Storm Wave Impact Analysis

Crab Bank Seabird Sanctuary Project, Charleston, South Carolina

Prepared for:

Audubon South Carolina

Charleston, SC

September 23, 2021

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Mount Pleasant, SC

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Executive Summary

Water Environment Consultants (WEC) prepared this report for Audubon South Carolina (Audubon) to support an economic benefit analysis of the proposed Crab Bank Seabird Sanctuary located in Charleston Harbor, South Carolina. As part of the Post 45 Harbor Deepening Project, the US Army Corps of Engineers (USACE) will add sand to Crab Bank to expand the site and provide suitable nesting habitat. This report evaluates additional project benefits attributable to storm wave damage reduction caused by the planned placement of sand on the bank.

WEC used the SWAN (Simulating WAves Nearshore) two-dimensional wave model to estimate storm wave conditions along the Mount Pleasant shoreline adjacent to the Crab Bank. Project effects were evaluated by modeling the existing conditions and post-project conditions, after the placement of fill, and comparing the resulting wave conditions. WEC modeled a range of storm conditions, including a 10-percent-annual-chance storm (10-yr return period), a 4-percent-annual-chance storm (25-yr return period), and a 1-percent-annual-chance storm (100-yr return period).

The model results show a large reduction in wave height along the new Crab Bank feature, which is caused by wave breaking as the waves travel over the bank. For the 10-year return period event, there is only very shallow water over the top of the bank (less than one foot), and therefore only very small waves pass over the bank in this scenario. For the less frequent events (25 and 100-year return period events), the storm surge is higher and there is a greater water depth over the top of the bank. As a result, larger waves can pass over the bank during these more extreme conditions. The modeling results did not show significant reductions in wave heights at residential structures, mostly because the structures were above the flood elevations during the modeled extreme event scenarios. The modeling did, however, show significant reductions in wave heights reaching the dock structures.

Based on WEC's wave model results, Freese & Nichols, Inc. (FNI), a subcontractor to WEC, estimated the reduction in storm damages to the dock structures. FNI developed an inventory of docks along the shoreline and compared existing dock elevations to the estimated extreme water level and wave crest elevations. FNI used published wave damage curves for coastal structures for the purpose of estimating the percent damage to the docks that would occur for each storm scenario. The results demonstrate modest but significant reductions for the 10-year return period event, for which FNI estimates a damage reduction benefit totaling approximately $1.6 million. Therefore, we expect all properties directly behind the newly constructed island with waterfront structures will benefit from damage risk reduction during the most frequent storm events. Because of the higher water levels and wave heights that occur during the 25-year return period event, FNI estimates a near total loss of the dock structures, and the damage reduction is smaller (about $0.4 million). Given the even higher water levels and wave heights associated with the 100-year return period event, the benefits of the restoration project for that scenario are negligible.

These estimates could be higher or lower based on uncertainty in the various assumptions used in this analysis including estimated water levels, structure replacement costs, structure elevations, construction quality, and applicability of the depth-damage curves. Nonetheless, the analyses provided herein provide a reasonable approximation of the coastal storm damage reduction economic benefits that can be expected upon completion of the of the Crab Bank restoration project.

The results from this analysis can be used to inform future projects at other locations. Although the shorelines near Crab Bank are stable, tor areas with eroding shorelines, a similar project would reduce erosion rates in the lee of the bird island. The modeled reductions in wave height at the dock locations in this study are indicative of the benefits that the island would have on reducing wave energy incident to the shoreline during storm events, and this would cause a reduction in erosion along the shoreline in the lee of the island. These types of islands cause the greatest reductions in wave energy (and potential shoreline erosion) during typical conditions when the island is not overtopped by storm surge. In general, bird island features can provide a benefit by reducing the potential for shoreline erosion. However, site-specific sediment transport patterns should be carefully considered, and for areas with high rates of littoral transport (i.e., flow of sediment along a shoreline) the project design should aim to avoid unintended effects on adjacent shorelines caused by changing littoral transport patterns.

