Coastal Hazard Analysis

Project Narrative: South Bethany, DE

February 2021

Compass
Identify, Interpret, Integrate

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Glossary

ADCIRC	Advanced Circulation Model for Oceanic, Coastal, and Estuarine Waters, a 2- to 3-dimensional free surface circulation and transport model
AE Zone	Areas of inundation by the 1-percent-annual-chance flood, including areas with the 2-percent-exceedance wave runup elevation less than 3 feet above the ground and areas with wave heights less than 3 feet
AO Zone	Areas of sheet-flow shallow flooding, where the potential wave runup is less than 3 feet above an overtopped barrier
BFE	Base Flood Elevation typically associated with the 1-percent-annual-chance flood
D_{50}	Median value of sand grain size distribution
DEM	Digital Elevation Model
DNREC	Delaware Department of Natural Resources and Environmental Control
ERDC-CHL	USACE Engineer Research and Development Center Coastal and Hydraulics Laboratory
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Study
G&S	FEMA Guidelines and Specifications
GIS	Geographic Information System
LiDAR	Light Detection and Ranging (System)
LiMWA	The Limit of Moderate Wave Action indicates the inland location where coastal wave heights equal 1.5 feet under base flood conditions
LOMR	Letter of Map Revision
MIP	Mapping Information Platform
MLLW	Mean Lower Low Water
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988. All elevations in this report are referenced to NAVD88, unless otherwise specifically noted.
NCMP	National Coastal Mapping Program
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
PFD	Primary Frontal Dune
PM	Procedure Memorandum
RAMPP	Risk Assessment, Mapping and Planning Partners

SFHA	Special Flood Hazard Area, the land area covered by the floodwaters of the base flood (including Zones A, AO, and VE)
SPM	Shore Protection Manual
SWAN	Simulating Waves Nearshore, two-dimensional shallow water wave model
SWEL	Stillwater Elevation (inclusive of wave setup)
TAW	Technical Advisory Committee for Water Retaining Structures, structure runup methodology
USACE	United States Army Corps of Engineers
VE Zone	Velocity Zone, coastal high hazard areas where wave action and/or high-velocity water can cause structural damage during the base flood
WHAFIS	Wave Height Analysis for Flood Insurance Studies
WISE	Watershed Information SystEm
X Zone	Areas above the 1-percent-annual-chance flood level

1. Introduction

Compass performed the detailed flood hazard analysis and mapping tasks for the Town of South Bethany, Sussex County, Delaware. This report serves as the project narrative for the coastal hazard analysis and floodplain mapping conducted for the updated Flood Insurance Study (FIS), to be submitted as a Letter of Map Revision (LOMR). The revised area is in the eastern portion of the Town of South Bethany, between the Coastal Highway/Route 1 and the eastern limit of the coastal mapping, usually located 500 to 1,000 feet seaward of the shoreline.

FEMA guidelines applicable to this study consist of:

- Atlantic Ocean and Gulf of Mexico Coastal Guidelines Update (February 2007)
- Guidance for Flood Risk Analysis and Mapping: Overland Wave Propagation (2015a)
- Guidance for Flood Risk Analysis and Mapping: Coastal Erosion (2018a)
- Guidance for Flood Risk Analysis and Mapping: Coastal Floodplain Mapping (2019a)
- Guidance for Flood Risk Analysis and Mapping: Coastal Wave Runup and Overtopping (2018b)
- Guidance for Flood Risk Analysis and Mapping: Coastal Structures (2019b)
- Guidance for Flood Risk Analysis and Mapping: Coastal General Study Considerations (2019c)

These reports provide guidance, standard methodologies, and technical approaches pertinent to modeling and mapping of coastal hazards and are collectively referenced as the 'FEMA G&S' in this document. In addition, coastal flood study procedure memorandums (PMs) that apply to Atlantic Coast studies were followed.

2. Transect Layout

The transect layout at South Bethany was based on the effective Sussex County FIS completed by Risk Assessment, Mapping and Planning Partners (RAMPP) in October 2014 (FEMA 2018c). The transect layout for this study is shown in Figure 1. Transects with IDs 1610, 1620, 1640, and 1645 were incorporated from the study. Transect 1595 was added at the north border of South Bethany to represent areas north of Ocean Drive. Transect 1630 was added to reduce spacing between transect 1620 and 1640. Transect 1600, previously modeled in the RAMPP study, was removed because it was not regionally representative of the dune feature to the north or south. As shown in Figure 2, the large dune feature at Transect 1600 was not a longshore consistent representation of the area.

Figure 1. South Bethany transect layout

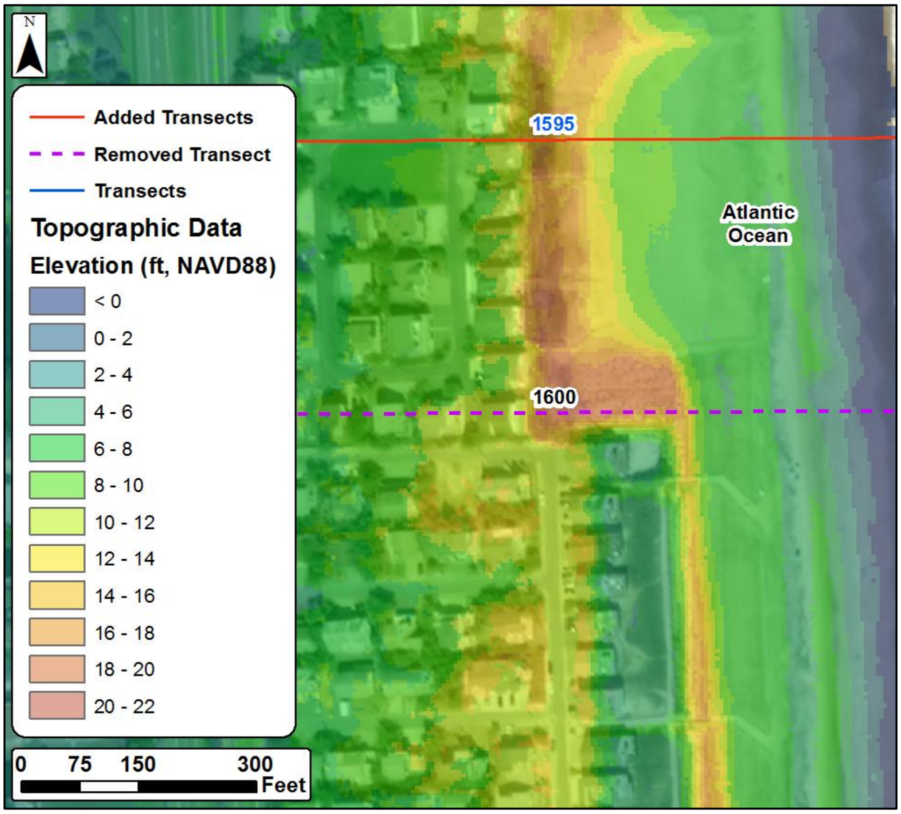

Figure 2. Topographic illustration of Transect 1600

Compass found one LOMR for the Town of South Bethany during review. However, this LOMR did not require incorporation into the revised mapping since the it was located outside of the revised area.

3. Data Sources

The following subsections describe the sources of the data that were collected or developed for use in the coastal flood hazard analyses. Details on how the data were processed or modified for use in specific analyses are contained in the respective sections.

3.1. Topography and Bathymetry

A seamless topographic-bathymetric Digital Elevation Model (DEM) was created to support the coastal hazard analysis within the study area. The DEM is composed of a collection of digital topographic and bathymetric data consolidated from various sources. The topographic data used in the effective Sussex County FIS was from 2005 (FEMA 2018c).

The predominant source for topographic data used for this LOMR was topobathy LiDAR collected by the U.S. Army Corps of Engineers (USACE) National Coastal Mapping Program (NCMP) in

2017, which was available as a 1-meter raster from the National Oceanic and Atmospheric Administration (NOAA) Data Access Viewer (https://coast.noaa.gov/dataviewer/). The data were downloaded on May 14, 2020. The horizontal projection of the data was in North American Datum of 1983 (NAD83) State Plane Zone 0700 Delaware Feet with elevations in feet, relative to North American Vertical Datum of 1988 (NAVD88). LiDAR was collected by USACE on behalf of the USACE NCMP from August 16, 2017, to August 19, 2017.

The bathymetric data comprised a combination of data from different sources, one of which was beach profile surveys collected by USACE at South Bethany for Hurricane Ida (2009) and Hurricane Sandy (2012a). The remaining sources of bathymetric data were from the 2017 USACE NCMP topobathy LiDAR on the East Coast and National Ocean Service (NOS) hydrographic surveys. The NOS hydrographic surveys were downloaded from the NOAA National Centers for Environmental Information (https://www.ngdc.noaa.gov/) for surveys H11648 and H11649 on May 14, 2020. The data were available as XYZ points with 50-centimeter and 1-meter spacing. The data for survey H11648 were collected between July 21, 2007, and November 11, 2007, while the data for survey H11649 were collected between August 17, 2007, and November 18, 2007. The data were in NAD83 State Plane Zone 0700 Delaware Feet horizontal projection with elevations in Mean Lower Low Water (MLLW) with units in feet.

As the hydrographic survey data listed above was collected prior to the 2008 beach nourishment, the nearshore bathymetry of these datasets differed significantly from the nearshore bathymetry included in the 2017 USACE NCMP topobathy dataset. A 2016 USACE survey profile dataset was found to closely correspond with the nearshore bathymetry of the 2017 USACE NCMP dataset and the offshore bathymetry of the hydrographic survey datasets; therefore, the survey profile data was leveraged to supplement the nearshore bathymetry of these areas. The data sources were prioritized, merged, and vertically converted to a common datum using the NOAA VDatum tool. The topographic and bathymetric datasets were projected and transformed into the vertical datum of NAVD88 and horizontal projection (i.e., State Plane Coordinate System) before being merged into the final DEM. All elevations in this report are referenced to the NAVD88. Topographic and bathymetric data source footprints are illustrated in Figure 3.

The source 2017 USACE NCMP topobathy data raster contained data voids over building footprints. Accordingly, the 2017 USACE NCMP 1-meter raster was converted to points and saved within a file geodatabase feature dataset, and an Esri terrain was created to interpolate the surface over the building footprints. The 2017 USACE NCMP points, beach profile survey data, and NOS hydrographic survey XYZ points were used as feature classes to create a seamless topobathy terrain. The seamless terrain was exported to a 5-foot raster. A new Watershed Information SystEm (WISE) Terrain Analyst (WTA) project was created from the 5-foot raster. The WTA tile index was set at 2,500 feet. The final seamless terrain elevations are shown in Figure 4.

The 0-foot contour derived from the DEM was used as the modeling baseline and starting station for all transects in the Wave Height Analysis for Flood Insurance Studies (WHAFIS) model.

