison of the final SBEACH model profile and the measured final profile for November is shown in **Figure VI-4** for one of the four selected transects. SBEACH model output for the remaining cross sections is presented in **Appendix E**. In general, the profiles show sediment being transported further offshore than the measured post-storm profile. In addition, the simulated profiles are generally smoother near the shoreline than the measured profiles. This may be an indication of onshore sediment recovery which occurred during the weeks between the end of the storm in mid November and the survey in late November and early December. It should also be mentioned that the calibration results near the west end of Willoughby Spit show less agreement between the calculated and measured post-storm profile. This is most likely due to the large influence of longshore transport in this area due to its location at the end of the littoral system and its proximity to terminal structures. Therefore, less reliable results from a cross-shore transport model are not unexpected in a region like this. A longshore transport model (i.e. GENESIS-T) may provide more reliable results and insight into sediment transport patterns in this area.

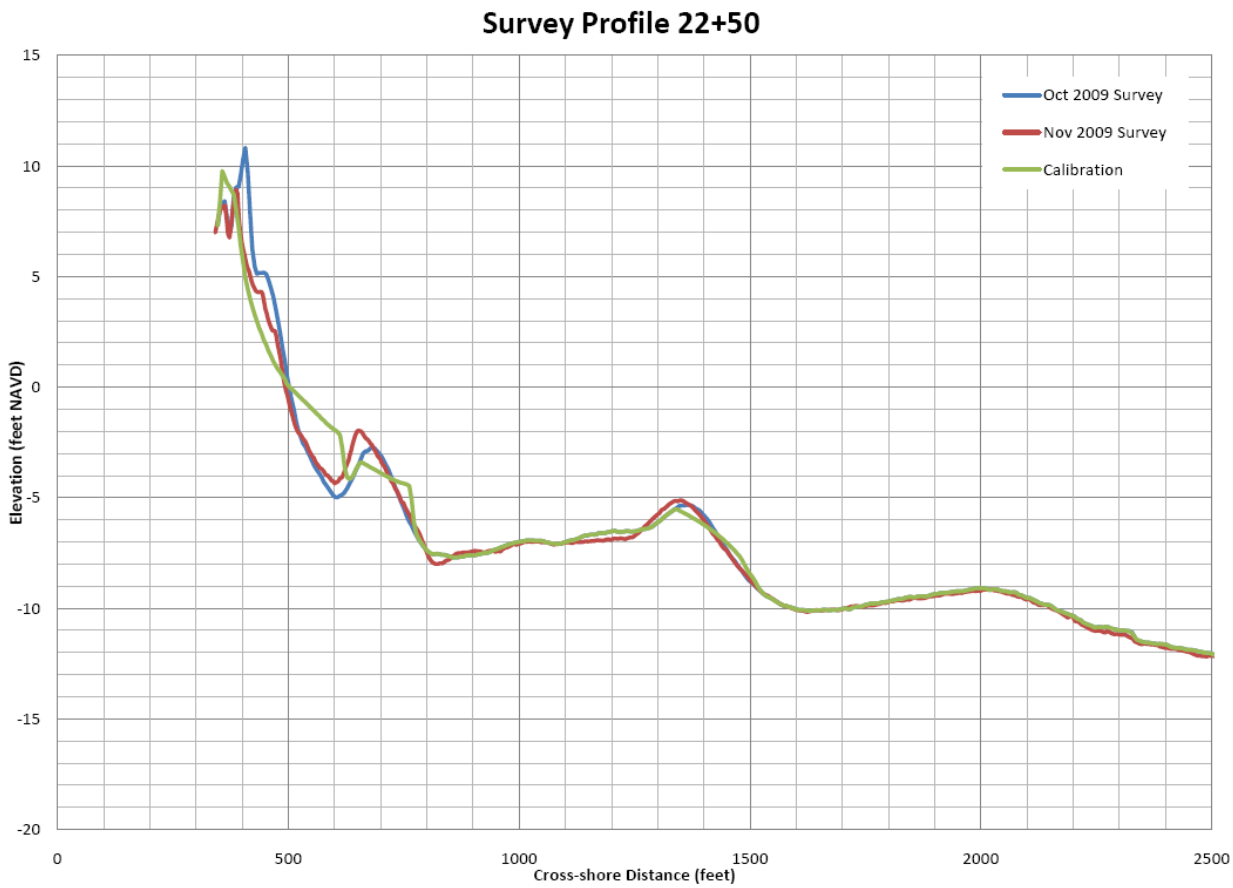

Figure VI-4 Comparison of SBEACH Final Profile and Measured Profile for Calibration Model

D. VERIFICATION MODEL

1. Profile Data (Verification Model)

The profile data was obtained from the City of Norfolk surveys done in March 2006 and October 2006. Both surveys were part of the bi-annual monitoring for the periodic survey evaluation. The same four profiles selected for the calibration were used for the verification process (see **Figure VI-2**). The measured March 2006 profile became the initial beach profile for the SBEACH model input. The measured October 2006 profile was also loaded into the model to serve as a reference profile position for the model verification.

2. Storm Data (Verification Model)

For the verification analysis, the simulation involved an 8 day time series of wave gage data spanning September 29, 2006 through October 7, 2006. The wave gage information used included significant wave height, peak wave period, wave angle, wind speed, and wind direction. Water elevation data was downloaded from Sewells Point for the same time period. While water level data is also collected at the wave gage, SBEACH is very sensitive to the elevation in terms of where erosion occurs on the profile. It was found during calibration that water level data from Sewells Point provided much better results, in terms of the elevation at which erosion occurred,

than that collected from the gage. **Figure VI-5** shows the storm data used for the Tropical Storm Ernesto verification (wave height, peak period, and water level).

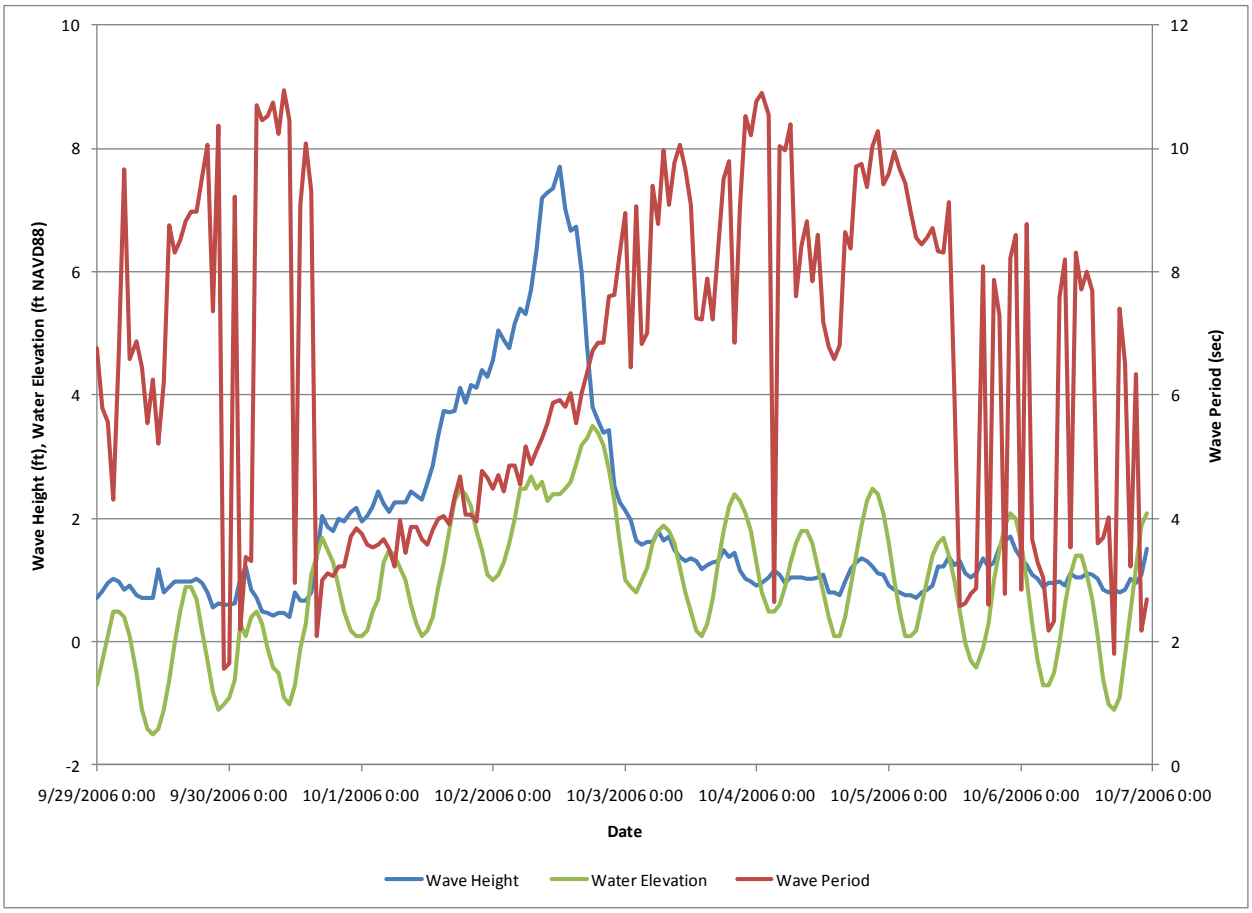

Figure VI-5 Storm Data For Tropical Storm Ernesto

3. Sediment Data (Verification Model)

For verification, the same sediment data as was used for the calibration model was input into SBEACH. As stated previously, an average grain size for this project was 0.4 mm. This was the post nourishment grain size as determined from the April 2004 study.

4. Model Calibration Coefficients (Verification Model)

The sediment transport parameters and beach characteristics as defined by the model calibration analysis were used.

5. Model Output (Verification Model)

A comparison of the final SBEACH model profile and the measured final profile for Tropical Storm Ernesto is shown in **Figure VI-6** for one of the four selected transects. SBEACH model output for the remaining cross sections is presented in **Appendix E**. In general, the simulated profiles are similar to the results for the November 2009 nor'easter and in relative agreement with the measured post-storm survey from 2006. One notable difference is that erosion was slightly under predicted during Ernesto simulations, particularly above elevation +5 ft NAVD88.

This could be the result of the time period over which the surveys cover. Although the storm happened in early September, the pre-storm profile was taken in March 2006. There may have been significant changes to the profile, possibly some additional erosion, before the storm impacted the coast which would not have been included in this analysis. In addition, the post-storm survey was taken over 1 month after the storm, accounting for more profile change which would not have been represented in this analysis. In summary, since one set of runs tended to overpredict erosion while another underpredicted, it was determined that the overall agreement was acceptable.

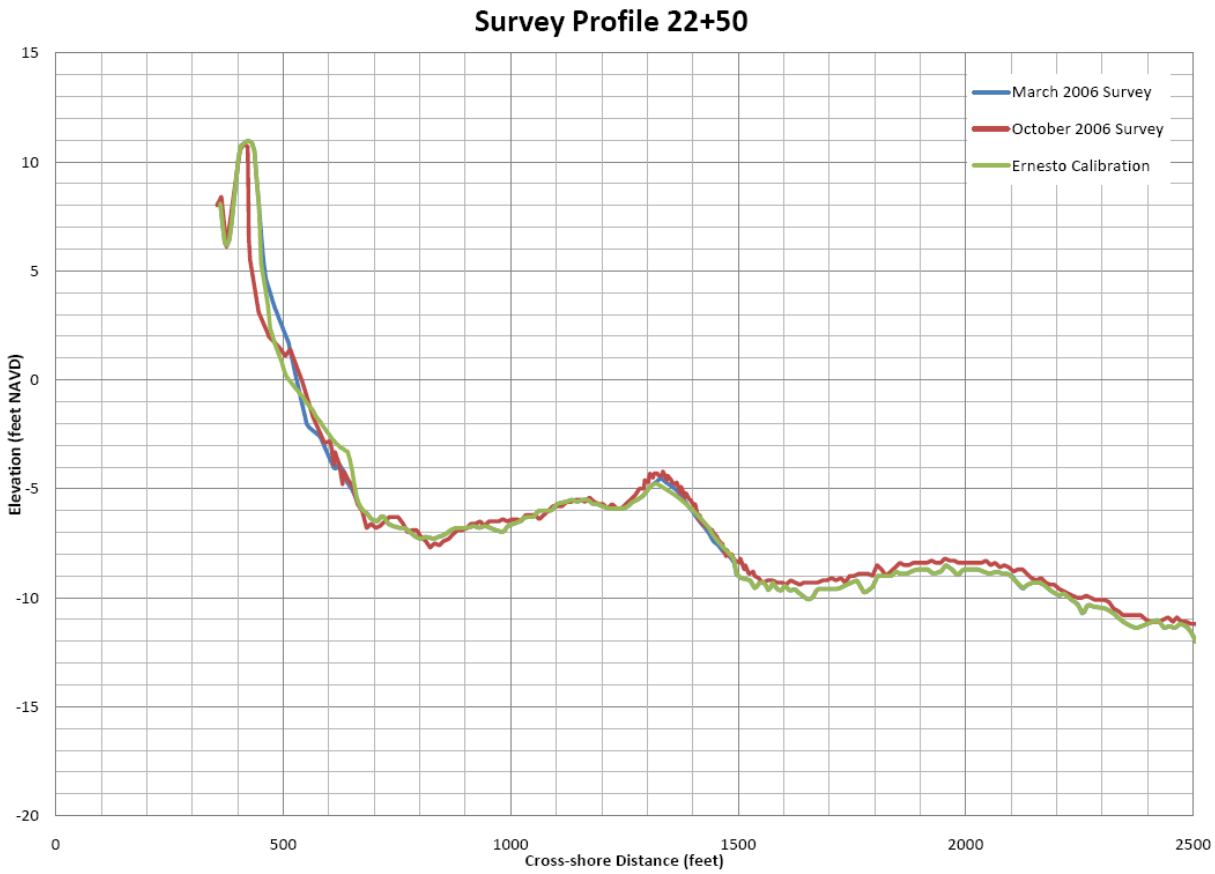

Figure VI-6 Verification SBEACH Model Results

E. EXISTING CONDITIONS MODEL

After setting the SBEACH calibration coefficients, an existing conditions model was developed to estimate the initial cross-shore beach change that the Willoughby Spit study area would be expected to experience following the same wave and water level impacts. The resulting profile indicates what would happen if the existing erosion problem at Willoughby Spit were not addressed.