In regard to damage reduction to upland structures, the benefits from bird island features are the greatest for structures at low elevations (i.e., those near the typical high water line), and the benefits decrease with increasing structure elevations. This is because the storm surge must increase for storm waves to reach structures at higher elevations, and as the storm surge increases, the effect of the island on wave breaking decreases because of the increased water depth over the top of the island. Furthermore, the maximum wave heights reaching upland areas at higher elevations may be depth-limited in height, which means that the maximum wave heights are limited by the local water depth near the structure and are not necessarily affected by features at lower elevations such as a bird island. In general, bird island features will provide the greatest damage reduction benefits to areas with structures at low elevations. For areas with newer habitable structures, the first floor elevation should be above the one-percent-annual-chance base flood elevation in the FEMA Flood Insurance Study maps, and low-crested bird islands will not provide significant damage reduction benefits to these structures. Areas that have older structures that pre-date FEMA Flood Insurance Study maps or pre-date local building code minimum elevation requirements will be at lower grade elevations and bird island features may provide greater damage reduction benefits. In general, a bird island will reduce maximum wave heights in areas where the ground elevation is lower than the crest elevation of the bird island.

1 Introduction

Water Environment Consultants (WEC) prepared this report for Audubon South Carolina (Audubon) to support an economic benefit analysis of the proposed Crab Bank Seabird Sanctuary located in Charleston Harbor, South Carolina. Crab Bank is a narrow strip of land located between Shem Creek and Fort Sumter (Figure 1-1). Crab Bank is constantly shifting in both size and location, vulnerable to erosion from storms and vessel wakes. As part of the Post 45 Harbor Deepening Project, the US Army Corps of Engineers (USACE) will add sand to Crab Bank to expand the site and provide suitable nesting habitat. This report evaluates the additional project benefits attributable to storm wave damage reduction caused by the planned placement of sand on the bank.

Based on the 2021 conceptual design figure provided by Audubon, the restoration project will place approximately 661,000 cubic yards of sand dredged from the federal navigation channel within the restoration project footprint shown in Figure 1-1. According to the USACE's Detailed Project Report (2018), the proposed fill will have a top elevation of 8 feet relative to the mean lower low water tidal datum. This is equivalent to 4.9 feet above the North American Vertical Datum of 1998 (NAVD88). From the top elevation, the bank will slope down to the existing grade at a 1:15 slope.

WEC used the two-dimensional wave model, SWAN (Simulating WAves Nearshore), to estimate storm wave conditions along the Mount Pleasant shoreline adjacent to the Crab Bank. Project effects were evaluated by modeling the existing conditions and post-project conditions, after the placement of fill, and comparing the resulting wave conditions. WEC modeled a range of storm conditions, including a 10-percent-annual-chance storm (10-yr return period), a 4-percent-annual-chance storm (25-yr return period), and a 1-percent-annual-chance storm (100-yr return period). Based on WEC's wave model results, Freese & Nichols, Inc. (FNI), a subcontractor to WEC, estimated the reduction in storm damages to structures along the shoreline in the vicinity of Crab Bank.

This report is summarized in the following sections:

- Section 2, Wave Model; and
- Section 3, Storm Damage Reduction Estimate

Figure 1-1. Project location map

2 Wave Model

WEC used the SWAN wave model to evaluate the effects of the Crab Bank on the wave climate during various storm events. Developed at Delft University of Technology, SWAN is two-dimensional steady-state spectral wave transformation model that simulates the growth and transformation of waves in the nearshore region. The wave model simulates the following wave processes: wave propagation, shoaling, refraction, wind wave growth, wave dissipation from white capping, bottom friction, and depth-induced breaking.