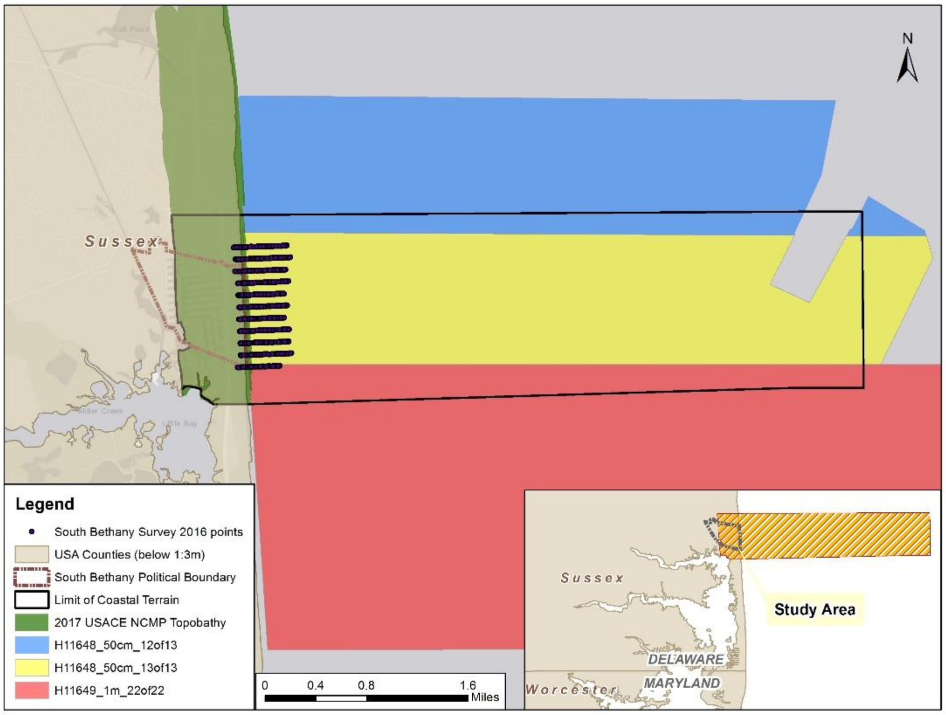

Figure 3. Topographic and bathymetric data sources contributing to DEM

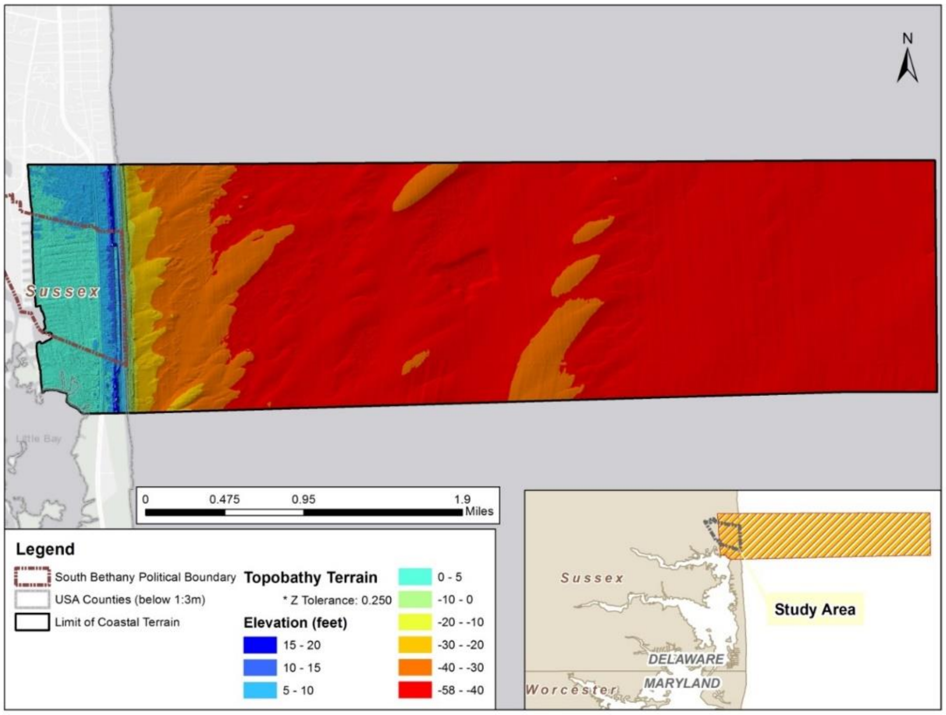

Figure 4. Terrain elevations for the South Bethany project area

3.1.1. Beach Nourishment

The loss of sand during coastal storm events can lower beach berms and push the shoreline farther inland. Some beaches may naturally recover from this erosion over time; however, the reduced beach profile can allow larger waves to propagate inland during storm events, reducing the beach's ability to function as a barrier to storm surge.

The intent of beach nourishment is to restore the shoreline and protect it from storm events. Such projects require periodic re-nourishment to replenish fill that is eroded over time. Consequently, the level of storm protection offered is constantly changing, being at a maximum immediately following the fill event and decreasing over time until the next nourishment takes place.

Nourishment projects are typically designed for higher frequency storm events and not the 1-percent-annual-chance event, although they may influence the flood hazard assessment. If fill volumes remaining in the project area are evident at the time of topographic data collection, overland wave propagation and wave runup modeling could be affected. Such nourishment projects were investigated in South Bethany to evaluate the effect on the flood modeling and mapping along the open coast.

South Bethany has been nourished several times historically, and particularly in response to storm-based erosion events. Prior to 2007, aerial imagery shows little or no evidence of vegetated dunes between oceanfront homes and the shoreline along Ocean Drive. More recent nourishment efforts began in 2007 and contributed to the more pronounced nourished dune and beach berm that are evident today. The Bethany Beach/South Bethany Coastal Storm Damage Reduction Project provided hurricane and coastal storm damage reduction measures consisting of beach and dune sand fill, in two independent segments, for both Bethany Beach and South Bethany. The project included a 150-foot-wide berm with an elevation of +7.0 feet NAVD88, and a dune with an elevation of +16.0 feet NAVD88. The project recommended providing 3.5 million cubic yards of initial beach fill, with subsequent nourishment of 480,000 cubic yards every 3 years. The initial construction was completed in June 2008. The project has been repaired/nourished multiple times since then. Table 1 lists the nourishment activities from the start of the Bethany Beach/South Bethany Coastal Storm Damage Reduction Project (2008) relative to the date of LiDAR collection for this study (2017). This project is still authorized through 2057. Nourishment volumes and project lengths were provided by the National Beach Nourishment Database (ASBPA 2020).

Table 1. Nourishment Activity between 2008 and 2017 (ASBPA 2020; USACE, 2020a; USACE 2020b)

Date	Activity	Volume (cy)	Length (ft)
June 2008	Initial Construction Completed	3,437,200	14,784
Jan. 2009 – June 2009	Emergency Repair	200,000	14,784
Oct. 2010 – Oct. 2011	Periodic Nourishment	1,300,000	10,500
Aug. 2013 – Sept. 2013	Flood Control and Coastal Emergency (FCCE) Repair	973,000	24,446
Aug 2017	LiDAR collection	-	-
June – July 2018	FCCE Repair & Periodic Nourishment	1,059,653	8,600
Sept. 2020	Contract Award for Periodic Nourishment	732,000	-

The nourishment inherent within the 2017 DEM was analyzed with respect to FEMA's *Guidance for Flood Risk Analysis and Mapping: Coastal General Study Considerations* (2019), which defines beach nourishment as a temporary disturbance. Temporary disturbances could affect flood hazard modeling during short-term periods but are not expected to persist on long-term time scales commensurate with the duration of an effective flood study (i.e., 5 to 20 years). Where temporary disturbances exist, the Mapping Partner should review available historical data to ensure that the modeling profiles reflect equilibrium conditions.

According to our review of the aerial imagery at South Bethany, the nourished footprint of the beach has been in place for nearly 13 years. Figure 5 shows the aerial images in the north of South Bethany Beach before the nourishment events in 2007, and after nourishment activities since 2008. Figure 6 shows the aerial imagery of the same area taken in 2017.

Figure 5. Aerial imagery of South Bethany Beach before and after nourishment

Figure 6. Aerial imagery of South Bethany Beach on 4/9/2017

Based on the analysis of beach survey profiles taken by USACE from 2012 to 2016, the 2017 LiDAR does not represent the maximum beach profile experienced at South Bethany, but more of an average, equilibrium geometry, as shown in Figure 7. Note the example survey profile 008 corresponds to the location of the numbered profile shown in Figure 17. Due to the length of record of nourishment maintenance at South Bethany, there is not sufficient justification to revert back to a pre-nourishment profile condition at this site, as it would not be representative of prevailing conditions. The 2017 LiDAR falls within a reasonable envelope of survey profile extents and does not reflect an anomalous beach profile condition with respect to recent history; this 2017 dataset was assumed to reflect prevailing conditions for this study. Thus, the 2017 LiDAR dataset was leveraged as a more representative surface for modeling and mapping flood risk at South Bethany Beach.

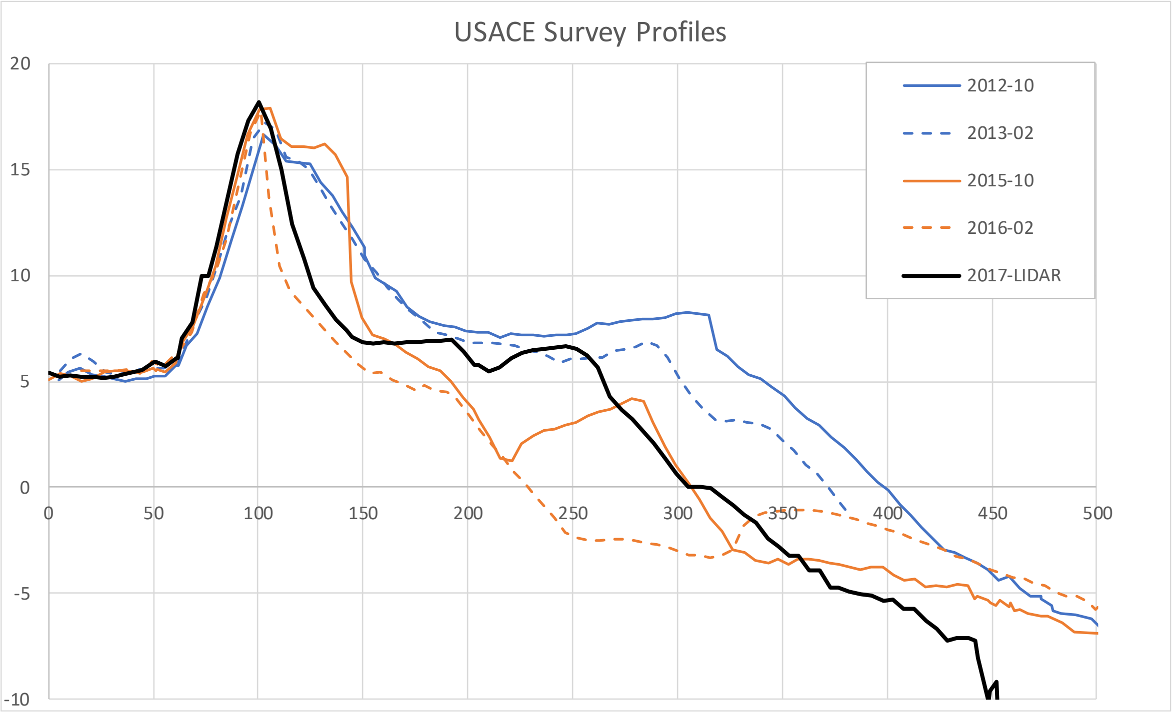

Figure 7. Survey Transect 008 changes from USACE beach survey (see Figure 17 for survey location)

3.2. 1-Percent-Annual-Chance Total Stillwater Levels

Stillwater Elevations (SWELs) for the 10-, 2-, 1-, and 0.2 percent-annual-chance exceedance levels for the Delaware Bay and the Atlantic Ocean were determined from the 2013 storm surge study conducted for FEMA Region III by USACE and its project partners under Project HSFE03-06-X-0023, "NFIP Coastal Storm Surge Model for Region III" and Project HSFE03-09-X-1108, "Phase II Coastal Storm Surge Model for FEMA Region III." The work was performed by the Coastal Processes Branch of the Flood and Storm Protection Division Engineer Research and Development Center Coastal and Hydraulics Laboratory (ERDC-CHL).