1. Profile Data (Existing Conditions Model)

The input profiles for the existing conditions model were taken from the April 2010 City of Norfolk survey. This survey was the most recent at the time of the study. Two profiles were extracted from locations where beach nourishment was incorporated into the final selected

alternative (see **Figure V-16**) in order to better compare the existing conditions with future project performance. **Figure VI-7** shows the locations of the profiles used for the existing conditions analysis. The profile stationing is in accordance with the city surveys.

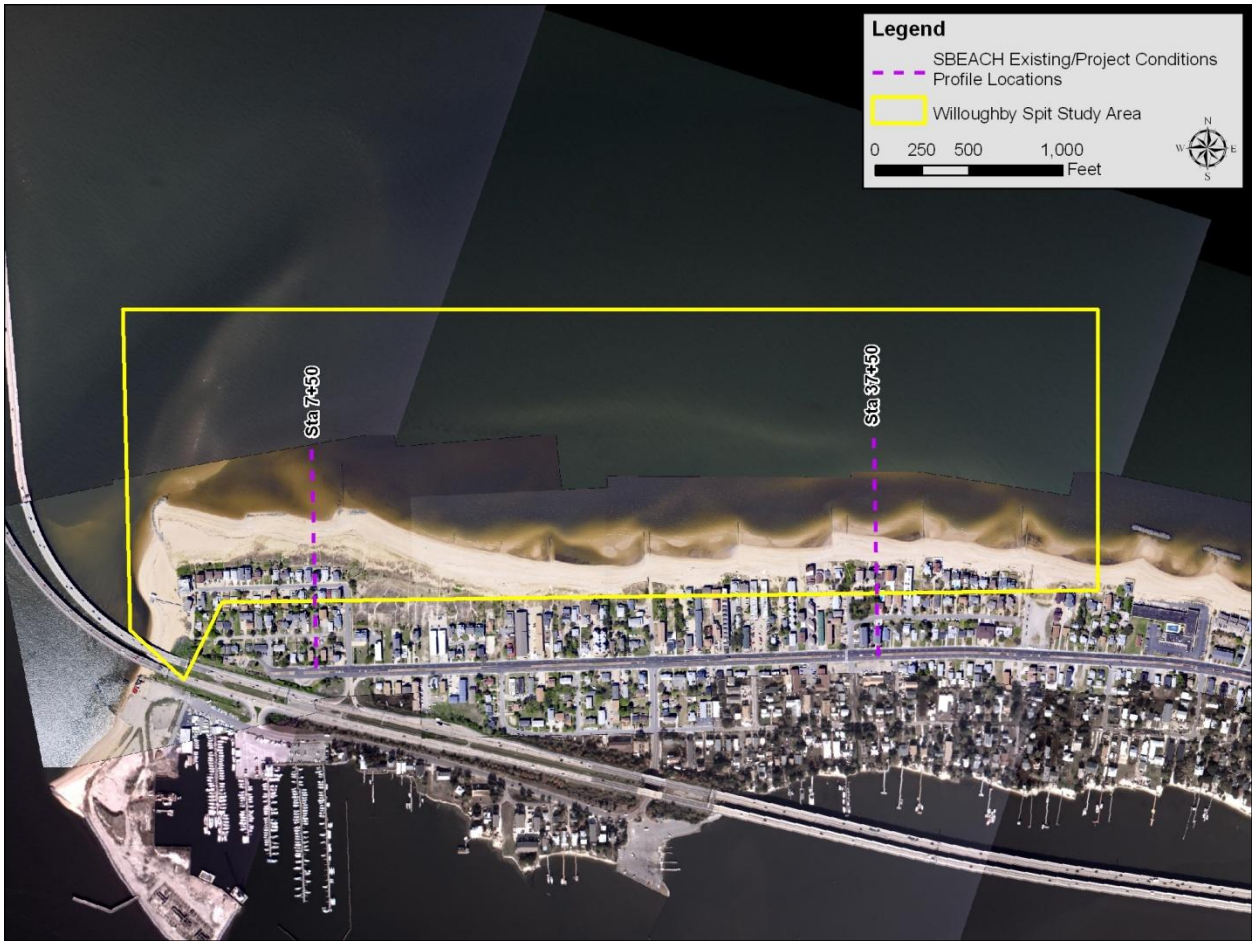

Figure VI-7 SBEACH Existing Conditions Profile Locations

2. Sediment Data (Existing Conditions Model)

The same sediment data as was used for the calibration model was input into SBEACH. As stated previously, an average grain size for this project was 0.4 mm. This was the post nourishment grain size as determined from the April 2004 study.

3. Storm Data (Existing Conditions Model)

The same time series of wave data which was used for the calibration model and verification model was used for the existing conditions model. The results provide predicted beach profiles if nothing was done to the beach and the same storm conditions (Tropical Storm Ernesto and November 2009 nor'easter) were to repeat themselves.

4. Model Calibration Coefficients (Existing Conditions Model)

The sediment transport parameters and beach characteristics as defined by the model calibration analysis were used. Therefore, the existing conditions model was run using the following parameters:

- Transport Rate Coefficient, K (m^4/N) = 6.0 x 10^{-7},
- Coefficient for Slope-Dependent Term, Eps (m^2/s) = 0.005,
- Overwash Transport Parameter = 0.002,
- Transport Rate Decay Coefficient Multiplier = 0.5,
- Water Temperature=15º C,
- Landward Surf Zone Depth = 1.6, and
- Avalanche Angle = 35º

5. Model Output (Existing Conditions Model)

Under existing conditions, SBEACH indicates that the dune near the terminal groin (Sta 7+50) could be completely inundated by a storm similar to the November 2009 nor'easter but would remain intact for a smaller storm like Tropical storm Ernesto. It should be noted that there are existing breakwaters in front of this location that cannot be properly modeled in SBEACH. Therefore, storm impacts seen in SBEACH modeling for this area are likely exaggerated which explains why the inundation seen in the modeling during the November 2009 nor'easter did not actually occur. **Figure VI-8** and **Figure VI-9** show the existing conditions model results for the area near the terminal groin from which material may be borrowed for future nourishment. It is interesting to note that the berm is totally removed in this area but again, these impacts will be lessened by the existing breakwaters in place.

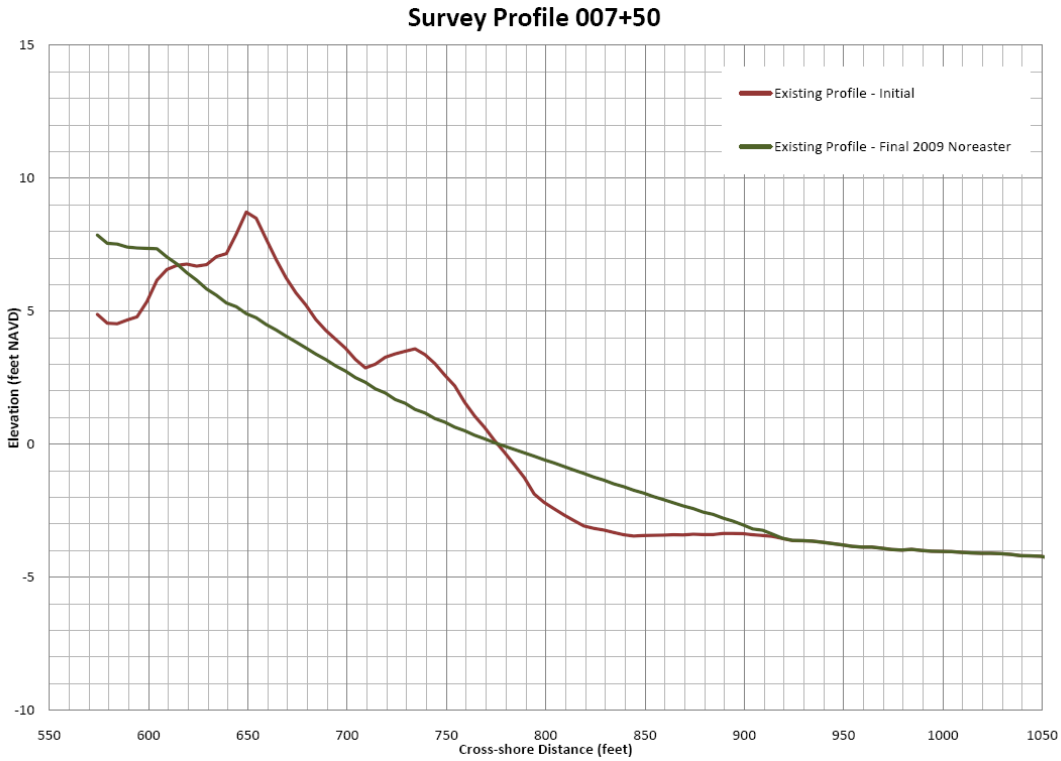

Figure VI-8 Existing Conditions SBEACH Model Results (Sta 7+50, November 2009 Nor'easter)

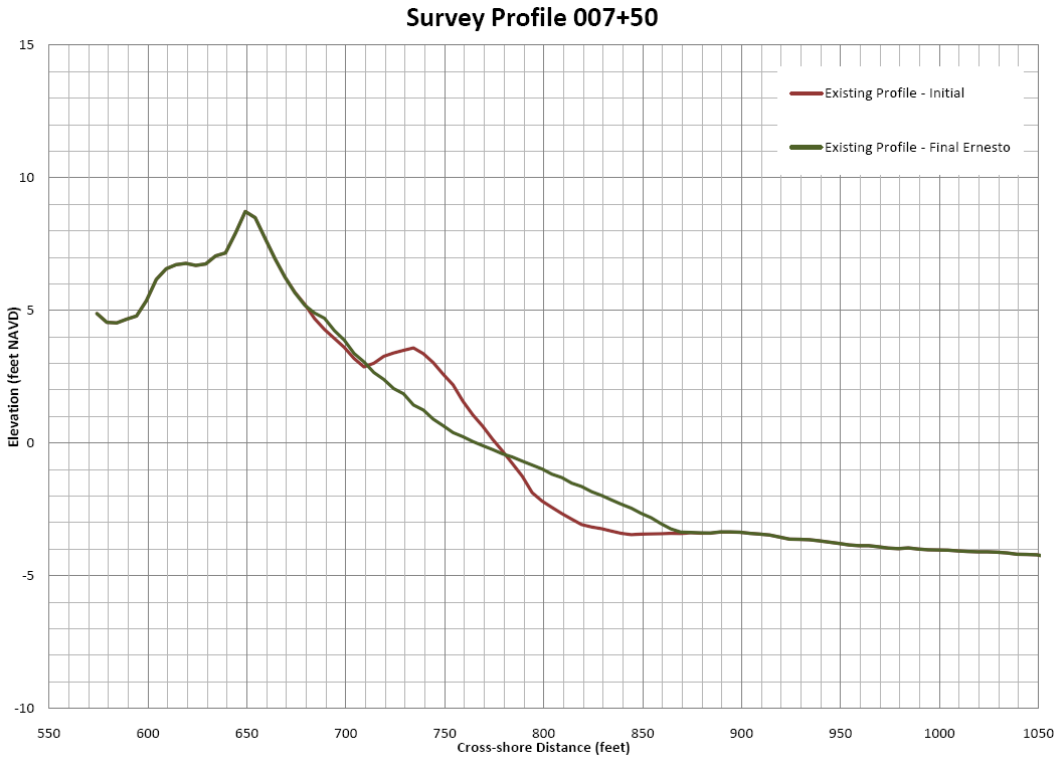

Figure VI-9 Existing Conditions SBEACH Model Results (Sta 7+50, Tropical Storm Ernesto)

Under existing conditions, SBEACH indicates that the berm at the eastern end of the study area (Sta 37+50) would be completely inundated by a storm similar to the November 2009 nor'easter and half way eroded (approximately 30 ft) due to a smaller storm like Tropical storm Ernesto. **Figure VI-10** and **Figure VI-11** show the existing conditions model results for the eastern portion of the study area which will receive nourishment as part of the preferred project. It is interesting to note that the berm is mostly pulled directly offshore and a small bar is formed.