2.1 Model Grid

WEC developed a two-dimensional triangular mesh model grid of the Charleston Harbor study area by refining the grid that was used to model storm surge and wave action for the Federal Emergency Management Agency's (FEMA's) effective Flood Insurance Study (FIS) for Charleston County. The South Carolina Department of Natural Resources (SCDNR) developed the model grid as part of the state-wide storm surge study, and the grid development process is described in detail in *South Carolina Storm Surge Project Deliverable 1: Grid Development Report* (URS 2009). The SCDNR grid includes coarse resolution encompassing the Western Atlantic basin and Gulf of Mexico and a high-resolution mesh along the South Carolina shoreline. Within South Carolina, the SCDNR grid extends inland to about the 9-m elevation, which extends beyond the inundation level of the 0.2-percent annual-chance (i.e., 500-yr return period) stillwater elevation. For this study, WEC used a subset of the SCDNR grid that encompasses the harbor area, and we refined it to provide higher resolution in the vicinity of Crab Bank and the Mount Pleasant shoreline north of Crab Bank. The resulting model domain includes a 11,112-ft by 8,131-ft rectangular area as shown in Figure 2-1. The grid is more coarsely spaced (185-ft) along the boundaries and refined with higher resolution (25-ft spacing) in the areas of interest. In total, the grid includes 9,743 nodes and 19,284 triangular elements.

2.2 Elevations

The SCDNR model grid elevations were updated using the most recent hydrographic survey data from the USACE, in both the federal navigation channel and in the Crab Bank restoration area. For the post-project conditions elevations, WEC modified the bathymetry conditions to include the filled extents of Crab Bank. As mentioned previously, the restoration project extends up to a crest elevation of 4.9 feet above NAVD88, and the side slopes will be 1V:15H. Figures 2-2 and 2-3 illutrate the existing and post-project model elevations, respectively.

2.3 Water Levels

The NOAA published tidal datums for the Charleston Customs House (Station 8665530) are listed in Table 2-1. The mean tide range is 5.2 feet, and the great diurnal tide range is 5.8 feet.

FEMA evaluated the extreme water levels or stillwater elevations (SWEL) for various return period events (i.e. 10-, 50-, 100-, and 500-year return period events), which are published in the effective FIS