The study involved an end-to-end storm surge modeling system including the Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters (ADCIRC) for the simulation of two-dimensional hydrodynamics. ADCIRC was dynamically coupled to the unstructured numerical wave model Simulating Waves Nearshore (SWAN) to calculate the contribution of waves to total storm surge (USACE, 2013b). The resulting model system is typically referred to as SWAN+ADCIRC. A seamless modeling grid, covering all of coastal FEMA Region III and more, was developed to support the storm surge modeling efforts. The modeling system validation consisted of comprehensive tidal calibration followed by validation using carefully reconstructed wind and pressure fields for three major flood events for the Region III study area: Hurricane Isabel, Hurricane Ernesto, and extratropical storm Ida (also referred to as "Nor'Ida"). Model accuracy was assessed by quantitatively comparing model output to wind, wave, water level, and high-water mark observations.

A total of 156 synthetic tropical and 30 historical extratropical storms were simulated, and the maximum modeled water levels for each storm were compiled and statistically analyzed to determine the return period stillwater levels. Full documentation of the storm study methodology and results is included in FEMA Region III Storm Surge Study Coastal Storm Surge Analysis Intermediate Data Submittal Nos. 1, 2, and 3 (USACE, 2011, 2013a, 2013b).

3.2.1. Input SWEL Conditions and SWEL Surface

The SWEL surface generated from the effective Sussex County FIS was used in this analysis. For use in erosion and runup analyses, input SWEL conditions were determined from the intersection of the open coast SWEL with the topographic profile for each transect. Consistent with effective modeling, SWEL conditions varied along each overland wave modeling profile (WHAFIS) based on the values of the SWEL surface along each transect. Table 2 lists the SWEL values for each of the WHAFIS model transects for the 1-percent-annual-chance model runs.

3.3. Starting Wave Conditions

Offshore starting wave conditions are required for WHAFIS modeling. The storm surge study provided significant wave heights (H_s) and peak wave periods (T_p) at each node contained in the ADCIRC mesh (USACE, 2013b). These results provided the wave conditions that could be expected during the types of extreme storm events that would produce 1-percent-annual-chance storm surge elevations. Results from the SWAN+ADCIRC modeling were used to develop starting wave conditions for the coastal hazard analyses within the study area.

Table 2. Starting Conditions for the 1-Percent-Annual-Chance WHAFIS Modeling

Transect	Flood Source	1%-Annual-Chance Starting Conditions		
		SWEL (ft)	Significant Wave Height H_s (ft)	Peak Wave Period T_p (sec)
1595	Atlantic	8.19	17.0	12.7
1610	Atlantic	8.18	16.8	13.1
1620	Atlantic	8.09	16.8	12.7
1630	Atlantic	8.01	16.8	12.7
1640	Atlantic	8.05	16.6	13.0
1645	Atlantic	8.04	16.6	12.9

3.3.1. 1-Percent-Annual-Chance Wave Conditions

The starting wave conditions used for this study were taken from the effective FIS starting wave condition surfaces. Starting wave conditions for each transect were selected from approximately 1,250 to 1,500 feet offshore so that wave conditions were extracted near the offshore extent of

Runup 2.0 modeling profiles, while still offshore of the depth of breaking. Table 2 lists the starting wave conditions for each of the WHAFIS model transects for 1-percent-annual-chance model runs.

3.4. Land Use Data

Land use information is used to create parameters for obstructions and open-fetch areas for the WHAFIS modeling. Compass created land use polygons based on the RAMPP study and ESRI aerial imagery, dated 9/11/2019.

4. Coastal Flood Hazard Analyses

4.1. Erosion Analysis

Compass conducted an erosion analysis for the South Bethany modeling transects along the Atlantic Ocean shoreline. Due to the beach profile geometry and the observed erosion trends at this site, several historic erosion events and erosion methodologies were evaluated to ensure that a suitable erosion approach was applied at this site. Based on the data provided by the Delaware Department of Natural Resources and Environmental Control (DNREC) and South Bethany local officials, the actual erosion experienced in this area could be greater than what would be modeled using a standard FEMA erosion analysis. A Modified Erosion Method was found to provide a more accurate representation of erosion at this site. The following subsections outline the historic erosion noted at this site, the site conditions, erosion trends, and alternative erosion methods that contributed to the determination of the final Modified Erosion Method.

4.1.1. Historic Erosion in South Bethany

Erosion from several tropical cyclones and winter storms has been documented at South Bethany. The most severe case of storm damage occurred from the Ash Wednesday Storm in 1962, during which most structures in South Bethany were destroyed. Figure 8 and Figure 9 show images of South Bethany documented from archived aerial video footage and photos captured after the storm.

Figure 8. Still image of flyover video footage taken of South Bethany after the Ash Wednesday Storm （Delaware Public Archives, 1962）

Figure 9. Image of post-storm damage to South Bethany (Delaware Public Archives, 1962)

In the 1990s, winter storms impacted South Bethany and caused overwash and damage to Ocean Drive. Storm damage from a January 1992 event was noted in a Delaware Geological Survey Report: “Washovers were common in South Bethany. Scarping and erosion of the road behind the first row of houses was common. Sewer lines and well heads were exposed and damage to wells was common” (Ramsey and Tally, 1992). Images from a 1994 winter storm in Figure 10 show damage to oceanfront homes, overwash and damage to Ocean Drive, and an exposed revetment fronting the roadway. The damage resulting from these storms resulted in relatively small-scale emergency nourishments in 1992, 1994, and 1998. Flooding in South Bethany was also documented due to the effects of Hurricane Isabel in 2003.

Figure 10. 1994 post-storm photos, South Bethany (Cannon, 1994)

After completion of the 2008 Bethany Beach/South Bethany Coastal Storm Damage Reduction Project, significant dune and berm features were constructed along the shoreline. More recent storms have had an erosion impact on the nourished features at South Bethany, including Nor’Ida (2009), Hurricane Sandy (2012), and most recently a winter storm in January 2016. Post-nourishment erosion from these storms was characterized by shoreline retreat and dune scarping. In one small area near the southern portion of South Bethany, the dune was breached during the 2016 storm, causing overwash and flooding of the swale between the nourished dune and the oceanfront homes, as shown in Figure 11 and Figure 12. Survey-based documentation of the storm-induced erosion impacts from the post-nourishment storms is detailed in Section 4.1.3.

Figure 11. 2016 post-storm dune erosion at South Bethany (Murray, 2016)

Figure 12. 2016 post-storm flooding at South Bethany (Murray, 2016)

4.1.2. Current (2020) Conditions

Review of historical imagery, survey data, and LiDAR and discussion with local officials has documented a number of changes to the site conditions at South Bethany since many of the historic storms impacted the area prior to 2008, including the Bethany Beach/South Bethany Coastal Storm Damage Reduction Project that provided a vegetated dune system and moved the shoreline farther seaward of oceanfront parcels. Discussion with DNREC provided details on a buried rock revetment that was constructed along the seaward edge of Ocean Drive. Figure 13 shows an example of an oceanfront home on Ocean Drive in 1994, compared to more a recent Google Street View image of the same location. The image comparison shows an older exposed revetment at the edge of Ocean Drive. The newer image shows a higher road elevation relative to the home, with gravel parking at the location of the previous revetment.

Figure 13. Conditions of oceanfront home in South Bethany in the 1990s (left - Cannon, 1994) compared to more current Google Street View captured in July 2014 (right)

Based on information from DNREC, a more recent revetment was incorporated along the majority of the seaward edge of Ocean Drive following a 1998 disaster declaration in response to storm damage of Ocean Drive and utilities. A typical section of the 1999 revetment design is shown in Figure 14. Note that the horizontal location of the landward extent of the revetment crest aligns with the eastern shoulder of Ocean Drive. Local observations of this structure during storm activity noted that the revetment has largely prevented severe erosion of Ocean Drive, but has been subject to overtopping. The crest elevation of the structure was shown as 10.5 feet, relative to Mean Low Water, which converts to approximately 8.33 feet NAVD88. The crest elevation was lower than the elevation of Ocean Drive, which was approximately 11 to 12 feet NAVD88. In many cases, the top of the revetment has been covered with gravel and is used for parking.