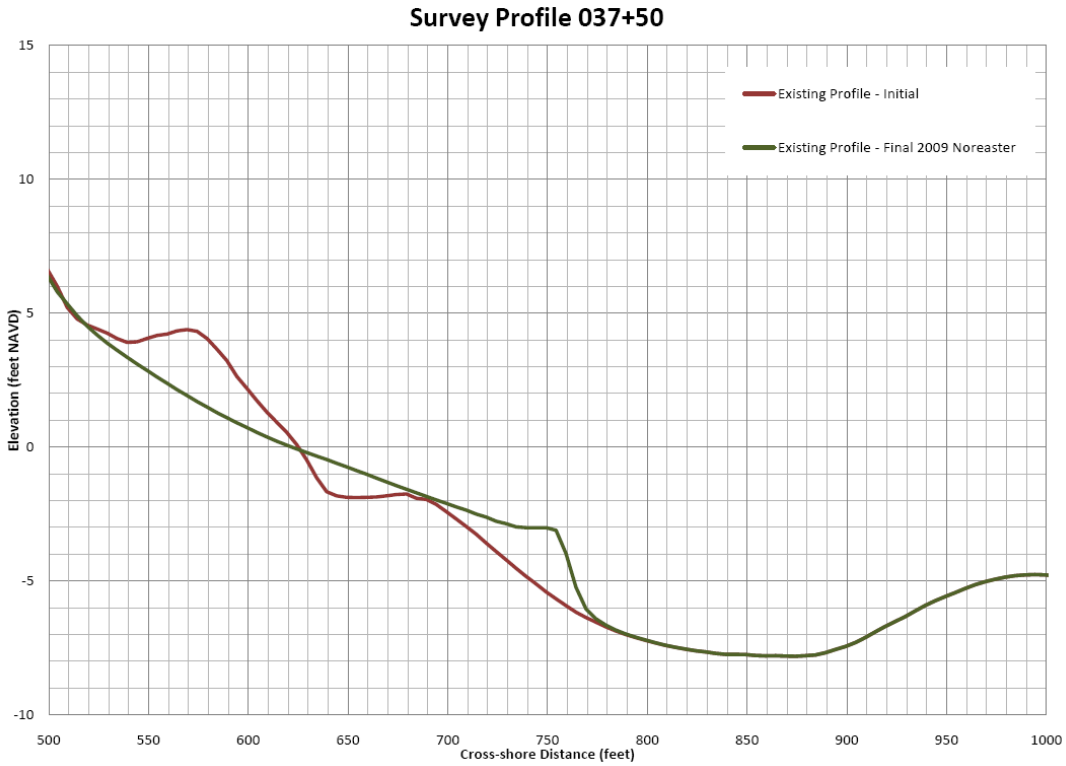

Figure VI-10 Existing Conditions SBEACH Model Results (Sta 37+50, November 2009 Nor'easter)

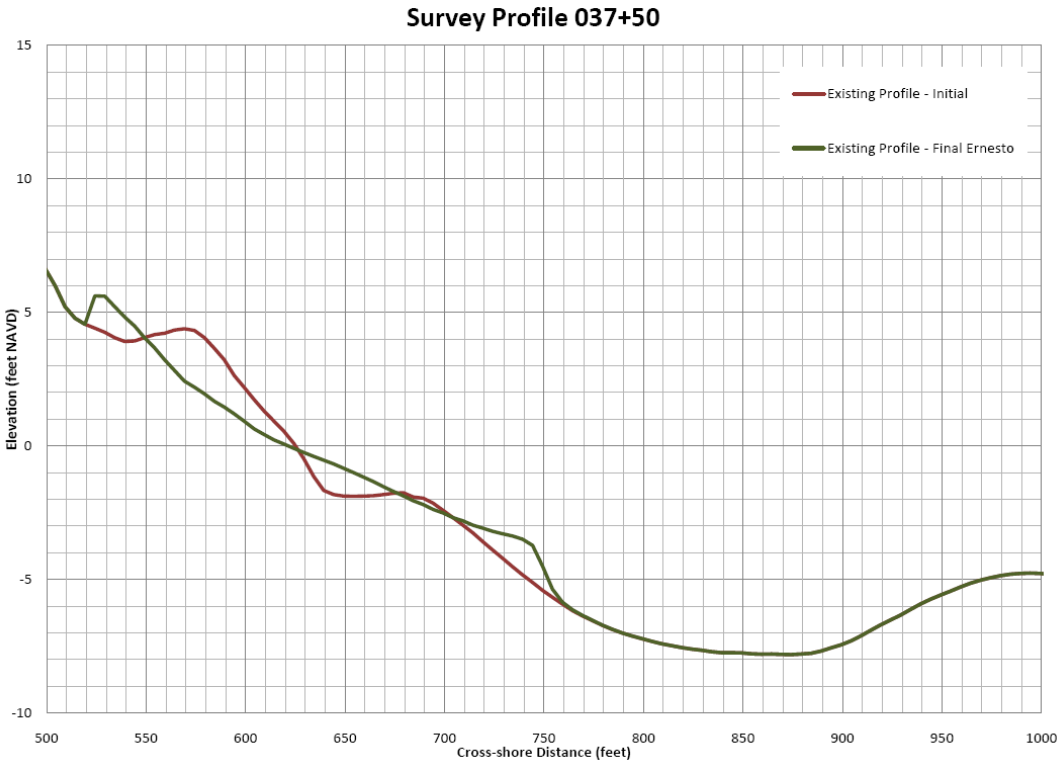

Figure VI-11 Existing Conditions SBEACH Model Results (Sta 37+50, Tropical Storm Ernesto)

F. MODELING OF PROPOSED ALTERNATIVES

The proposed alternative based on GENESIS-T modeling (see **Section V.H)**, is to perform a beach fill at the eastern end of the study area, adding approximately 45 ft of berm width to the beach (given the lack of longshore transport in this area) and a dune project at the western end (given the longshore transport that does reach this area), creating a 30 ft wide dune (see **Figure V-16**). These options were modeled using one profile from each area of nourishment.

1. Profile Data (Proposed Alternative Model)

The April 2010 profiles from the City survey run for the existing conditions model (**Figure VI-7**) were modified to include dune construction and beach nourishment projects. Sta 7+50, near the Willoughby Spit terminal groin, was modified to include a dune project in which a 30 ft wide dune was added to the existing profile at a 1:10 construction slope. Sta 37+50, at the eastern end of the study area, was modified to add 45 ft of berm to the existing profile at a 1:15 offshore construction slope. An example of the dune project is presented in **Figure VI-12** and an example of the beach nourishment project is presented in **Figure VI-13**.

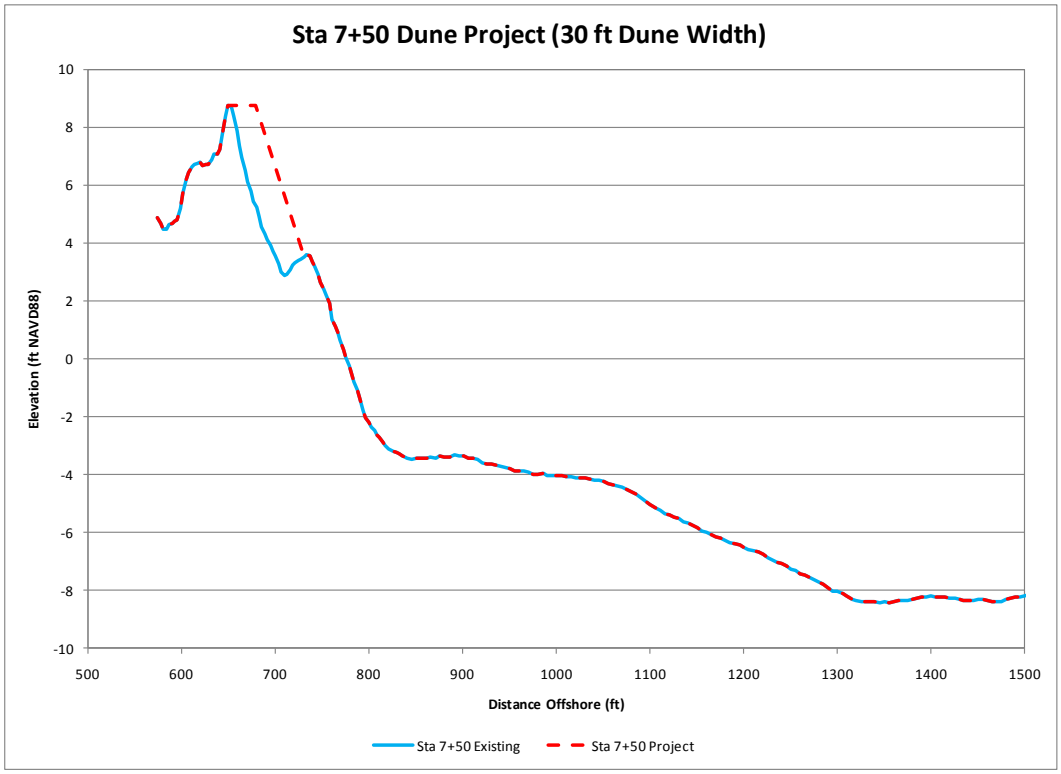

Figure VI-12 Dune Project Template (Sta 7+50)

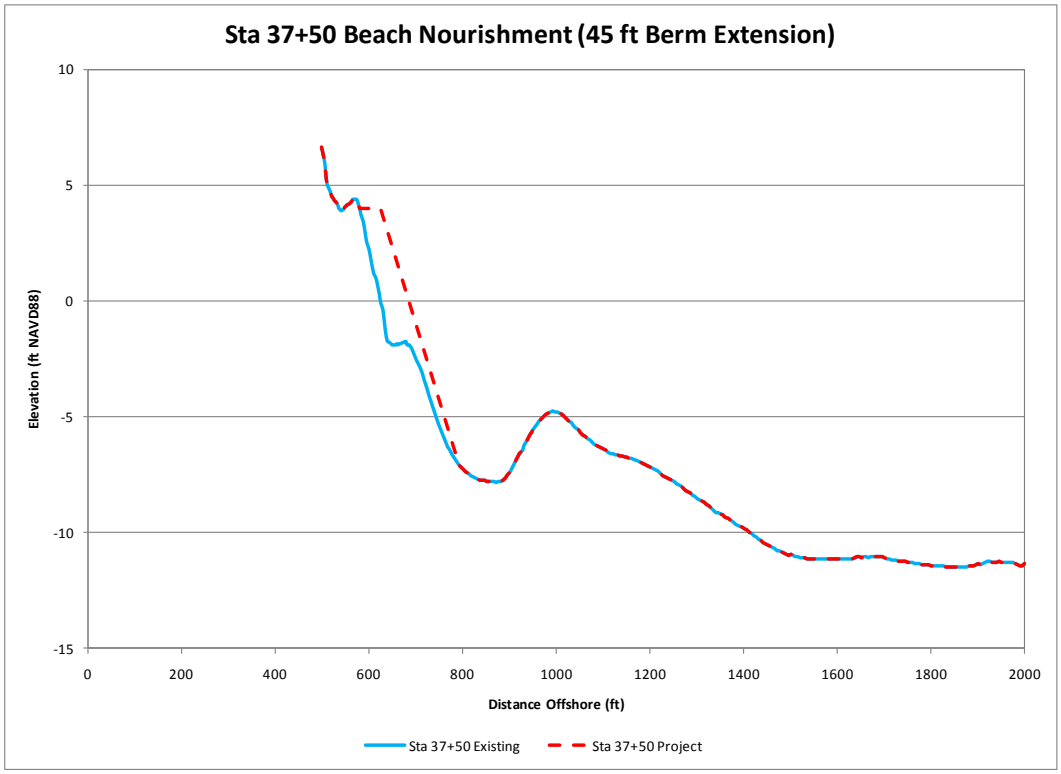

Figure VI-13 Beach Nourishment Project Template (Sta 37+50)

2. Sediment Data (Proposed Alternative Model)

The same sediment data as was used for the calibration model was input into SBEACH. As stated previously, an average grain size for this project was 0.4 mm. This was the post nourishment grain size as determined from the April 2004 study.