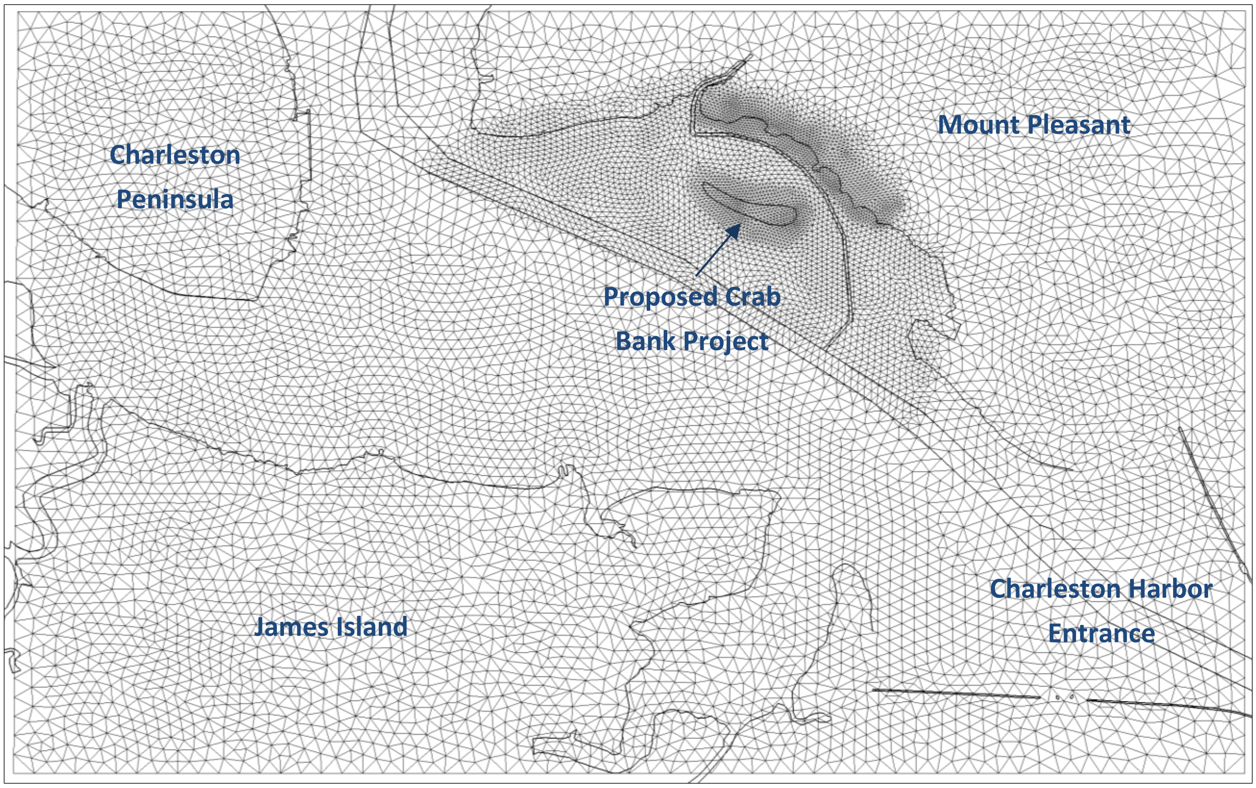


Figure 2-1. Wave model domain and grid

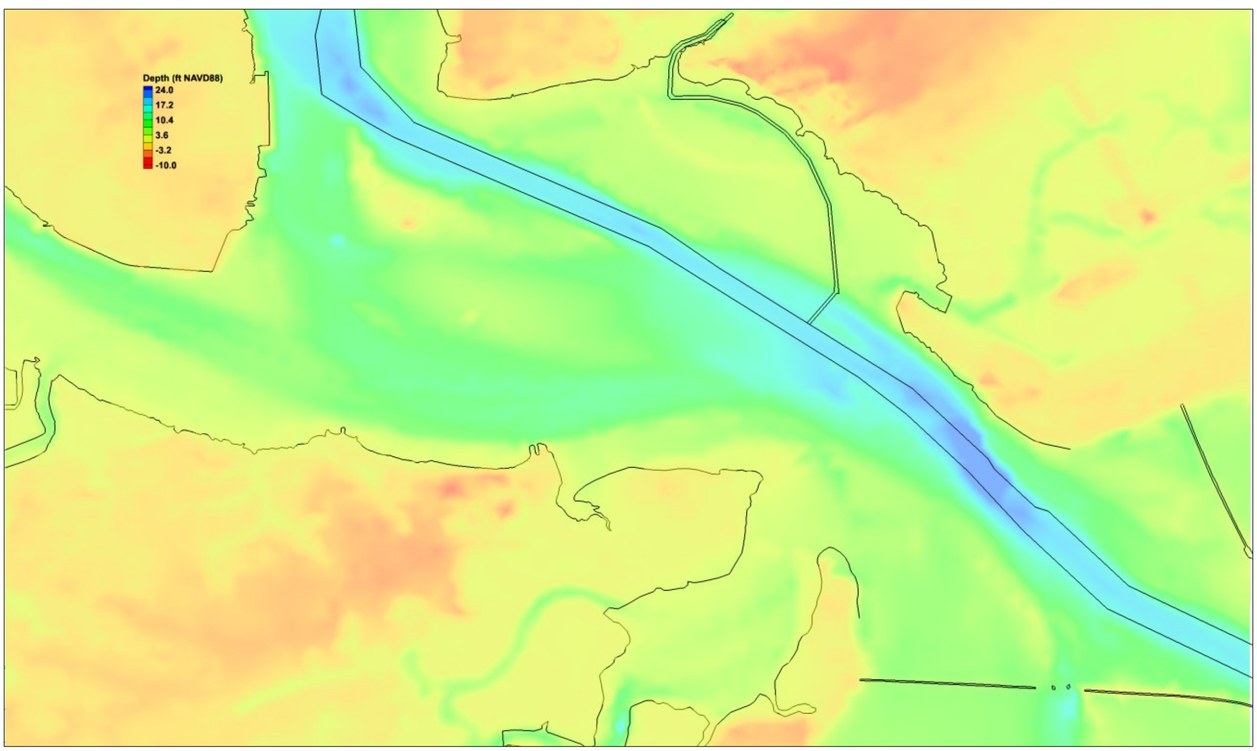


Figure 2-2. Existing conditions model grid elevations within model domain

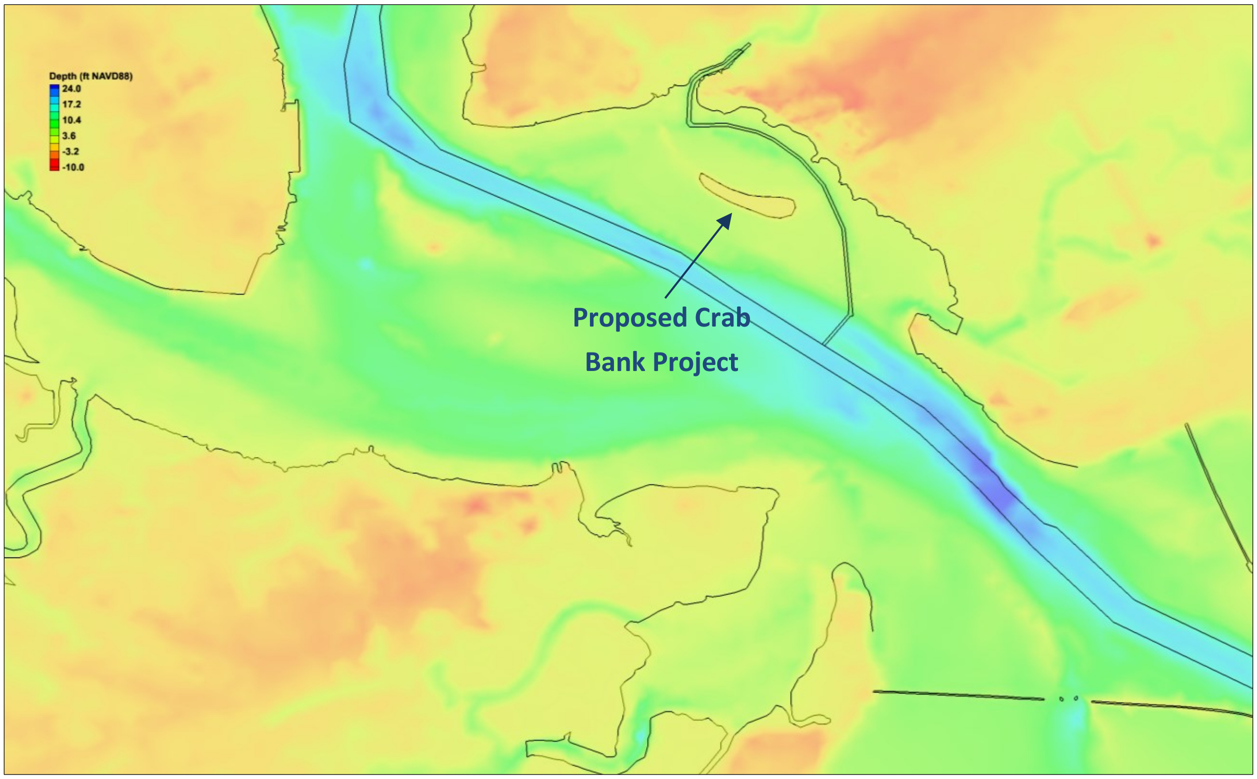


Figure 2-3. Post-project model grid elevations within model domain

Table 2-1. Tidal water level datums

Datum	Description	Elevation (ft NAVD88)
HAT	Highest Astronomical Tide	4.13
MHHW	Mean Higher-High Water	2.63
MHW	Mean High Water	2.27
NAVD88	North American Vertical Datum of 1988	0
NGVD29	National Geodetic Vertical Datum of 1929	-0.98
MSL	Mean Sea Level	-0.21
MLW	Mean Low Water	-2.95
MLLW	Mean Lower-Low Water	-3.14
LAT	Lowest Astronomical Tide	-4.65

for Charleston County (FEMA 2021). The SWEL is the projected elevation of floodwaters, in the absence of waves, due to astronomical tides, storm surge, and wave setup. Table 2-2 lists extreme stillwater elevations for at the project site from the FIS, plus an interpolated value for the 25-year return period event.