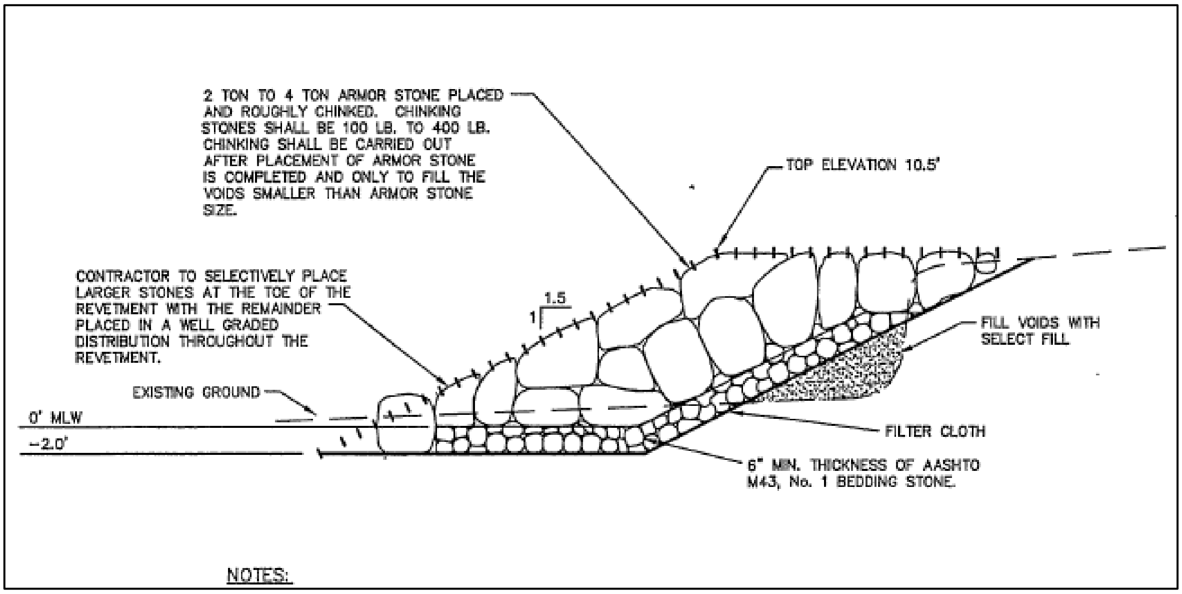

Figure 14. Revetment design specifications provided by DNREC (Soulé & Associates, 1999)

4.1.3. Post-Nourishment Erosion Analysis

Due to the profile conditions that exist at this site following the 2008 Bethany Beach/South Bethany Coastal Storm Damage Reduction Project, Compass conducted an evaluation of shoreline and volume change of the following three storms: 2009 Nor'Ida, 2012 Hurricane Sandy, and the 2016 Winter Storm. Compass obtained pre-storm and post-storm survey data for each of these storms and evaluated the post-nourishment erosion response for each. Each storm was evaluated relative to the peak observed water levels near the site, which are shown in Table 3, similar to the original dune erosion volume analysis conducted to develop FEMA's dune erosion guidelines (Hallermeier and Rhodes, 1988). Figure 15 and Figure 16 show the survey data locations and a sample of pre- and post-storm survey profiles for Nor'Ida. Figure 17 shows Hurricane Sandy and 2016 Winter Storm survey data locations, Figure 18 shows Hurricane Sandy pre- and post-storm profiles, and Figure 19 shows 2016 Winter Storm pre- and post-storm profiles. As shown in Figure 15, odd-numbered survey profile stations were available for pre- and post-storm Nor'Ida, whereas in Figure 17, even-numbered survey profile stations were available for both Hurricane Sandy and the 2016 Winter Storm.

Table 3. Peak Water Levels for Post-Nourishment Storms

Storm Event	Date	Lewes, DE, Water Elevation (ft, NAVD88)	Ocean City, MD, Water Elevation (ft, NAVD88)
Nor'Ida	11/13/2009	5.26	3.56
Hurricane Sandy	10/29/2012	6.08	1.53
2016 Winter Storm	1/23/2016	6.64	3.13