3. Storm Data (Proposed Alternative Model)

The same time series of wave data which was used for the calibration model, verification model, and existing conditions model was used. The results provide predicted beach profiles if a beach nourishment project was completed and the same storm conditions (Tropical Storm Ernesto and November 2009 nor'easter) were to repeat themselves.

4. Model Calibration Coefficients (Proposed Alternative Model)

The sediment transport parameters and beach characteristics as defined by the model calibration analysis were used.

5. Model Output (Proposed Alternative Model)

As shown in **Figure VI-14** and **Figure VI-15**, the addition of a 30 ft wide dune project near the terminal groin (Sta 7+50) will provide adequate protection from storms such as the November 2009 nor'easter and Tropical Storm Ernesto. Again, the damage estimated by SBEACH is likely larger that what would happen in reality due to the existing offshore breakwaters. Therefore it appears that the dune project will provide the added protection being sought for the houses in this area if some sand were to be borrowed from beach near the existing offshore breakwaters for

nourishment of the eastern portion of the study area (which ultimately would also likely return to this location by longshore transport).

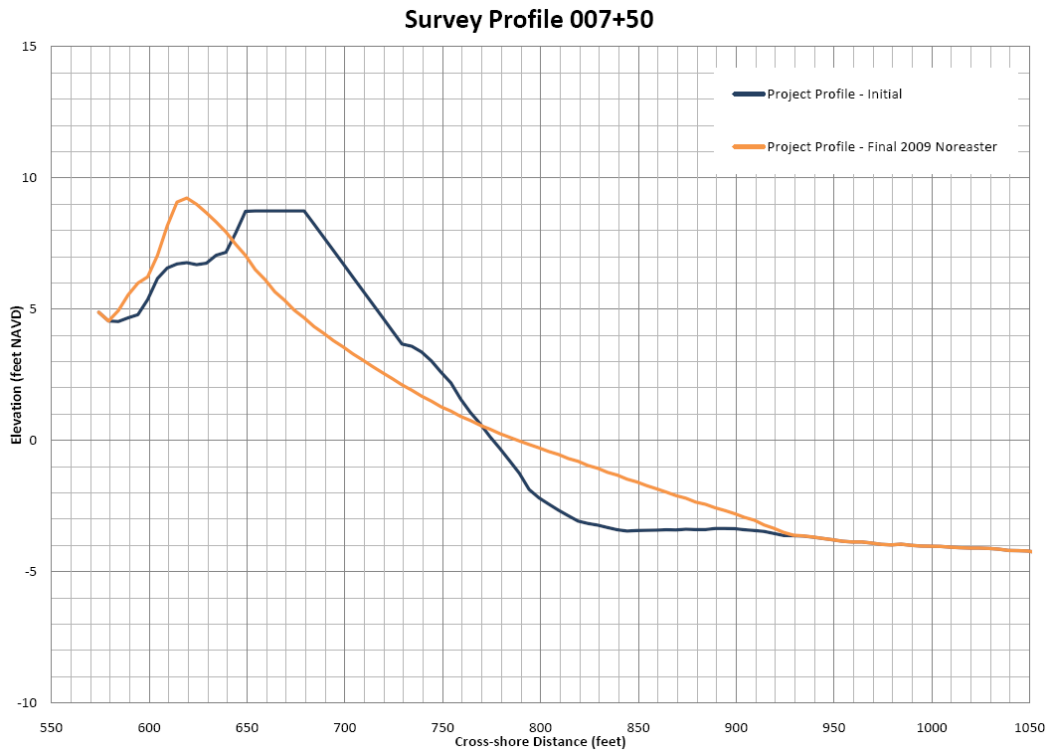

Figure VI-14 SBEACH Results for Dune Project (Sta 7+50, November 2009 Nor'easter)

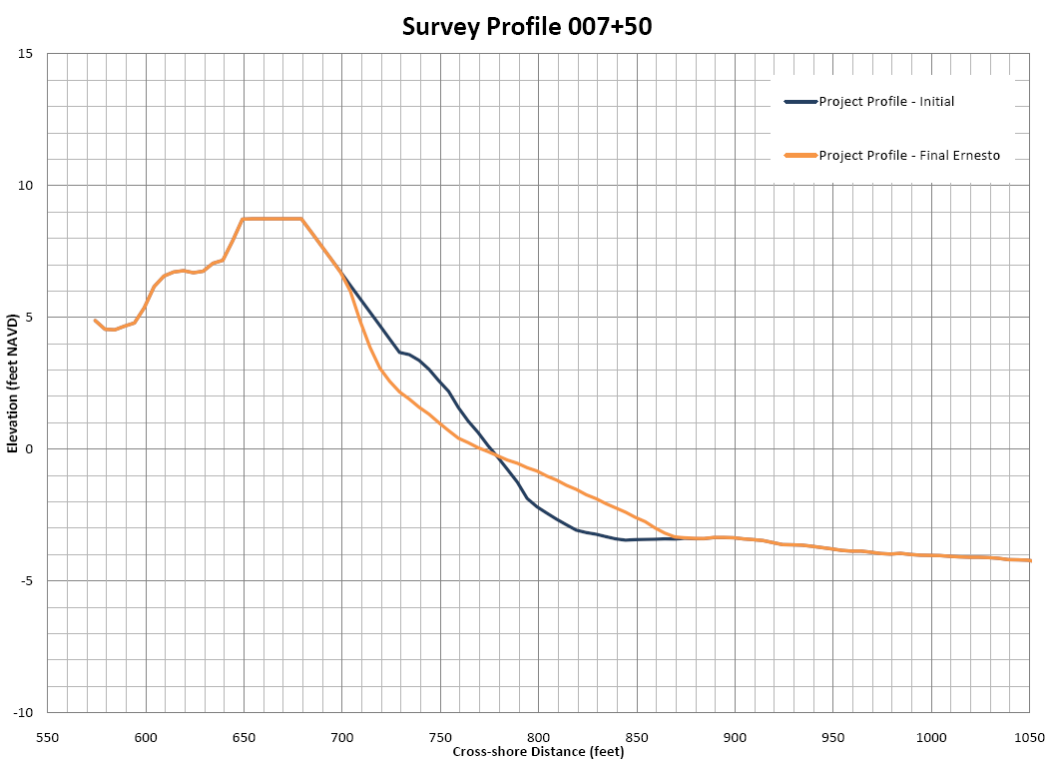

Figure VI-15 SBEACH Results for Dune Project (Sta 7+50, Tropical Storm Ernesto)

As shown in **Figure VI-16** and **Figure VI-17**, the addition of a 45 ft wide berm at the eastern end of the study area (Sta 37+50) will provide additional protection from storms such as the November 2009 nor'easter and Tropical Storm Ernesto. SBEACH model results indicate that while the project portion of the berm could be eroded during the storms, there is still additional protection in place as compared to the existing conditions. It should be noted that in the final alternative, offshore breakwaters would be placed in front of this region, lessoning the impact of storms on the beach nourishment, and therefore the damage estimated by SBEACH is likely larger than what would happen. Therefore, it appears that the beach nourishment project will provide the added protection being sought for the structures in this area.

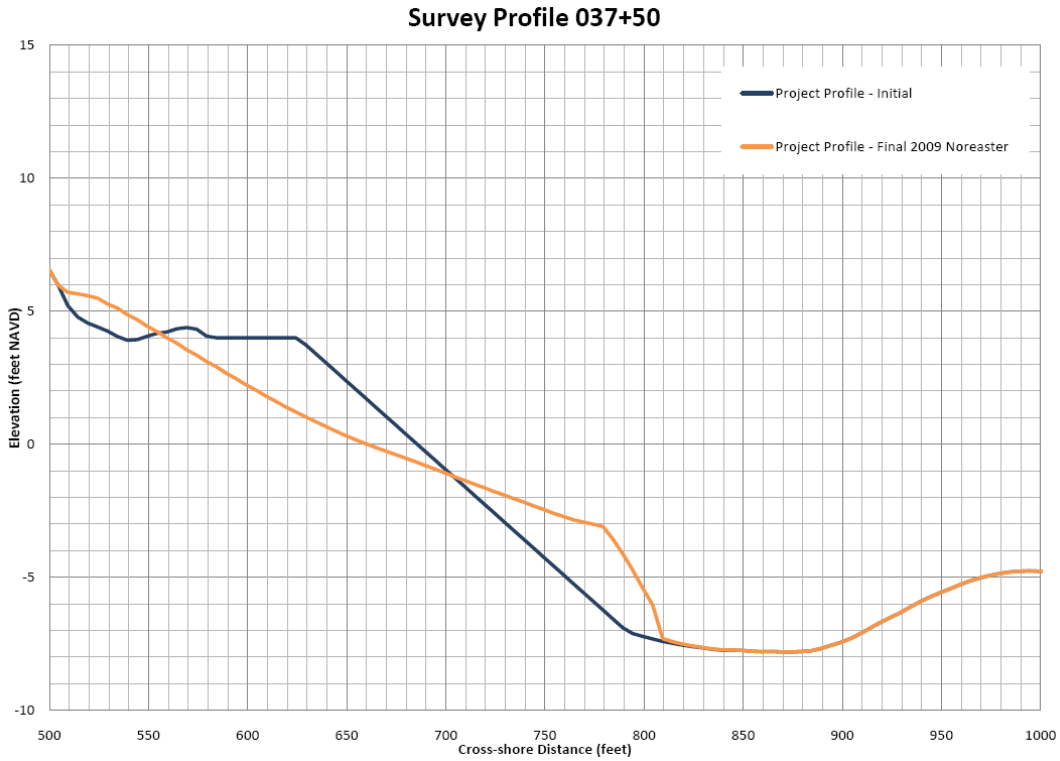

Figure VI-16 SBEACH Results for Nourishment Project (Sta 37+50, November 2009 Nor'easter)

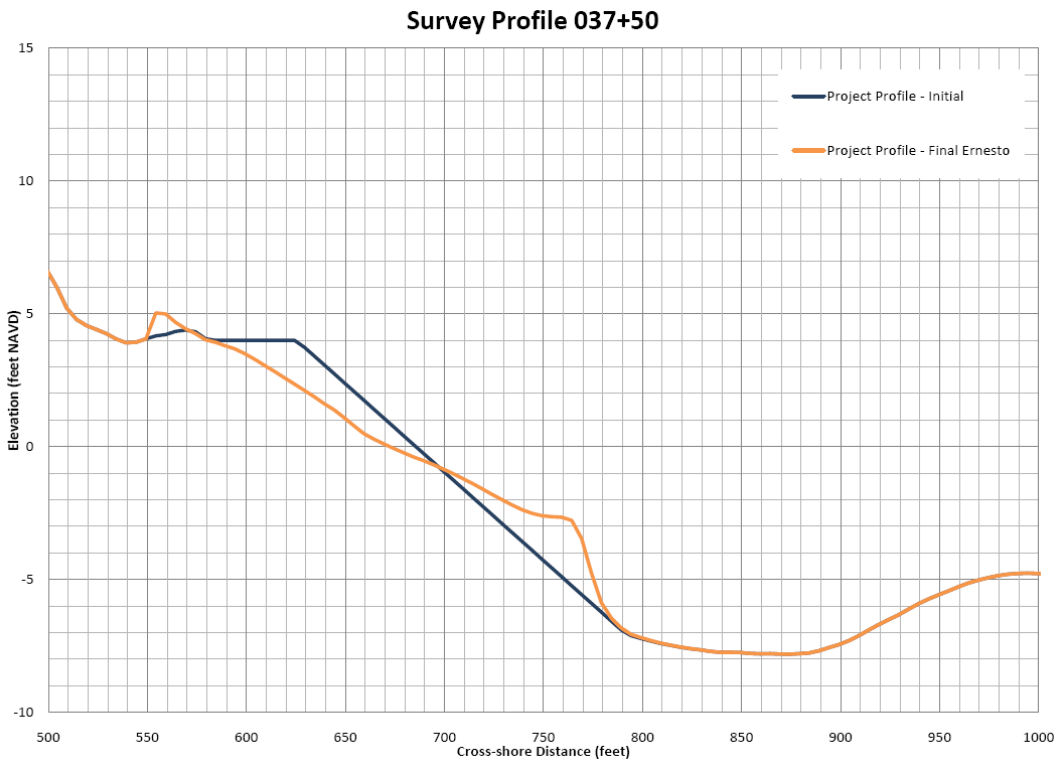

Figure VI-17 SBEACH Results for Nourishment Project (Sta 37+50, Tropical Storm Ernesto)

VII. OPINION OF PROBABLE COSTS FOR MODELED ALTERNATIVES

A preliminary opinion of probable costs was developed for each of the proposed alternatives and is presented in **Table VII-1**. Details of the preliminary opinions of probable costs are presented in **Appendix F**. The unit costs used in the opinions of probable cost were provided by local contractors familiar with constructing these types of projects as well as from past projects completed for the City. In addition to initial costs, lifecycle costs were developed for each of the alternatives to determine what the true long-term costs for each alternative would be. A project design life of 30 years was assumed as well as an interest rate of 3%. Project O&M costs were assumed to be mainly beach nourishment, and GENESIS-T results were used to determine the required renourishment frequency. Using this approach allowed for a fair comparison between alternatives.