Table 2-2. Extreme stillwater elevations at the project site

Return Period (yr)	SWEL (ft NAVD88)
10	5.40
25	6.78
50	7.90
100	9.80
500	14.00

2.4 Wind Speeds

Extreme wind speeds are dominated by different meteorological events (i.e., extratropical cyclones, thunderstorms, hurricanes and tornadoes) in different regions of the country. Along the Atlantic and Gulf coastal regions, extreme wind speeds are dominated by hurricane and tropical storm events.

The American Society of Civil Engineers (ASCE) produced the consensus national standard for the engineering field for wind load design provisions as defined in *ASCE 7 - Minimum Design Loads on Buildings and Other Structures*. Prior to 2010, editions of ASCE 7 were based on hurricane wind speed predictions from an advanced hurricane model developed by Applied Research Associates under funding from the National Science Foundation during the period 1995-1997. This hurricane model analysis was published in two journal papers (Vickery et al. 2000a and 2000b). The 2010 edition of ASCE 7 was updated based on a newer and more complete analysis of hurricane characteristics (Vickery et al. 2008a, 2008b and 2009). The 2016 edition is the most recent ASCE 7 standard (referred to as the ASCE 7-16 standard).

WEC retrieved the ASCE 7-16 data for extreme wind speeds in the Charleston Harbor from the Applied Technology Council database. Table 2-3 provides the distribution of wind speeds for the 10-, 25-, and 100-year return period events. WEC adjusted the wind speed averaging durations using the methods prescribed by the Coastal Engineering Manual (USACE 2002) to convert the 3-sec gust wind speeds to the appropriate duration for fetch-limited wave growth (i.e., the duration winds must blow to create the maximum wave height given a fetch length).

Table 2-3. Extreme wind speeds at the project site

Return Period (yrs)	3-sec Gust (mph)	Adjusted wind speed (mph)	Duration (min)	Adjusted wind speed (m/s)
10	77	51.5	52.7	23.0
25	90	59.8	50.0	26.7
100	114	75.8	46.1	33.9

2.5 SWAN Inputs

Table 2-4 summarizes the SWAN model inputs. The model was executed with one wind direction, blowing from the southwest. Given that extreme winds at the project site typically occur during tropical storms, the wind can come from multiple directions during a single storm. Given the project location, modeled wind and waves approaching from the southwest will have the greatest impact to the project site and the adjacent Mount Pleasant shoreline. Therefore, the greatest project effects on storm wave reduction may be evaluated by waves approaching from southwest direction. If the direction shifts more southward or westward, the project effects on waves reaching the shoreline will shift to the west or east, but simply modeling the southwest direction is sufficient to estimate the general effects of the project on the shoreline structures.

Table 2-4. SWAN input parameters

Return Period (yrs)	Adjusted wind speed (mph)	SWEL (ft NAVD88)
10	51.6	5.4
25	59.9	6.8
100	75.9	9.8

2.6 Model Results

The SWAN model results are illustrated in the contour plots of significant wave heights shown in Figures 2-4 through 2-6 for the 10, 25 and 100-year return period events, respectively. These figures show contours of wave height as well as vector representation of wave height and wave direction (vector length is proportional to wave height). The top plot in each figure shows the modeled wave heights for the existing bathymetry conditions, and the bottom plot shows the modeled wave heights for the planned Crab Bank Restoration Project conditions. Figure 2-7 through 2-9 show the change in significant wave height calculated as the modeled post-project wave conditions minus the modeled existing conditions.

As shown by these results, the results show a large reduction in wave height along the new Crab Bank feature, which is caused by wave breaking as the waves travel over the bank. For the 10-year return period event, there is only very shallow water over the top of the bank (less than one foot), and therefore only very small waves pass over the bank in this scenario. For the less frequent events (25 and 100-year return period events), the storm surge is higher and there is a greater water depth over the top of the bank. As a result, larger waves can pass over the bank during these more extreme conditions. Northeast of the bank, the reduction in wave heights gradually decreases as distance from the bank increases.