Figure 15. Nor'Ida survey transect locations

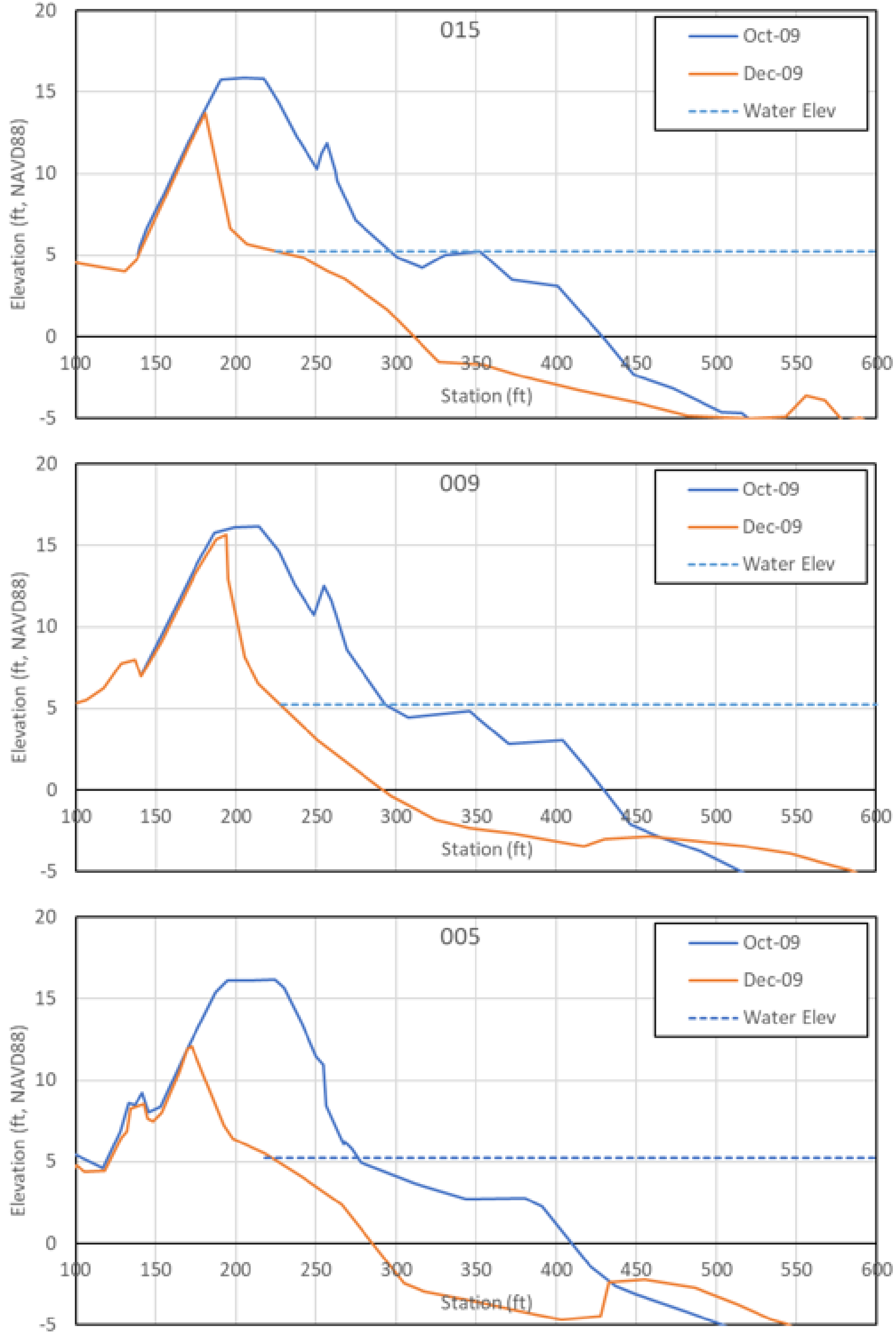

Figure 16. Nor'Ida pre- and post-storm profiles

Figure 17. Hurricane Sandy and 2016 Winter Storm survey transect locations

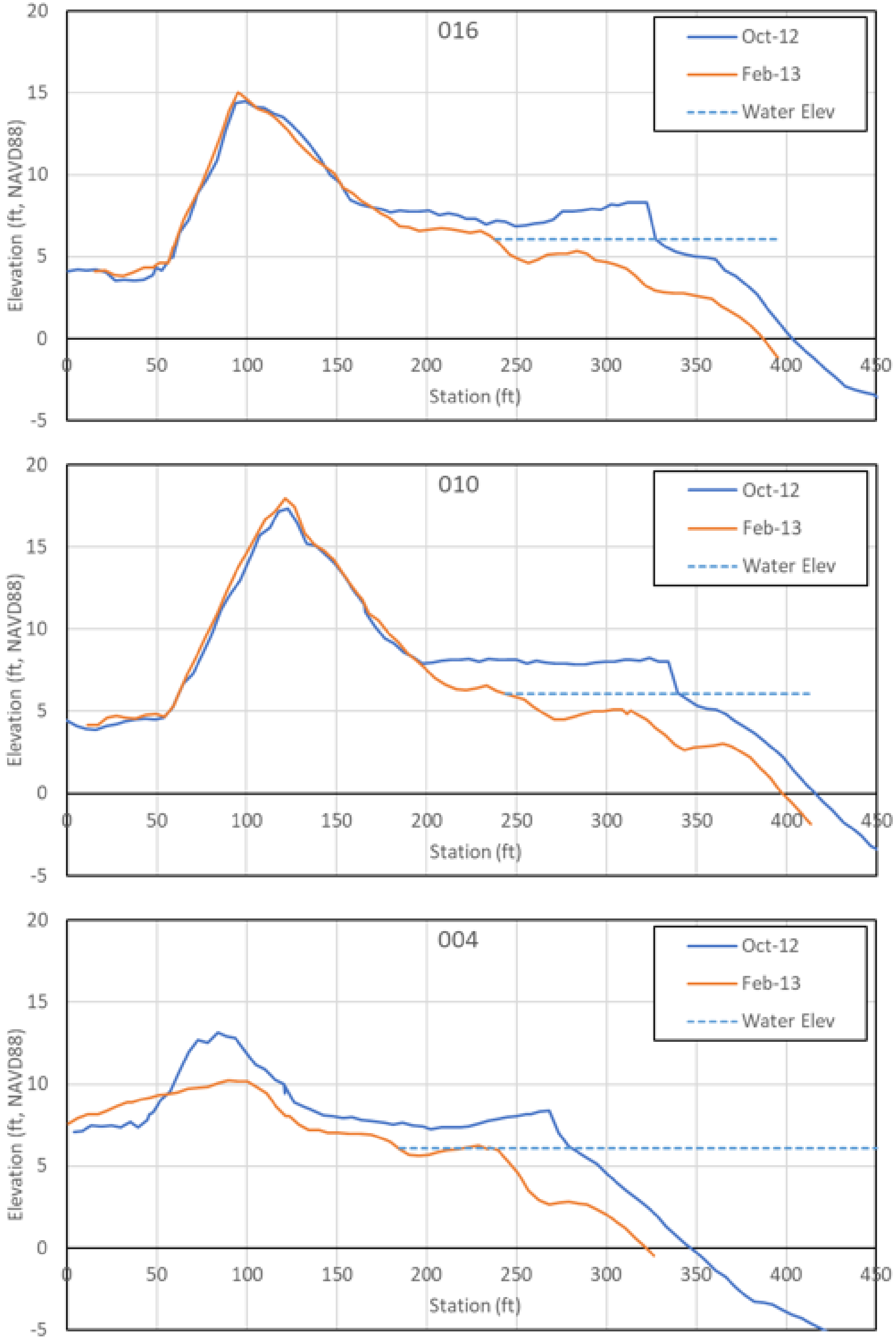

Figure 18. Hurricane Sandy pre- and post-storm profiles

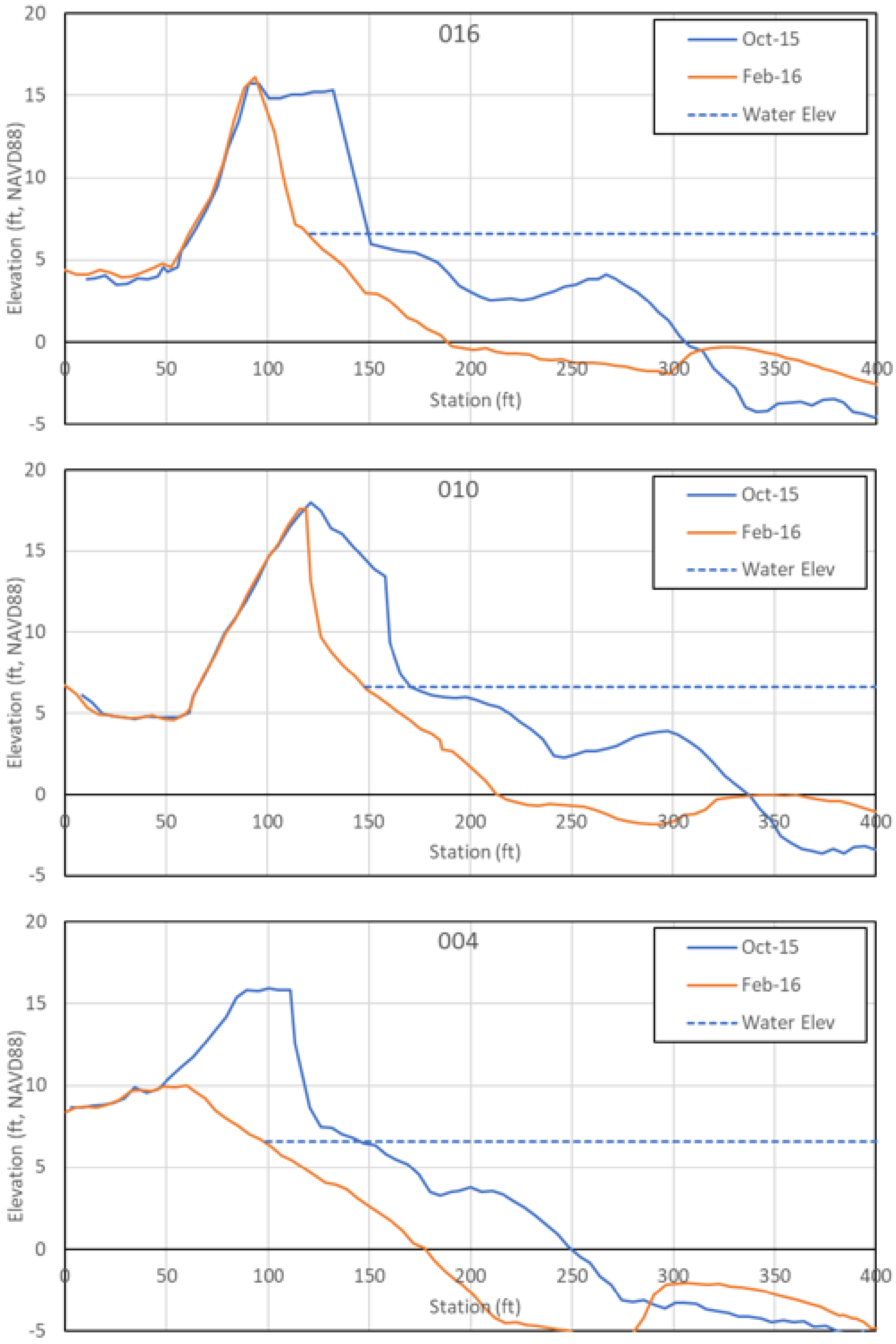

Figure 19. 2016 Winter Storm pre- and post-storm profiles

Review of the pre- and post-storm profile data revealed a number of trends in beach and dune storm response. In each of the three storm events, shoreline retreat (shoreline in this case, referring to the location of 0 feet NAVD88) and significant beach berm erosion were observed. In the cases of Nor'Ida and the 2016 Winter Storm, more significant erosion impacted the dunes and, in most cases, caused a dune scarp of the seaward face of the dunes that closely resembled a FEMA dune-retreat geometry. Near the southern portion of South Bethany, overwash or breaching of the dunes was noted. Table 4 shows the average shoreline retreat and average erosion measured as sand loss above the peak measured water elevation from the Lewes, DE, tide gage. The values shown are average values of all survey datasets fronting Ocean Drive for each corresponding storm.

Table 4. Erosion Measurements for Post-Nourishment Storms in South Bethany

Storm Event	Lewes, DE, Water Elevation (ft, NAVD88)	Average Shoreline Retreat (ft)	Average Erosion Measured Above Peak Gage Level (ft^2)
Nor'Ida	5.26	-125	616
Hurricane Sandy	6.08	-22	213
2016 Winter Storm	6.64	-71	316

4.1.4. Modified Erosion Method

Common practice for flood studies along the Atlantic and Gulf Coast of the United States is to evaluate open coast dune erosion using FEMA's standard erosion approach, then validate the erosion assessment based on historical evidence (FEMA, 2007). The 2018 *FEMA Guidance for Flood Risk Analysis and Mapping: Coastal Erosion* report states that "at many sites, historical evidence may be available regarding the extent of flooding, erosion, and damage in an extreme event comparable to the local 1-percent-annual-chance flood. In these instances, an erosion treatment providing results more consistent with historical records may be selected as appropriate."

With respect to South Bethany, FEMA's standard erosion method was evaluated first, but results were not consistent with observed historical erosion. Modifications were therefore made to the standard erosion method according to FEMA guidance, to ensure that the erosion treatment was more consistent with local conditions.

4.1.4.1 Background: FEMA Standard Erosion Method

FEMA's standard erosion methodology, often referred to as the '540 Rule,' adjusts the geometry of a dune feature based on the size of the primary frontal dune (PFD) reservoir area. As shown in Figure 20, the frontal dune reservoir area is measured as the cross-section of dune seaward of the dune peak and above the elevation of the 1-percent-annual-chance SWEL. According to the 540 Rule, if the dune reservoir area is greater than 540 square feet, the dune is anticipated to withstand the effects of the 1-percent-annual-chance event (i.e., retreat scenario), and 540 square feet is removed from the dune and deposited offshore using standard slopes and geometries, shown as the bottom scenario in Figure 21. If the dune reservoir area is less than 540 square feet, then the dune is not expected to withstand the effects of the 1-percent-annual-chance event, and the dune is removed using a 1:50 slope from the seaward toe of the dune, shown as the upper scenario in Figure 21.

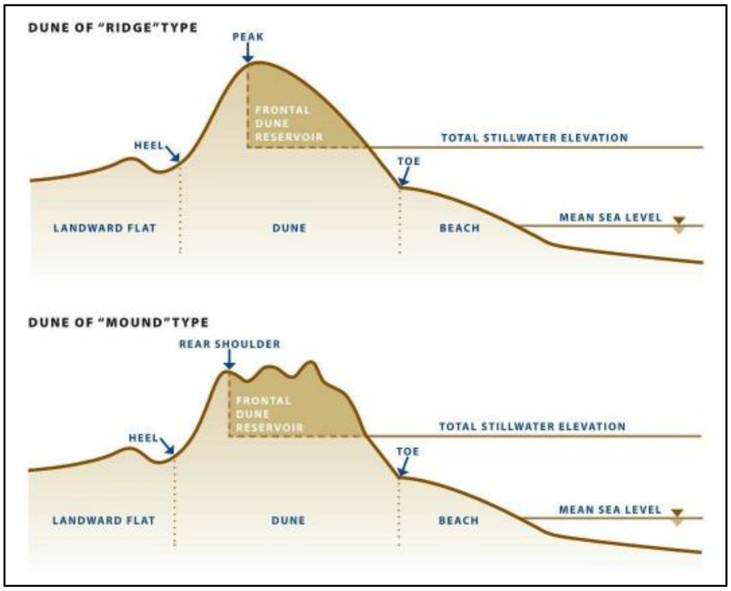

Figure 20. Primary frontal dune reservoir illustrations (FEMA, 2018a)

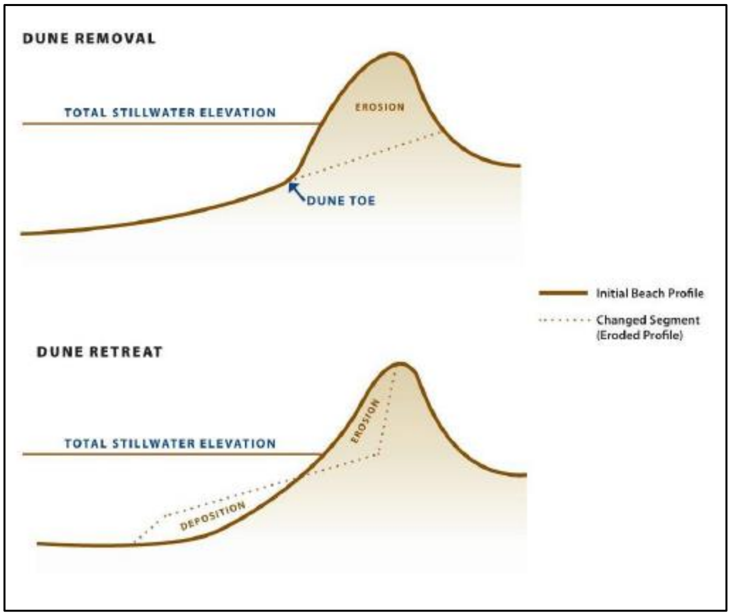

Figure 21. 540 Rule dune retreat and dune removal geometry (FEMA, 2018a)