Table VII-1 Opinions of Probable Costs for Modeled Alternatives

OPTION	DESCRIPTION	INITIAL COST	30-YR TOTAL COST
1	Remove 7 Existing Groins, Improve Terminal Groin	$660,000	$660,000
2	Remove 7 Offshore Groins, Improve Terminal Groin, Beach Nourishment (≈ 45,000 cy yards every 4 years)	$1,550,000	$4,840,000
3	Remove 7 Existing Groins, Improve Terminal Groin, Add 3 Offshore Breakwaters, Beach Nourishment (≈ 45,000 cy yards every 8 years)	$2,260,000	$3,810,000
4a	Remove 3 Existing Groins, Improve Terminal Groin, Add 3 Offshore Breakwaters, Beach Nourishment (≈ 45,000 cy yards every 8 years)	$2,080,000	$3,630,000
4b	Remove 4 Existing Groins, Improve Terminal Groin, Add 3 Offshore Breakwaters, Beach Nourishment (≈ 45,000 cy yards every 8 years)	$2,360,000	$3,910,000
4c	Remove 5 Existing Groins, Improve Terminal Groin, Add 3 Offshore Breakwaters, Beach Nourishment (≈ 45,000 cy yards every 8 years)	$2,640,000	$4,190,000
5	Remove 7 Existing Groins, Improve Terminal Groin, Add 6 Offshore Breakwaters, Beach Nourishment (≈ 45,000 cy yards every 8 years)	$3,690,000	$5,240,000
6	Remove 7 Existing Groins, Improve Terminal Groin, Add 7 Offshore Breakwaters, Beach Nourishment/Dune Project (≈ 35,000 cy yards initially; 30,000 cy every 8 years after)	$3,650,000	$4,690,000

It was assumed that removal of groins would cost approximately $35,000 per groin due to the increased expense to remove the offshore portions. Improvements to the terminal groin (adding an additional layer of stone) were determined to cost roughly $500 per linear foot of groin. Beach nourishment was determined to cost approximately $15 per cubic yard. Breakwater construction was determined to cost roughly $1,500 per linear foot. These values were used to compute the above mentioned initial and total 30 year costs.

Based on the costs outlines above, it is interesting to note that while some options have lower initial costs (e.g. Option 2), the 30 year total costs can be quite high due to increased maintenance (beach nourishment). The selection of the preferred option should weigh initial and long term costs against the project goals of providing equal protection and improving conditions around the terminal groin.

VIII. SELECTION OF PREFERRED ALTERNATIVE FOR DELFT3D MODELING

Option 6 (**Figure V-16**) was selected as the preferred alternative for further analysis in DELFT3D based on GENESIS-T and SBEACH modeling results and a comparison of probable costs. In this option, all seven (7) of the existing groins were removed and seven breakwaters added offshore, spaced with their centerlines at the old groin positions. The five (5) westernmost breakwaters are 180 ft long while the two (2) easternmost are smaller, at 140 ft and 120 ft long, to avoid impeding the sediment transport around the curve in the shoreline from the 800 Block. This new breakwater field connects the 800 Block breakwaters with the existing breakwaters near the terminal groin at Willoughby Spit. In addition to a new structural configuration, the option included nourishment of the beach in front of Fish Eye Condos and Toler Place with approximately 28,000 cy of material and a 7,000 cy dune project in front of the houses on Lea View Avenue. The GENESIS-T modeling results revealed that this option provided the best equivalent protection shoreline as well as an option for sand recycling from material build up at the western end of the study are near the terminal groin and behind the existing breakwaters as well as from City owned land just east of the existing breakwaters. It would also be an option to use material that passes around and over the terminal groin to the west facing beach once the groin pocket has filled back up. SBEACH results indicated that the beach nourishment and dune project components to Option 6 should be adequate to protect against future storms. The opinion of probable cost for this option is $4.69M (30-yr total cost) with an initial cost of $3.65M. The option was also modeled in DELFT3D as will be discussed in the following **Section IX**, where the results of slight terminal groin improvements were also analyzed to be included with this option (as they could not be analyzed in GENESIS-T).

IX. MODELING OF COASTAL PROCESSES WITH DELFT3D

This section describes the development of a suite of models and a simulation approach used to examine coastal processes (i.e., hydrodynamics, waves, sediment transport, and morphological changes) under existing, and future with project conditions for the selected design alternative presented in the previous section (**Section VIII**).

It should be noted that while the Delft3D model cannot specifically simulate a long-term time series of waves and water levels, it can be used to assess and compare the relative performance of various alternatives under representative hydrodynamic conditions. The Delft3D modeling system is a good complement to a long-term one-dimensional shoreline simulation model.

A. OVERVIEW OF THE DELFT3D MODELING SYSTEM

Modeling of coastal processes for this part of the study was performed using the Delft3D modeling system. Delft3D is an integrated surface water modeling system developed by WL|Delft Hydraulics in the Netherlands. The system is based on a flexible framework which simulates two- and three-dimensional flow, waves, water quality, ecology, sediment transport and bottom morphology and the interactions between those processes. The package gives direct access to state-of-the-art process knowledge, accumulated and developed at one of the world's oldest and most renowned hydraulic institutes. Delft3D consists of a number of well-tested and validated modules, which are linked to and integrated with one-another. Descriptions of the modules used in this study are provided in the following sections.

1. Hydrodynamics: Delft3D-FLOW

The hydrodynamic module Delft3D-FLOW simulates two-dimensional (2D, depth averaged) or three-dimensional (3D) unsteady flow and transport phenomena resulting from tidal and/or meteorological forcing, including the effect of density differences due to a non-uniform temperature and salinity distribution (density-driven flow). This model can be used to predict the flow in shallow seas, coastal areas, estuaries, lagoons, rivers and lakes. When the fluid is vertically homogeneous, a depth-averaged approach is appropriate. Delft3D-FLOW is able to run in two-dimensional mode (one computational layer), which corresponds to solving the depth-averaged equations.

Delft3D-FLOW's system of equations consists of the horizontal equations of motion, the continuity equation and the transport equations for conservative constituents. The equations are formulated in orthogonal curvilinear coordinates. The flow is forced by tide at the open boundaries, wind stress at the free surface, and pressure gradients due to free surface gradients (barotropic) or density gradients (baroclinic). Delft3D-FLOW solves the Navier Stokes equations for an incompressible fluid, under the shallow water and the Boussinesq assumptions.

2. Waves: SWAN Wave Model

The SWAN wave model, developed at Delft University of Technology in Netherlands, is based on the discrete spectral action balance equation and is fully spectral (in all directions and frequencies). The latter implies that short-crested random wave fields propagating simultaneously from widely different directions can be accommodated (e.g. a wind sea with super-imposed swell). SWAN computes the evolution of random, short-crested waves in coastal regions with deep, intermediate and shallow water and ambient currents. The SWAN model

accounts for (refractive) propagation due to current and depth and represents the processes of wave generation by wind, dissipation due to whitecapping, bottom friction and depth-induced wave breaking and non-linear wave-wave interactions explicitly with state-of-the-art formulations. The SWAN model has successfully been validated and verified in several laboratory and complex field cases (Ris et al., 1999).

The SWAN model also has a dynamic interaction with the flow module of Delft3D (i.e. two way wave-current interaction). By this the effect of waves on current (via forcing, enhanced turbulence and enhanced bed shear stress) and the effect of flow on waves (via set-up, current refraction and enhanced bottom friction) are accounted for if the SWAN model is applied within Delft3D.

3. Sediment Transport and Morphology: Delft3D-FLOW

Three-dimensional transport of suspended sediment is calculated in Delft3D by solving the three-dimensional advection-diffusion (mass-balance) equation for the suspended sediment. The local flow velocities and eddy diffusivities are based on the results of the hydrodynamic computations.

Delft3D computes the sediment transport and morphological changes at the hydrodynamic computational time-step. At each time-step, the change in the mass of bottom sediment that has occurred as a result of the sediment sink and source terms is calculated. This change in mass is then translated into a change in thickness of the bottom sediment layer using the density of the bed material. This change in thickness is equivalent to a change in bed elevation, which is applied to the depth values stored at computational points.

The hydrodynamic model implementation used in the sediment transport and morphology model includes the effects of the waves on both nearshore hydrodynamics (i.e., longshore currents and wave setup) and sediment transport (i.e., increased bottom shear stresses and turbulence). It should be noted, however, that the model does not include all of the physics affecting beach profile changes during storm conditions, such as the three-dimensional wave and hydrodynamic processes that generate undertow and offshore sand transport. Nonetheless, this model will provide additional insight into erosion and accretion patterns along Ocean View Beach in the Willoughby Spit project area.

B. MODELING SCOPE AND APPROACH

In addition to the larger scale GENESIS-T modeling for the project, the Delft3D modeling system was used in order to provide insight into sediment transport patterns and morphological changes in the terminal groin area of Willoughby Spit as well as potential morphology changes due to construction of a new breakwater field.

Two hydrodynamic computational models were developed, namely: a large *regional* model of Chesapeake Bay and a *local* model. **Figure IX-1** shows the relative location of both models. The regional model was used to provide hydrodynamic boundary conditions to the local model which was used to simulate hydrodynamics as well as sediment transport and morphological processes at a higher resolution.

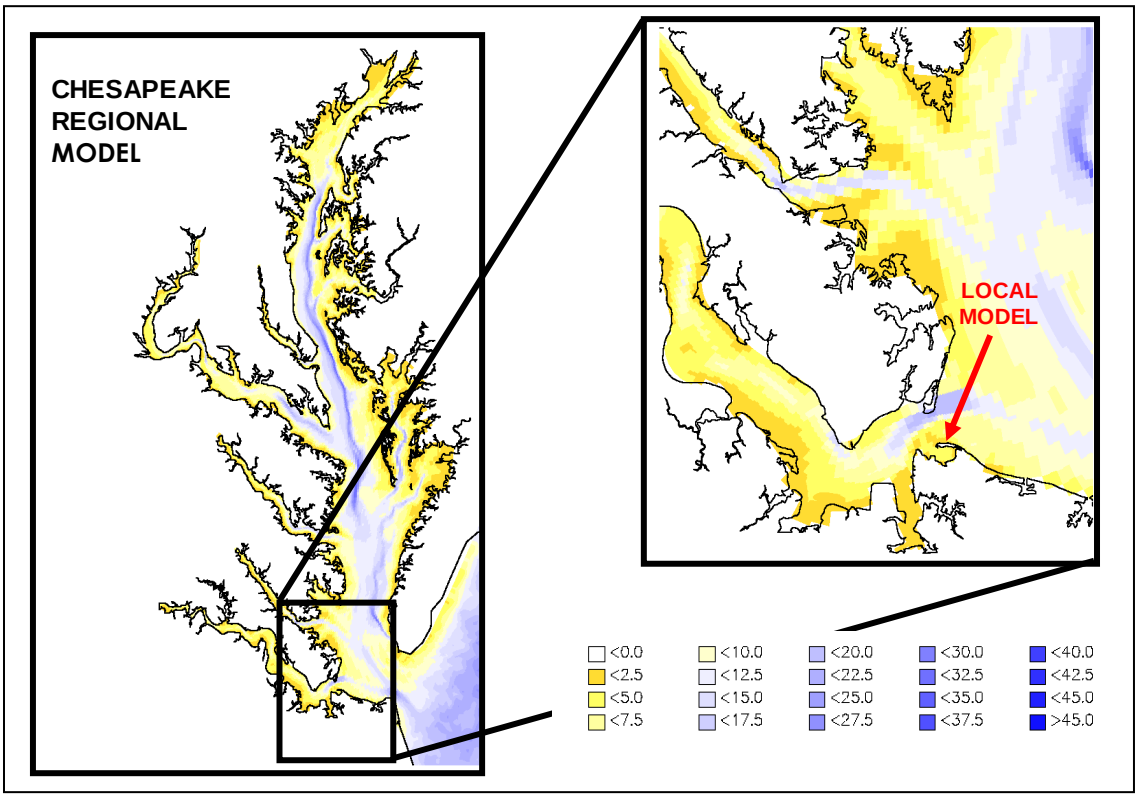

Figure IX-1 Relative Locations of Delft3D Regional and Local Models

C. REGIONAL HYDRODYNAMICS

The Moffatt & Nichol 3D Hydrodynamic model of the Chesapeake Bay was used as the regional model. This model was used in 2D mode to create time series of boundary conditions for the local morphological model of Ocean View Beach. The Chesapeake Bay model extends in the north from the entrance of the C&D canal on the Elk River approximately 200 miles south to the Chesapeake Bay bridge tunnel and then approximately further 100 miles offshore into the Atlantic Ocean. The model is built on a curvilinear computational grid. Over 23,000 computational grid points define the entire model. The grid resolution is variable throughout the model domain. The highest resolution is found at the offshore boundary throat: 11 km grid spacing along the axis of the shoreline and 3.5 km spacing cross shore.