The 540 Rule is based on a historical quantitative analysis of pre- and post-storm erosion measurements from 38 storm events with recurrence intervals ranging from 1.25 to 300 years, as determined from peak flood elevations using long-term gage records (see Figure 22) (Dewberry and Davis, 1989). As part of the original study that led to the 540 Rule, dune-face retreat erosion was measured for each storm event, and the resulting median erosion for each storm was compared to the storm's return period. The regression analysis of eroded area versus return period produced the following equation, which corresponds to 50 square meters, or 540 square feet, of erosion for the 1-percent-annual-chance return period:

$$Erosion\ [m^2] = 8\ (Recurrence\ Interval\ [yr])^{0.4}$$

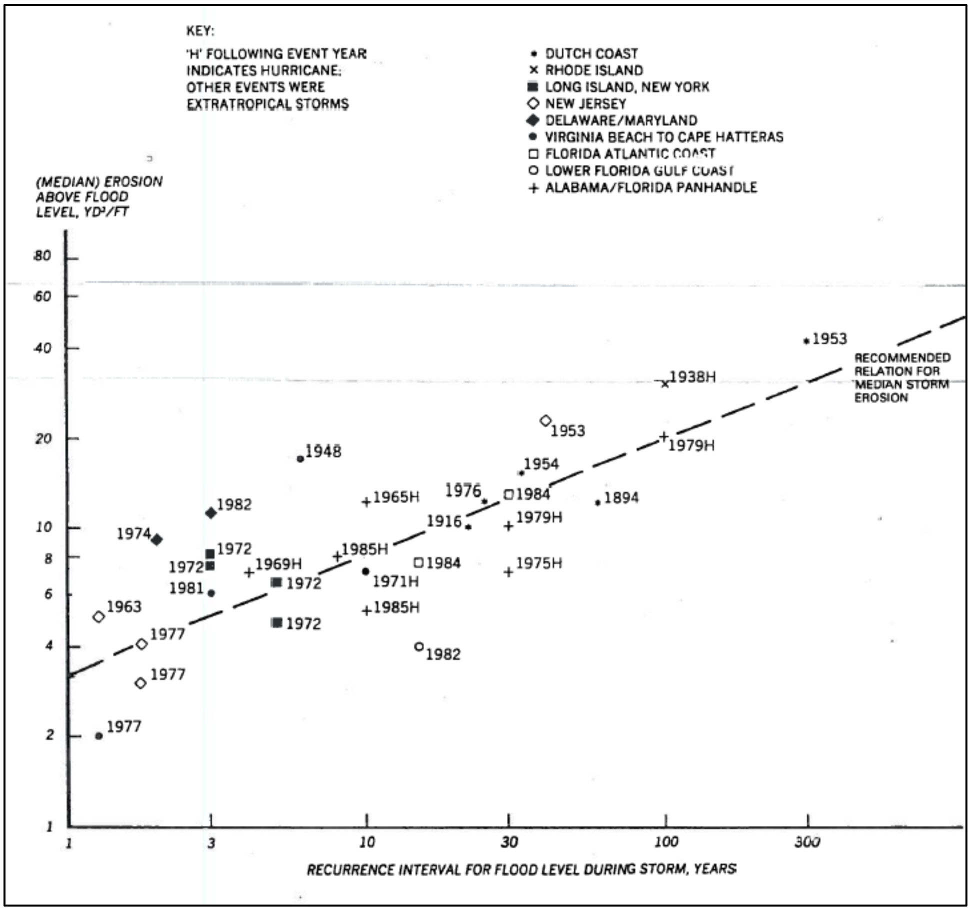

Figure 22. Median profile erosion versus recurrence interval (Dewberry and Davis, 1986)

4.1.4.2 South Bethany Standard Erosion Relative to Historical Evidence

When evaluating the dune areas in South Bethany according to the 540 Rule, Compass found the nourished dunes fronting Ocean Drive all had insufficient sand to withstand the effects of the 1-percent-annual-chance event, as shown in Table 5. The small dune reservoir volumes would indicate dune removal using the standard erosion methodology. Areas north of Ocean Drive had dune reservoirs that had slightly more than 540 square feet of sand and would indicate dune retreat.

Table 5. Dune Reservoir Volumes and Corresponding FEMA Standard Erosion Treatment for South Bethany

Transect	Transect Location	Dune Reservoir Volume (ft^2)	Dune Standard Erosion Treatment
1595	North of Ocean Dr.	550	Retreat
1610	Ocean Dr.	179	Removal
1620	Ocean Dr.	173	Removal
1630	Ocean Dr.	151	Removal
1640	Ocean Dr.	107	Removal
1645	Ocean Dr.	82	Removal

According to common practice and based on FEMA guidance, the standard erosion dune retreat and dune removal analysis was first applied to the transects at South Bethany. An example of dune removal for an Ocean Drive transect is shown in Figure 23. Guidance advises that the mapping partner should determine that resulting estimates of eroded dune profiles are consistent with available historical evidence for a specific site; if this is not the case, the mapping partner should choose an alternative erosion treatment (FEMA, 2007).

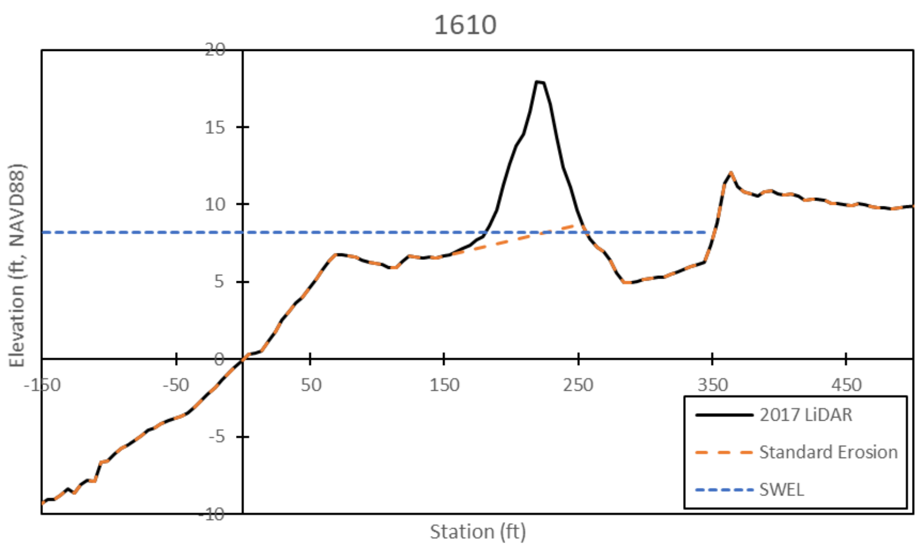

Figure 23. Standard removal erosion geometry example for Transect 1610

Review of the dune removal profiles at South Bethany showed significant inconsistencies with the erosion trends from post-nourishment storms (as shown in Figure 16, Figure 18, and Figure 19). The standard removal geometry accounted for removal of the dune but did not account for the shoreline retreat and berm erosion that would be expected based on storm trends reviewed in Section 4.1.3.

In addition to the differences in removal geometry versus the historical storm evidence, the dune erosion areas from a removal geometry appeared to underestimate the quantity of historical erosion observed at South Bethany. Based on the small size of the dune reservoirs fronting Ocean Drive, the dune removal geometry would remove a relatively small amount of sand from above the 1-percent-annual-chance SWEL. When looking at the historical survey datasets in Section 4.1.3, the amount of sand loss above the peak measured water elevations were significantly higher than what would have been expected according to the underlying regression equation used as the basis for the 540 Rule.

For example, assuming the peak water level from the Lewes tide station, the flood level from the 2016 Winter Storm would correspond to the 10-percent-annual-chance flood level at South Bethany, which was reported as 6.6 feet (NAVD88) in the effective Sussex County FIS Report (FEMA 2018c). Based on a 10-percent-annual-chance event (or 10-year recurrence interval), the expected dune erosion would be 216 square feet according to the 540 Rule regression equation (equation shown above Figure 22). In the case of the 2016 Winter Storm, the average dune erosion above the peak water elevation was 316 square feet, which is higher than what would have been predicted using the historical storm regression equation.

Similarly, as shown in Table 4, the erosion measured as a result of Nor'Ida was 616 square feet, even higher than what the FEMA standard approach would calculate for a 1-percent-annual-chance event. Hurricane Sandy, although having a peak gage elevation that was approximately 0.5 foot lower than the 10-percent-annual-chance storm event, resulted in an average of 213 square feet of erosion, which would be expected of a 10-percent-annual-chance erosion result according to the FEMA standard approach. In all three post-nourishment storm cases analyzed in Section 4.1.3, the average field erosion measurements were higher than what would be predicted from the regression equation used to develop the FEMA standard erosion analysis.

In addition to the larger erosion area noted in post-nourishment cases, a similar trend was noted in the original storm population used to create the regression equation. Looking closely at the storm locations referenced in the original Dewberry and Davis documentation (see Figure 22) revealed that the two nearest storm events, one located in Delaware and one in Maryland, both produced significantly more erosion than what would have been expected of that particular recurrence interval using the regression equation. As noted in FEMA guidance, "the [540-square-foot] threshold value may not be wholly accurate for any given study location as site characterizes as well as storm characteristics are always unique" (FEMA, 2018a).

Given the above findings, the historical evidence indicates that the FEMA standard removal erosion underestimates the level of erosion risk at South Bethany in both geometric erosion patterns as well as the area of eroded material.

4.1.4.3 Modifying Standard Erosion Method Based on Historical Evidence

Although dune removal applied using FEMA's standard erosion approach produced an unreasonable geometric and volume-based estimate of erosion for South Bethany, some aspects of dune retreat geometry are consistent with the historical evidence. For example, the FEMA dune retreat geometry would contribute to both shoreline retreat and beach berm erosion, as noted in historic cases. Also, the steep scarp at the landward extent of the retreat face would correspond closely to the dune-face scarping observed in the more severe field erosion cases for Nor'Ida and the 2016 Winter Storm.

In previous flood studies with unique dune geometry or documented storm response, the standard erosion method was adjusted to be more representative of site observations. Some flood studies have found that in areas where dune removal was not representative, a dune retreat geometry was a more realistic beach profile response and could be justified by increasing the landward extent of erodible material in the dune reservoir, as shown in the mound-type dune illustration in Figure 20. FEMA guidance recommends that in areas with more complex dune geometry, the Mapping Partner use judgment to separate the sand reservoir expected to be effective in resisting dune removal from the landward portion of the pre-storm dune (FEMA, 2007).

In the case of South Bethany, the Modified Erosion Method builds on the above guidance, recognizing that there was a significant volume of erodible sand between the nourished dune and Ocean Drive that would likely contribute to protection, and subsequent erosion, of inland developed areas. This was supported by the current delineation of the PFD line, which runs along the landward side of oceanfront homes along Ocean Drive. The proposed Modified Erosion Method allowed the dune retreat to extend inland to account for inland volumes of sand and also preserved the slope conditions of standard dune retreat geometry that were similarly noted in the historical evidence.

Before the dune retreat could extend inland to account for a full 540 square feet of sand loss, the retreat profile intersected the crest of the buried rock revetment detailed in Section 4.1.2, (see Figure 14). Although there has been photographic evidence of the previous revetment being damaged at South Bethany, the older revetment shown in photos was more exposed, i.e., less protected by nourished beach, than the current revetment.

Since the 2008 Bethany Beach/South Bethany Coastal Storm Damage Reduction Project, there has not been any historical evidence to detail how the current revetment could respond to a major storm event as the erosions caused by storms (Nor'Ida, Hurricane Sandy and the 2016 Winter storm) did not reach the revetment. Because the exposure of the revetment crest requires a significant amount of eroded area to be removed from the profile, there was insufficient justification to model failure of the coastal armoring structure. As the exposed armoring would contribute to a higher level of wave dissipation, the inland extent of the retreat profile was halted at the intersection of the crest of the revetment, as shown in the orange profile in Figure 24. As the longshore representative feature covering the top of the revetment was sand and gravel, this erodible material was removed from the profile under the assumption that wave attack would eliminate it during the 1-percent-annual-chance event, as shown in the red profile in Figure 24. Following the development of the Modified Erosion Method, DNREC officials (with abundant local storm and erosion knowledge) reviewed and agreed with the structure treatment and erosion geometry applied in this study.

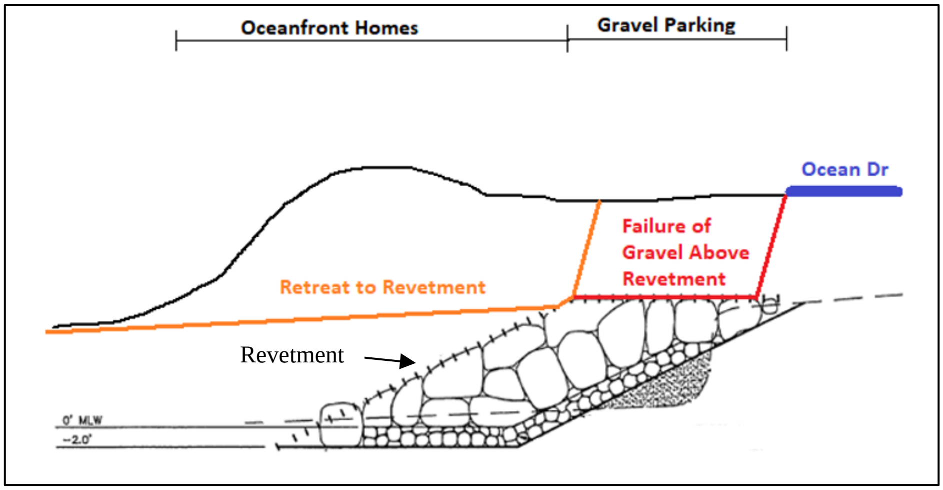

Figure 24. General illustration of Modified Erosion Method, exposing the crest of buried revetment

Resulting modified erosion method profiles for South Bethany showed extensive open coast erosion justified by historical evidence. In all cases fronting Ocean Drive, the amount of eroded material above the 1-percent-annual-chance SWEL was less than 540 square feet but was limited by the horizontal location of the buried rock revetment, as shown in Figure 25. For the case north of Ocean Drive, because the dune reservoir was greater than 540 square feet, a standard retreat erosion geometry was applied to Transect 1595 at the north border of South Bethany.

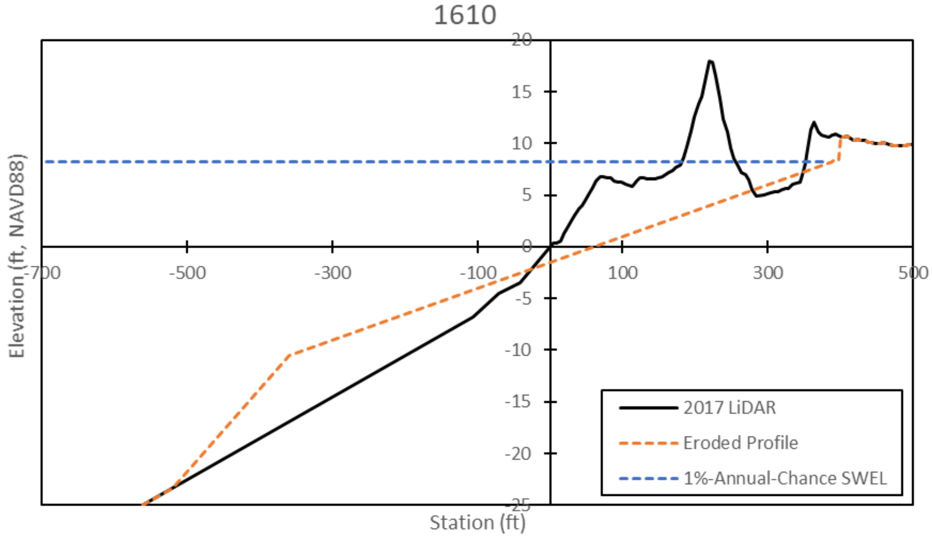

Figure 25. Example of Modified Erosion Method

4.1.5. Alternative Methods Evaluated

In addition to evaluating the FEMA standard erosion analysis (540 Rule) and modifying the standard erosion to produce the Modified Erosion Analysis, two other alternative erosion models were investigated to identify if there were other accepted FEMA methodologies that would reflect historical evidence: the K&D model developed by Kriebel and Dean (1993) and the MK&A model that was developed by Komar et al. (2002) and further modified by McDougal and MacArthur (2004). Both models were tested on the Pacific Coast and rely on the generation of a Most Likely Winter Profile prior to erosion modeling.

The K&D model is an equilibrium profile erosion model that has traditionally been applied to sandy beaches backed by dunes in California. The model considers the total water level, storm duration, breaking wave height, the median value of the sand grain size distribution, D_{50}, and profile characteristics to determine the maximum beach erosion potential for a particular storm event. This potential is represented as the cross-shore recession displacement of the profile. Conservation of sand volume between the erosion of the dunes and the offshore deposition is maintained. According to the FEMA *Guidance for Flood Risk Analysis and Mapping: Coastal Erosion* (2018a), the K&D model is not applicable when overtopping occurs and was therefore not found to be a suitable erosion approach for South Bethany.

Similar to the K&D model, the MK&A model considers the total water level, storm duration, breaking wave height, D_{50} of the beach material, and profile characteristics to determine the maximum beach erosion potential for a particular storm event. The shoreline recession profile is characterized by the beach face slope, m, the beach-dune juncture elevation, E_j, and the cross-shore location of the beach-dune juncture, y_j. These are shown in Figure 26. The juncture elevation is taken to occur at the maximum extent of the total water level, which is the sum of the stillwater level plus wave setup and runup. The beach face slope, m, can be estimated from the D_{50} of beach sand, based on the Wiegel's regional relationship (1964). As with the K&D model, once the maximum recession potential is determined, the storm duration recession reduction factor needs to be considered to calculate the inland extent of erosion for a particular storm event.

Figure 27 shows the eroded profile from the MK&A analysis for Transect 1610. Similar to the eroded geometry from the FEMA standard methodology, the resulting eroded profile from the MK&A model showed poor agreement to the historical storm evidence in this area, as shown in Figure 16, Figure 18, and Figure 19. Due to the poor agreement and the lack of precedent for application of this model in this region, this analysis was disregarded, and the Modified Erosion Method was selected as the more appropriate erosion methodology.

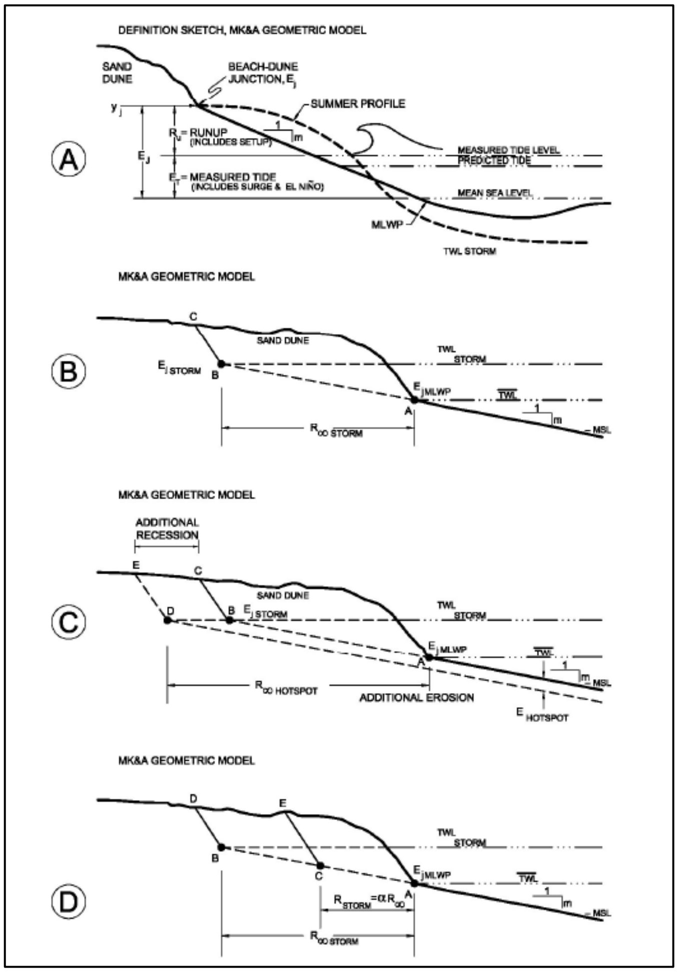

Figure 26. Definition Sketch for MK&A Geometric Model

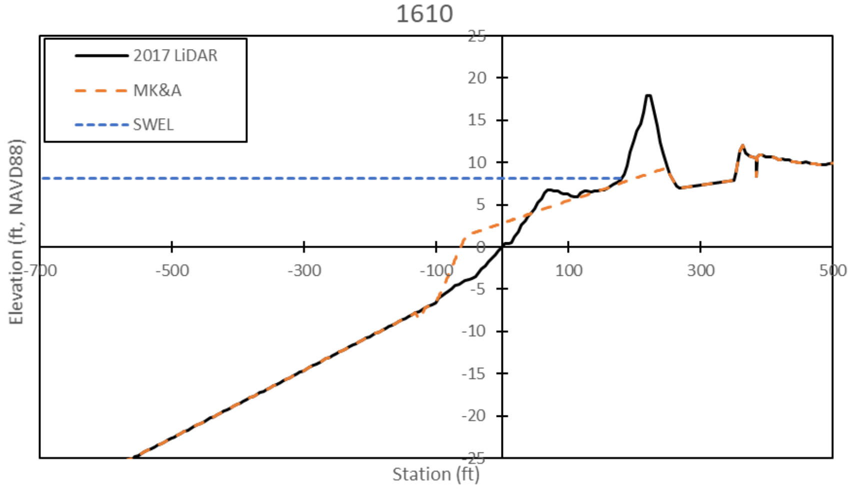

Figure 27. MK&A eroded profile for Transect 1610

4.2. Overland Wave Propagation

4.2.1. WHAFIS Modeling

FEMA's WHAFIS model, version 4.0, was used to model overland wave propagation per the FEMA *Guidance for Flood Risk Analysis and Mapping: Overland Wave Propagation* (2015). The basic input information required by WHAFIS includes SWELs (inclusive of regional wave setup), wave and wind conditions, ground elevations, and land use classifications with the corresponding vegetation or building parameters, which are detailed in Section 3.

4.2.2. Shoreline

The transect baseline for the WHAFIS modeling is the 0-foot contour (relative to NAVD88). The 0-foot contour was derived from the seamless DEM developed for this analysis, as detailed in Section 3.1.

4.2.3. WHAFIS Results

WHAFIS model results show that South Bethany is exposed to wave hazards along the open coast. Overland waves propagate inland during the 1-percent-annual-chance flood and end at above-surge areas in the vicinity of Ocean Drive. Overland waves regenerate in below-surge areas in the western portion of the town.