Regional model bathymetry was developed using NOAA data, particularly the NOS estuarine bathymetry for the bay area and the National Geophysical Data Center's GEODAS data sets. These data sources are integrated within the Delft3D modeling system by interpolating the values into the model grid using triangular interpolation. In areas of overlap, the most recent data was used. **Figure IX-1** presents the regional model bathymetry derived from the above sources.

Open boundaries to the model were defined at two locations – at the southern offshore boundary and at the northern most location at the junction of the Elk River with the C&D canal. The offshore boundary is defined as time series of water surface elevations. These time series were constructed from nine major tidal constituents extracted from the *Eastcoast 2001* database of tidal elevation and velocity constituents (Mukai et al, 2002). This database was developed to

allow surface-water elevation and currents to be quickly and easily defined in open waters within the Western North Atlantic Tidal (WNAT) domain. The northern most boundary location of the model is where the C&D canal joins the Elk River at Welch point. Current velocity time series based on NOAA constituents were applied at the boundary. In addition, the major contributions of fresh water into the system are also included. These contributions include the Susquehanna River, Potomac River, and James River.

Simulated and observed water levels and currents were compared at various locations within the bay. Locations were selected so as to assess the model performance to the maximum possible spatial extent. All the calibration data were obtained from NOAA/NOS predictions. After the model calibration, it was concluded that the regional model performs well for both water level and current predictions.

D. LOCAL MORPHOLOGICAL MODEL

Modeling of nearshore hydrodynamics, waves, sediment transport and morphology requires a grid with a relatively fine resolution. The regional grid used for modeling of regional hydrodynamics and waves is not well-suited for this task because increasing resolution in such a large grid would require extremely long simulation times. Therefore, a local high-resolution grid was developed to resolve these nearshore coastal processes along the Willoughby shoreline.

Figure IX-2 and **Figure IX-3** present the local grid and bathymetry, respectively. The grid extends approximately 9,000 feet from east to west; 2,000 feet north to south. The eastern portion of the offshore boundary is located in a water depth of 20 feet. The depth along the western portion of the offshore boundary is ranges from 6 to 10 feet and is influenced by shallow water depths along the Willoughby Shoal. The grid sizes range from 10 feet at the breakwater field to 70 feet near the offshore open boundary. A total of over 64,000 computational points comprise the local grid. The regional grid was used to drive the local grid during model simulations.

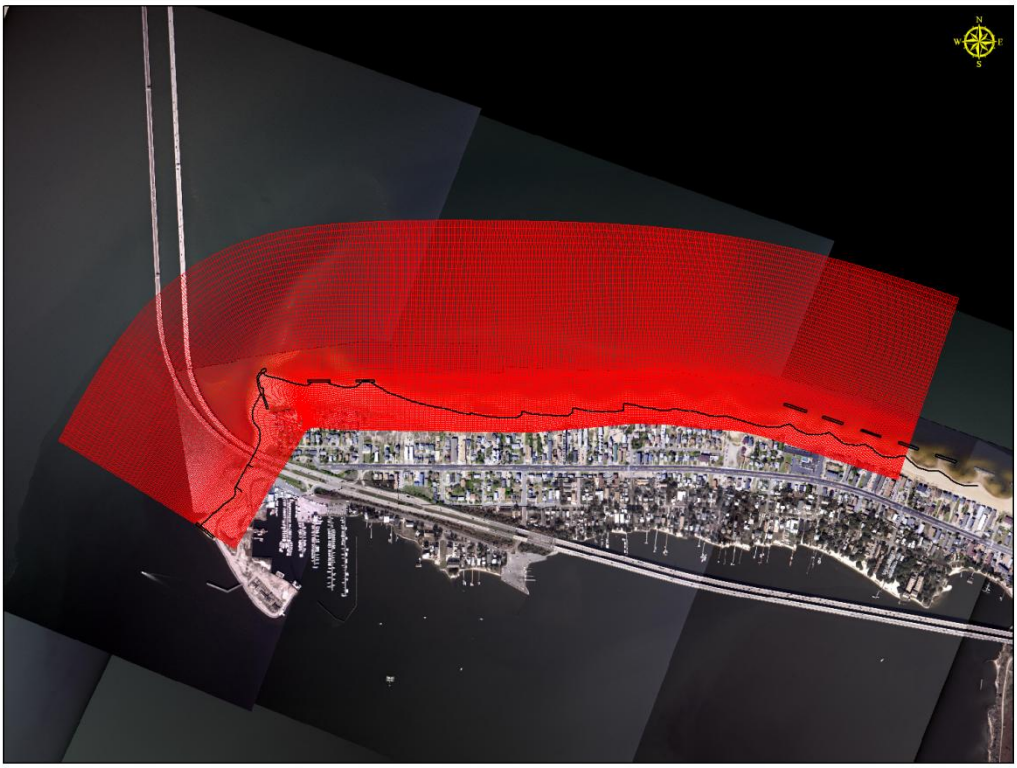

Figure IX-2 Delft3D Local Model Grid and Extent

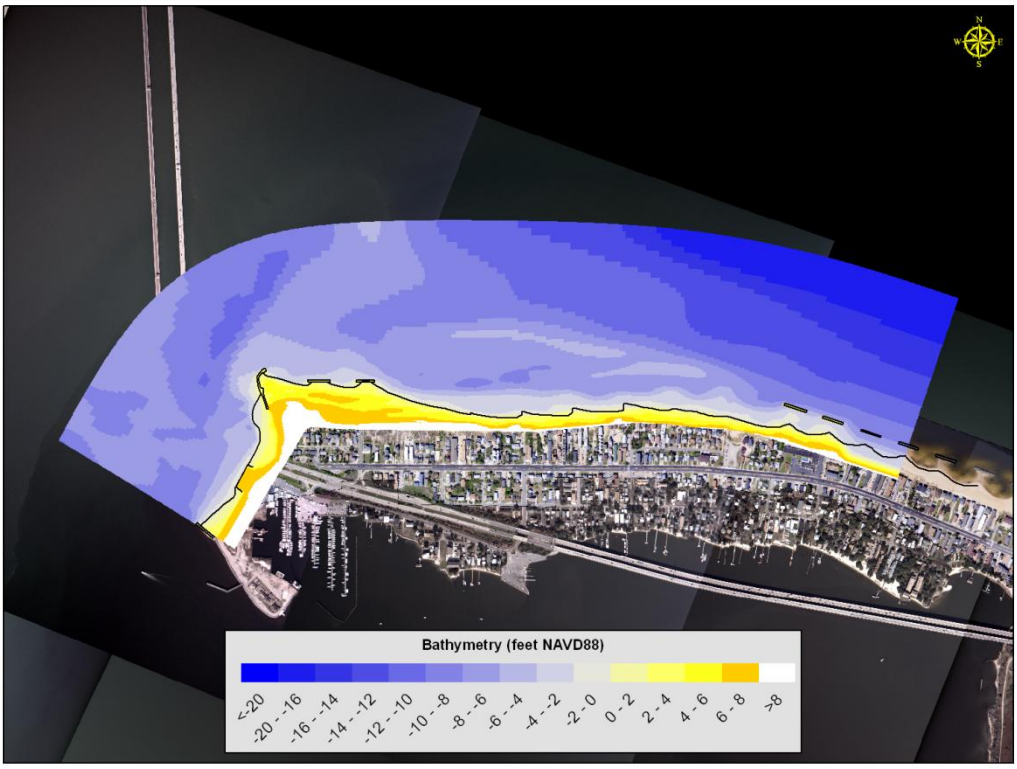

Figure IX-3 Delft3D Local Model Bathymetry, April 2010 (ft NAVD88)

For this application of the Delft3D sediment transport and morphology model, a constant grain size representing the average for the study area was applied throughout the domain: D_{50}=0.40 mm. This value is based on the median grain size of samples from the project site. Sand was modeled with a specific density of 2650 kg/m^3 and a dry bed density of 1600 kg/m^3. Boundary conditions are only required at the open boundaries. Separate boundary conditions are required for suspended and bed load transport. For the suspended sediment transport, the boundary condition during inflow is defined as a concentration equal to equilibrium concentration, and during outflow it is equal to upstream concentration. For the bed load transport, a bed level condition is imposed where the bed level remains constant at the boundary segment.

The Delft3D morphological model integrates the effects of waves, currents and sediment transport on morphological developments. The different processes (hydrodynamics, waves, sediment transport and morphology) are coupled via a bottom evolution model based on sediment conservation, and therefore, the flow fields are always calculated using the latest updated bathymetry. Hence, a local wave model must be developed so that the effects of the waves may be incorporated in the morphological model. The local wave model grid used in SWAN is based on the grid presented in **Figure IX-2** but extended further to the east and to the west. When the incoming wave direction is not perpendicular to the offshore boundary, the wave solution computed by SWAN near the lateral boundaries is not correct, due to the lost of energy through the boundary. Because the wave grid extends further to the east and west than the hydrodynamic model grid, the solution of the wave model is correct throughout the whole hydrodynamic model extent.

E. SIMULATED SCENARIOS

The local Delft3D model was run for two structural configurations.

- Existing Conditions: This scenario is based on the existing structural configuration.
- Option 6: This alternative represents the best solution obtained from all the alternatives tested using GENESIS-T (**Section V.G**).

The local model bathymetry was developed using beach profiles collected during March 2010. The March 2010 survey did not include the area west of the terminal groin. Therefore, beach profiles collected in October 2009, and aerial images from April 2010 were used to develop the bathymetry in this area. All breakwater structures were defined in the model according to their geometry (e.g. crest elevation of +2 feet NAVD88). The elevation of the terminal groin was set equal to +3 feet NAVD88 (which is believed to be equivalent to roughly 4 ft listed on the engineering log-unknown datum).

F. REPRESENTATIVE INPUT WAVE AND SURGE DATA

Detailed modeling over large space and time scales requires excessively long simulation times; consequently wave and water level inputs for local morphological model must be schematized. A five (5) year morphological simulation using the actual wave and water level conditions is not possible. Therefore, a representative wave and water level condition was used to estimate the long term morphological changes resulting from strong storm events.

Previous morphological studies at Block 800 and Bay Oaks concluded that morphological changes in this area primarily result from the action of storm waves. Therefore, the following representative wave and surge conditions corresponding to the approximate 1-year return period were used: significant wave height (H_s) of 5.6 ft, peak wave period (T_p) of 5 s, wave direction (θ) of 22 degrees from the North.

Water level data was obtained from the results of the regional hydrodynamic model and applied at the local model open boundaries. The regional hydrodynamic water level conditions were extracted during a spring tide. An additional surge value of 1.87 feet was added to the water level data based on measured versus predicted values during past storms at Sewells Point. The approximate 1-year return period conditions were applied continuously in the model for approximately 30 days, which is equivalent to roughly five (5) years of storm impacts. It is important to note that this model does not account for natural recovery processes that would take place between storm events. Furthermore, the Delft3D model runs only considered one set of wave conditions while the GENESIS-T modeling considered wave conditions at the site over a 8-yr time period. Therefore, the Delft3D model results do show the expected behavior during strong nor'easters but not the long-term shoreline response as GENESIS-T does.

G. EXISTING CONDITIONS AND PREFERRED ALTERNATIVE MODEL

For the existing conditions, initial model bathymetry was created using the profile information collected in April 2010. Model results indicated that morphological changes to the existing conditions during the simulated period show some erosion of the shoreline, especially at the eastern end of the study area near the 800 Block breakwaters. This is consistent with recent field observations as well as GENESIS-T results from the existing conditions model. **Figure IX-4** shows the initial and final bathymetry for the existing conditions simulation as well as the bathymetry change.