4.3. Wave Runup

Wave runup is the maximum vertical extent of wave uprush on a beach, dune, or structure above the SWEL. Wave runup can produce higher risks for structures or natural profiles with steeper slopes, such as bluffs. FEMA guidance identifies different methods for runup calculations based on shoreline exposure, structure type, and profile slope.

The Runup 2.0 model was applied along South Bethany, due to the mildly sloped sandy beaches where the SWEL did not overtop the crest of the eroded profile (i.e., beaches gentler than a slope of 1:8). Runup 2.0 was run on SWEL (with wave setup), as recommended by the FEMA guidance. This same approach has been implemented in other FEMA studies, including the effective Sussex County FIS (2018c).

Runup 2.0 requires the mean wave height, H_m, and mean wave period, T_m, as input wave conditions. Mean wave conditions were converted from the significant wave height and peak wave period conditions according to FEMA guidance.

The wave runup profile represents the eroded topographic conditions for each transect. Runup 2.0 produced the mean runup value; these runup results are based on a combination of nine runup values derived from variations of the input wave conditions. A 10 percent variation of wave conditions was used as the input for Runup 2.0 modeling in South Bethany. Mean runup is converted to the 2-percent-exceedance runup value using a multiplication factor of 2.2; the 2-percent-exceedance value is used for mapping in accordance with FEMA's *Guidance for Flood Risk Analysis and Mapping: Coastal Wave Runup and Overtopping* (2018b).

4.3.1. Wave Runup Results

Runup modeling was applicable to all modeling transects in this study. Runup results are provided in Table 6 and also summarized in the file "Modified_Erosion_SummaryData.xlsx" included in the submittal to FEMA Mapping Information Platform (MIP).

Table 6. Runup Results Summary

Transect	SWEL (ft)	Runup Method	2%-Exceedance Runup (ft)	Wave Runup Elevation (ft, NAVD88)	Profile Crest Elevation (ft, NAVD88)
1595	8.19	*Runup 2.0*	4.17	12.36	17.56
1610	8.18	*Runup 2.0*	4.14	12.32	10.66
1620	8.09	*Runup 2.0*	3.80	11.89	11.64
1630	8.01	*Runup 2.0*	4.02	12.03	10.34
1640	8.05	*Runup 2.0*	4.00	12.05	10.49
1645	8.04	*Runup 2.0*	4.04	12.08	9.89

4.4. Overtopping

A barrier such as a partially eroded bluff or a structure is overtopped when the crest elevation is lower than the runup elevation. When a barrier is overtopped, waves splash or flow cause water to flood into the area behind on the leeward side until reaching another flooding source or ponding area. For overtopping profiles in South Bethany, the methodology outlined in FEMA's *Atlantic Ocean and Gulf of Mexico Guidelines Update* (2007) Section 2.8.2.3 was used to calculate overtopping. Table D.2.8-6 in Section 2.8.2.3 provides direction in mapping flood zones as a function of mean overtopping rate. Overtopping rates were calculated using Equation D.2.8-18 of the FEMA *Atlantic Ocean and Gulf of Mexico Coastal Guidelines Update* (2007) for each overtopped case. This method prevented any subjective selection of a toe or inflection point on the beach profile, which is likely to change due to storm erosion. Overtopping results are provided in Table 7. Splash zone mapping is tracked in the ‘Overtopping’ tab of file “Modified_Erosion_SummaryData.xlsx” included in the submittal to FEMA MIP.

Table 7. Overtopping Results Summary

Transect	SWEL	2%-Exceedance Runup (ft)	Runup Elev.	Crest Elev.	Base Flood Elev.	Flood Zone Behind Barrier
1595	8.19	4.17	12.36	17.56	12	AO2
1610	8.18	4.14	12.32	10.66	12	AO2
1620	8.09	3.80	11.89	11.64	12	AO2
1630	8.01	4.02	12.03	10.34	12	AO2
1640	8.05	4.00	12.05	10.49	12	AO2
1645	8.04	4.04	12.08	9.89	12	AO2
All elevations are in –ft, referenced to NAVD88						

5. Coastal Flood Hazard Mapping

Following the FEMA *Guidance for Flood Risk Analysis and Mapping: Coastal Floodplain Mapping* (November 2019), flood hazard zones were mapped in accordance with the modeling results (i.e., WHAFIS, runup, and overtopping) and delineated between transects following the topography, changes in SWEL, and land use.

5.1. Primary Frontal Dune

The PFD from the effective Sussex County Coastal Flood Study was applied to the mapping of this study. It is standard practice to follow the historical PFD line for LOMRs and new coastal analyses.

5.2. Interpretation of Modeling and Mapping Results

Zone VEs were mapped to the limit of the PFD, where applicable, or the Zone VE limit from WHAFIS or runup analyses, whichever was farther inland. For the South Bethany open coast, the landward location of the PFD determined the landward extent of Zone VE.

The proposed LOMR mapping in South Bethany ties into the 2015 effective mapping of Sussex County on both the north and south ends. Proposed AE and AO zone delineations line up with areas to the north and south of the South Bethany political boundary. VE zone BFE’s may differ between the South Bethany proposed mapping and the effective mapping of surrounding areas (a common occurrence along shorelines where wave runup is mapped), however, the landward extent of the VE zones of these areas line up with the effective PFD (See Appendix A, Figure 29A).

Within the Town of South Bethany, a proposed Zone VE with runup-based Base Flood Elevation (BFE) of 12 feet was mapped to the effective PFD line. Zone VE then transitions to a Zone AO with a depth of 2 feet, and then transitions to Zones AE6 and AE7 from the inland SWEL boundary.

A summary of the proposed LOMR mapping results at each transect is listed in Table 8. Note that the value 'Zone VE Limit' explains the dominating characteristic (e.g., PFD, runup, or wave height) that determined the mapping location of the first Zone VE. Additionally, the 'SFHA Boundary' describes the dominating characteristic (e.g., overtopping, wave height, or SWEL) that determined the most seaward extent of the Special Flood Hazard Area (SFHA), which includes all zones associated with land areas covered by the floodwaters of the base flood.

Table 8. Summary of LOMR Mapping Results

Coastal Transect	Primary Frontal Dune (PFD) Identified	Wave Runup Analysis	Wave Height Analysis	Zone VE Limit	SFHA Boundary
		Zone Designation and BFE (ft)	Zone Designation and BFE (ft)		
1595	✓	VE12 AO2	AE6-7	PFD	SWEL
1610	✓	VE12 AO2	AE6-7	PFD	SWEL
1620	✓	VE12 AO2	AE6-7	PFD	SWEL
1630	✓	VE12 AO2	AE6-7	PFD	SWEL
1640	✓	VE12 AO2	AE6-7	PFD	SWEL
1645	✓	VE12 AO2	AE6-7	PFD	SWEL

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Appendix A – Effective and Proposed Mapping

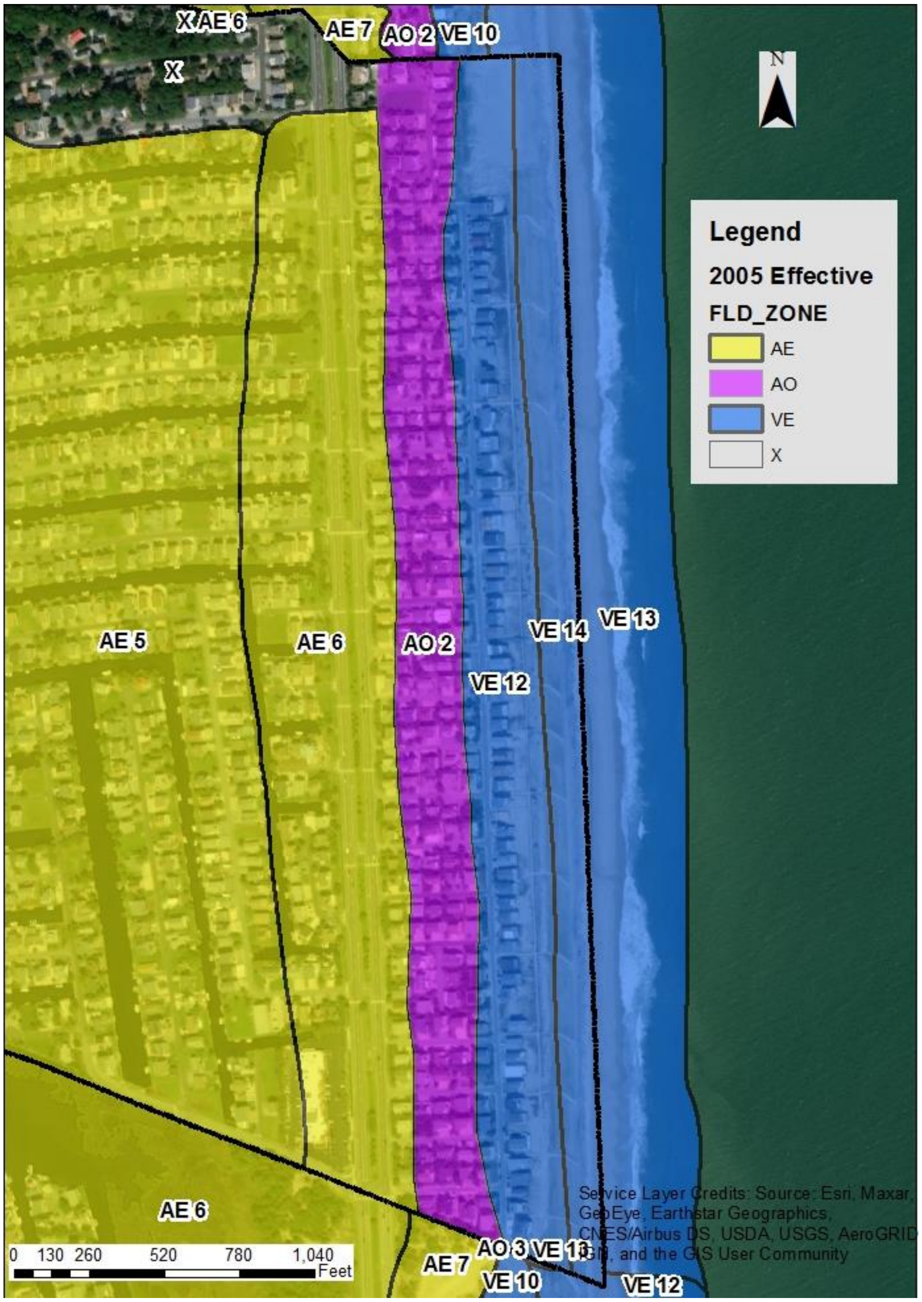

Figure 28A. Effective mapping for Town of South Bethany (2005) and surrounding areas (2015)

Figure 29A. Proposed mapping within Town of South Bethany (zones labeled in black) with effective mapping of surrounding areas (zones labeled in red)