Initial model bathymetry from the existing conditions case was modified slightly for the preferred project case. Sediment was removed from the groin pocket near the terminal groin, behind the existing Willoughby breakwaters, and to the east of the existing breakwaters from the City owned land. Sediment was then added to the eastern end of the study area, just west of the 800 Block, in front of Fish Eye Condos and Toler Place. Seven additional breakwaters were placed offshore in accordance with the proposed alternative (Option 5 from GENESIS-T modeling) and the terminal groin was raised by approximately three (3) ft (equivalent to one additional layer of stone). **Figure IX-5** shows the initial and final bathymetry for the project simulation as well as the bathymetry change. **Figure IX-6** shows how the new breakwaters effectively reduce the wave heights reaching the shoreline, allowing for accretion behind the new breakwaters with salient formation between the breakwaters while not creating additional erosion west of the shoreline bend.

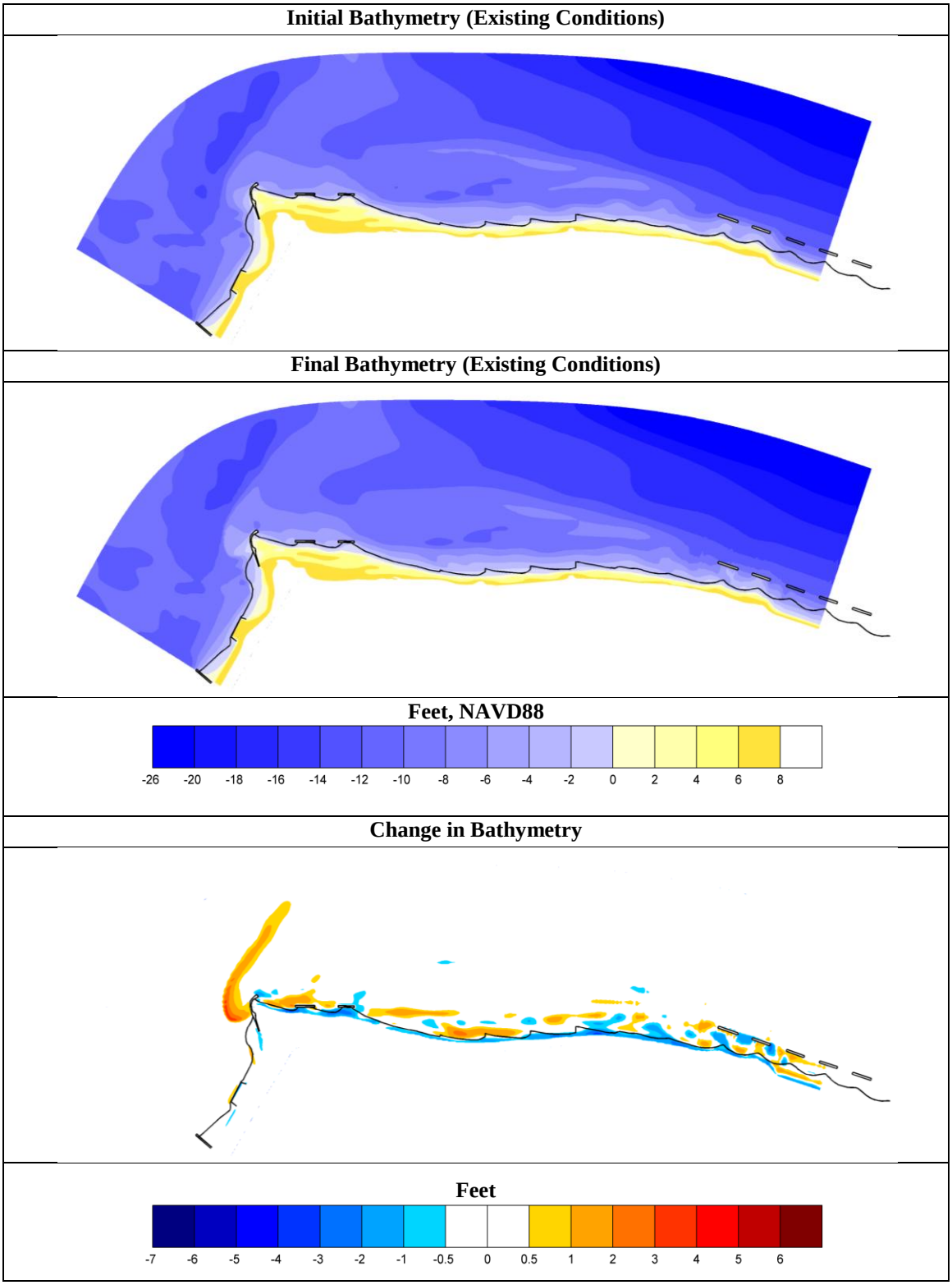

Figure IX-4 Initial and Final Bathymetry (Existing Conditions)

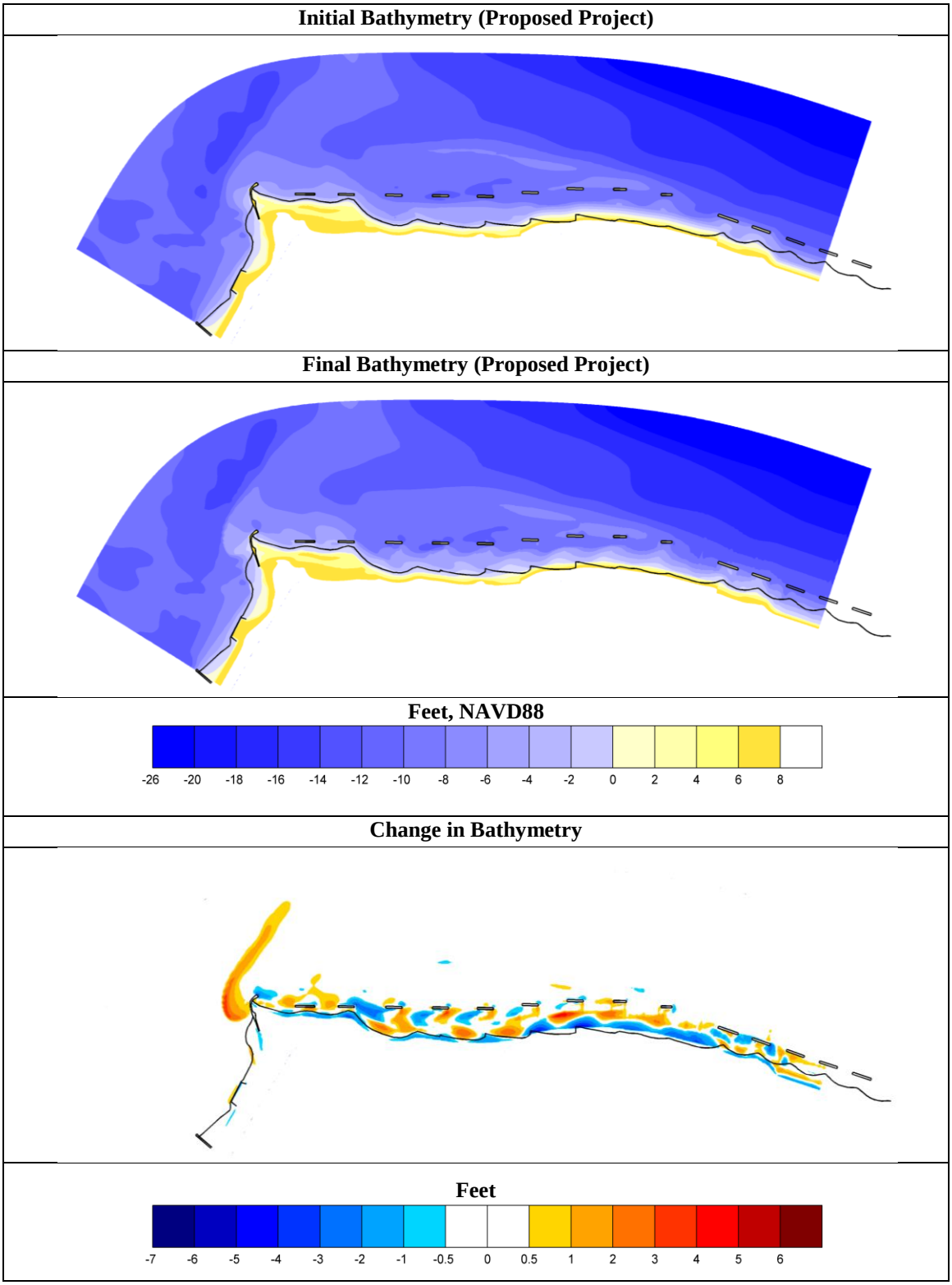

Figure IX-5 Initial and Final Bathymetry (Proposed Project)

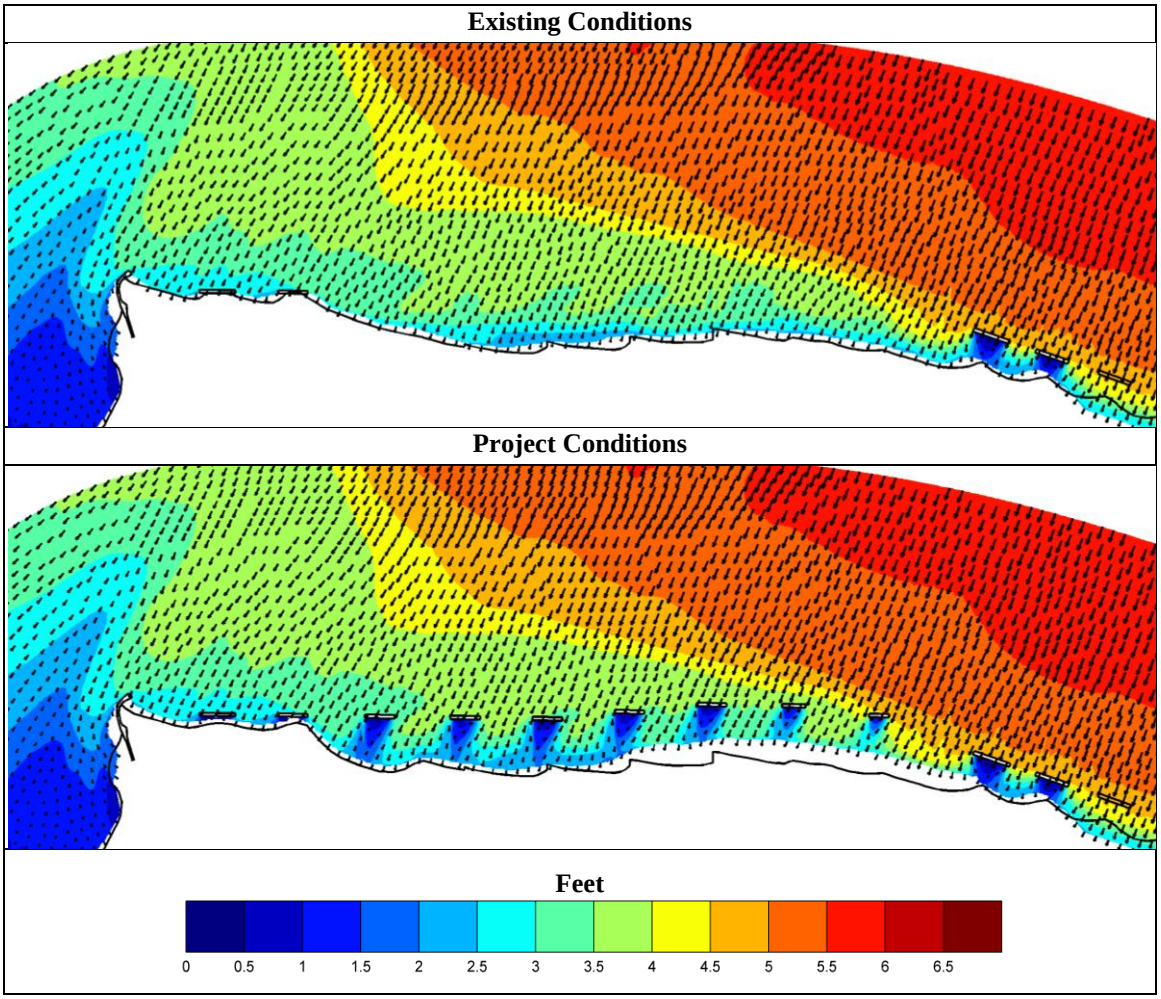

Figure IX-6 Wave Heights for Existing and Project Conditions

Based on the Delft3D model results, the GENESIS-T model results for the preferred alternative (Option 5) have been confirmed. The morphological changes (erosion/accretion patterns) expected due to the new breakwater field show accretion behind the new breakwaters and some erosion at the shoreline due to equilibration of the nourishment project as expected (**Figure IX-5**). In addition, some accretion is evident the groin pocket, behind the existing Willoughby breakwaters, and just east of the existing breakwaters in the areas where material was taken for nourishment of the eastern portion of the study area. This confirms the ability to use sand recycling in this area for future nourishment needs.

One adjustment to the preferred alternative that was considered was to make all of the new breakwaters the same length (180 ft). Delft3D and GENESIS-T both showed increased probability of tombolo formation behind the easternmost breakwaters if they were lengthened to 180 ft. Therefore, it was decided to keep them slightly smaller so as not to impede sediment transport through the area.

H. STUDY OF EXISTING TERMINAL GROIN

In addition to the performance of the new breakwater field, the terminal groin was studied in detail to determine the cause of accretion downdrift of the terminal groin. It was determined from Delft3D modeling that a majority of the material was being transported around the groin from the Willoughby Spit Shoreline as well as from offshore Willoughby Bank. **Figure IX-7** shows the existing sediment transport pattern around the terminal groin as modeled by Delft3D. The strong sediment transport pattern around the groin indicated by the magnitude and direction of the arrows appears to be responsible for a majority of the accretion seen on the downdrift side of the terminal groin. A small portion of material, however, was likely being transported over the terminal groin during storm events. Raising the groin elevation in the Delft3D model showed some minimal effect on trapping more sand, however the dominant issue is transport around the groin. Lengthening the groin was studied in GENESIS-T, but the effects of lengthening were not substantial due to the location of the existing breakwaters immediately east of the terminal groin. Therefore, to improve sand retention as much as possible, raising of the groin is recommended.

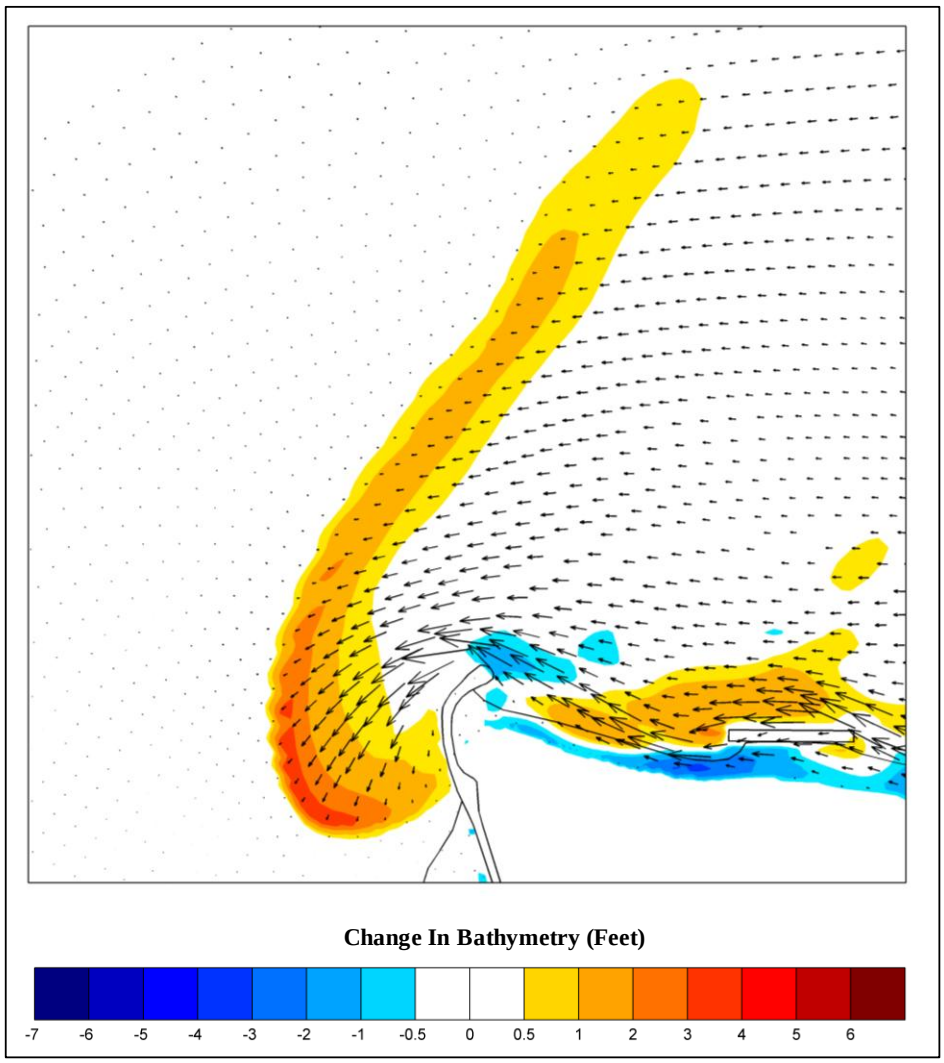

Figure IX-7 Willoughby Spit Terminal Groin Sediment Transport Pattern

X. STUDY FINDINGS & RECOMMENDATIONS

This study involved an extensive review of historical data and engineering activities along the Ocean View shoreline and the Willoughby Spit region in particular. The shoreline behavior in the region was investigated to develop a solution to improve the shoreline position in areas of concern, create a stable shoreline providing equivalent protection to the entire area, and reduce issues with sediment transport through and around the terminal groin. Historical aerial photography, digitized shorelines, beach transect surveys, available sediment sampling data, and measured wave data were examined to aid in the determination of the existing littoral transport patterns and in modeling of potential alternatives. Extensive shoreline change modeling was performed using GENESIS-T (Generalized Model for Simulating Shoreline Change) to examine longshore transport of both the existing conditions and to investigate potential alternatives. Additional aspects were investigated using SBEACH to evaluate cross shore storm induced change of both the existing conditions and any nourishment activities incorporated into the final preferred alternative. DELFT3D was used to verify the GENESIS-T results and examine 3 dimensional morphological changes, especially in the vicinity of the terminal groin.

Analysis of the historical and recent shoreline change indicates that in the past, the groin field has performed well, producing a strong groin signature and stabilizing the shoreline along Willoughby Spit. As expected, the terminal groin and existing offshore breakwaters have been successful in trapping sand and causing accretion at the western end of Willoughby Spit. However, in more recent years, it appears that the timber groin field which exists along the remainder of the Willoughby Spit shoreline has not performed as well, especially during storm events, most likely due to its dilapidated condition. This is an issue in areas like Toler Place and Fish Eye Condos where the seaward position of existing infrastructure relative to adjacent structures already lends itself to a narrow beach. Consequently, equivalent protection along the Willoughby Spit shoreline is an issue with some portions of the beach being less that 100 ft wide while other portions are greater than 200 ft wide. In addition, it appears that littoral transport around the terminal groin to the west facing beach is the main cause of accretion of the west facing beach, with some sediment transport over the terminal groin during storm conditions.

The main goals in developing alternatives were to improve the shoreline position at Fish Eye Condos and Toler Place, create equivalent protection for the Willoughby Spit shoreline, incorporate a sand recycling plan for any potential nourishment which would make use of the abundant material around the terminal groin and existing breakwaters, and maintain the shoreline aesthetic. The basic alternatives examined were to keep the existing conditions, remove the existing groin field, remove just the offshore portion of the groins in conjunction with beach nourishment, and the addition of offshore breakwaters in combination with beach nourishment. Improvements to the terminal groin such as raising the elevation were included in each option.

Erosion typically occurs in the immediate area downdrift of structures such as breakwater fields. The primary objectives of an offshore breakwater system are to increase the longevity of a nourished beach, provide a wider beach for recreation and provide protection to upland areas from waves and flooding. It is important to seek to minimize negative impacts of structures on the downdrift shoreline by allowing some movement of longshore transport through the project area. The resulting shoreline configuration depends on the sediment size, supply, and transport,

beach slope, wave climate, currents, tidal range and breakwater configuration (length, gap, distance from shore, depth). These parameters were all modeled during this study.

The GENESIS-T model configuration and runtime allows comparison of various cases simulating years of shoreline change whereas the Delft3D model requires high computational times and is not suitable to testing a large number of scenarios. Numerous alternatives were modeled with GENESIS-T and the results compared based on the goals of improving the shoreline position at areas of concern, creating equivalent protection for the Willoughby Spit shoreline, reducing the transport of sediment through and around the terminal groin, and maintaining the shoreline aesthetic.

GENESIS-T model results indicate that an ideal shoreline which provides equivalent protection by improving the shoreline position at the current areas of concern and using excess material from near the terminal groin for nourishment can be achieved with the addition of an offshore breakwater field which connects the existing 800 Block breakwater field to the existing offshore breakwaters at the western end of Willoughby Spit. GENESIS-T model simulations show the existing shoreline retreating significantly in front of Toler Place in the next eight (8) years if no action were taken. Initial and periodic beach nourishment will be required as part of an ongoing solution to restore and maintain the beach in this area due to the curvature of the shoreline and influence of the 800 Block breakwater field end effects. The amount and frequency of this nourishment can be reduced by stabilizing the shoreline with offshore breakwaters, reducing the wave climate and associated sediment erosion. The breakwater field will also help to provide more equivalent protection along the Willoughby Spit shoreline. DELFT3D results further indicate that while a majority of the accretion on the downdrift side of the terminal groin is due to littoral transport around the groin from Willoughby Bank, some relief would be provided by elevating the groin, preventing material from overtopping the groin during storms. While the initial cost of this option is significantly higher than options with no breakwater field, the decrease in nourishment interval due to the breakwater field over the next 30 years makes the long-term cost approximately the same and the shoreline would gain more benefits and protection.

Based on the historical shoreline analysis, and the modeling results, the recommended alternative for Willoughby Spit consists of a beach nourishment and dune construction project to mitigate the beach width issue in the current areas of concern and provide additional protection to areas from which sand will be borrowed in combination with the addition of an offshore breakwater field to stabilize the entire shoreline and reduce nourishment frequency. The existing dilapidated groin field would be completely removed. The proposed preferred alternative seeks to balance the need to protect shoreline in areas where existing infrastructure is located seaward of adjacent structures while creating equivalent protection for the remainder of the shoreline as well as improving safety and aesthetics of the beach. The addition of seven (7) offshore breakwaters was chosen to connect the 800 Block breakwater field with the existing breakwaters at Willoughby Spit, eliminating the erosional end effect issue that often accompanies breakwater fields. The breakwaters were staggered offshore with respect to the existing shoreline position and designed with varying lengths, particularly the two (2) nearest the 800 Block breakwater field. These two (2) breakwaters were designed slightly shorter than the remainder of the field so as to avoid any impedance of sediment transport at the bend in the shoreline just west of the

800 Block breakwaters. In addition, this option allows for some sand recycling in which material can be taken from the historically accreting areas nearest the terminal groin (both updrift and downdrift) and placed at areas of concern. Due to littoral transport from east to west in this area, some of the material would eventually return to its initial position and could be used again. Modeling results showed that 28,000 cy of material placed from Leclaire St to Worth St, adding approximately 45 ft of berm width, would address the issues at Fish Eye Condos and Toler Place. In addition, a 7,000 cy dune construction project at Lea View Avenue would add protection to the area from which sand would be borrowed for the previously mentioned nourishment. Sand recycling from both the updrift and downdrift sides of the terminal groin in addition to raising the elevation should help mitigate the issue of accretion of the west facing beach by keeping the groin pocket from overfilling, preventing overtopping, and making beneficial use of any material that does accrete in this area. The addition of a staggered offshore breakwater field, connecting the current 800 Block breakwaters with the existing Willoughby Spit breakwaters, in conjunction with beach nourishment and sand recycling showed an improved shoreline in the areas of concern, equivalent protection along the entire beach, improved aesthetic, and reduction in the frequency of future beach nourishment requirements.

The SBEACH results showed that the nourishment associated with the final alternative will provide additional protection to the Willoughby Spit area. The DELFT3D model results further verify the expected erosion and accretion patterns. These patterns indicate that the new breakwater field will stabilize the shoreline and provide equivalent protection. In addition, sand recycling and terminal groin improvements will help reduce the transport of sediment over the terminal groin.

A preliminary opinion of probable cost for initial construction is approximately $3.65M for removal of the existing groin field, 35,000 cubic yards of beach nourishment, the construction of the 7 offshore breakwaters, and slight improvements to the terminal groin. Assuming renourishment would be required every eight (8) years, the total cost (present worth) is approximately $4.69M over 30 years.

It is recommended that an official sand management program be put in place to deal with excess sediment near and around the terminal groin at Willoughby Spit that may be used for nourishment. It is expected that this sand recycling will need to be completed once every eight (8) years on average (barring large storm events), and the City should monitor conditions (using the spring/fall periodic surveys) around the terminal groin and Fish Eye Condos/Toler Place to determine when the recycling should take place.

XI. REFERENCES

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