The wave heights were output at selected points along the seaward limits of the dock and residential structures in the area (shown in Figure 2-10). The wave heights at these locations are summarized in

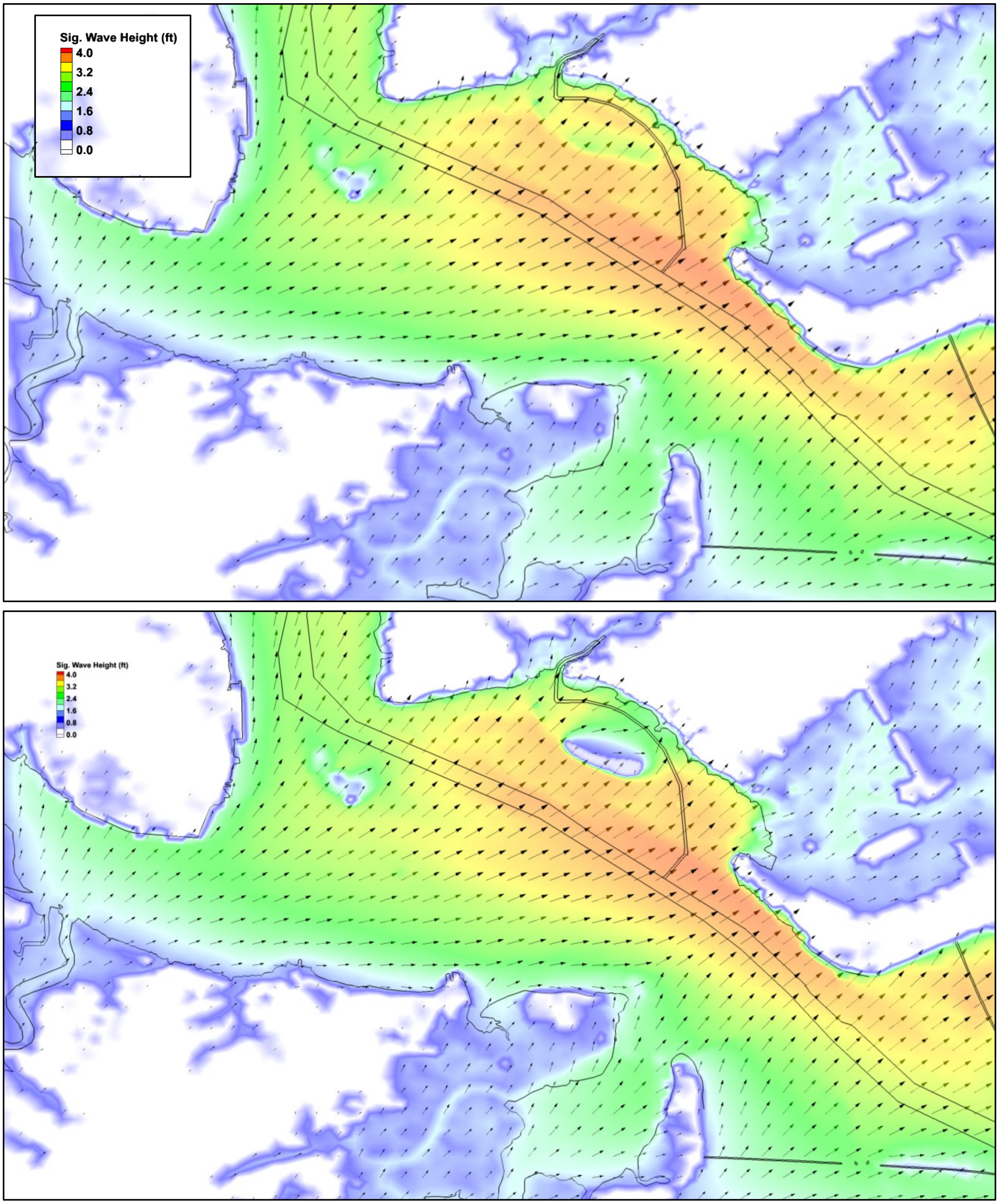


Figure 2-4. 10-year return period event modeled significant wave heights for existing (top) and post-project conditions (bottom)

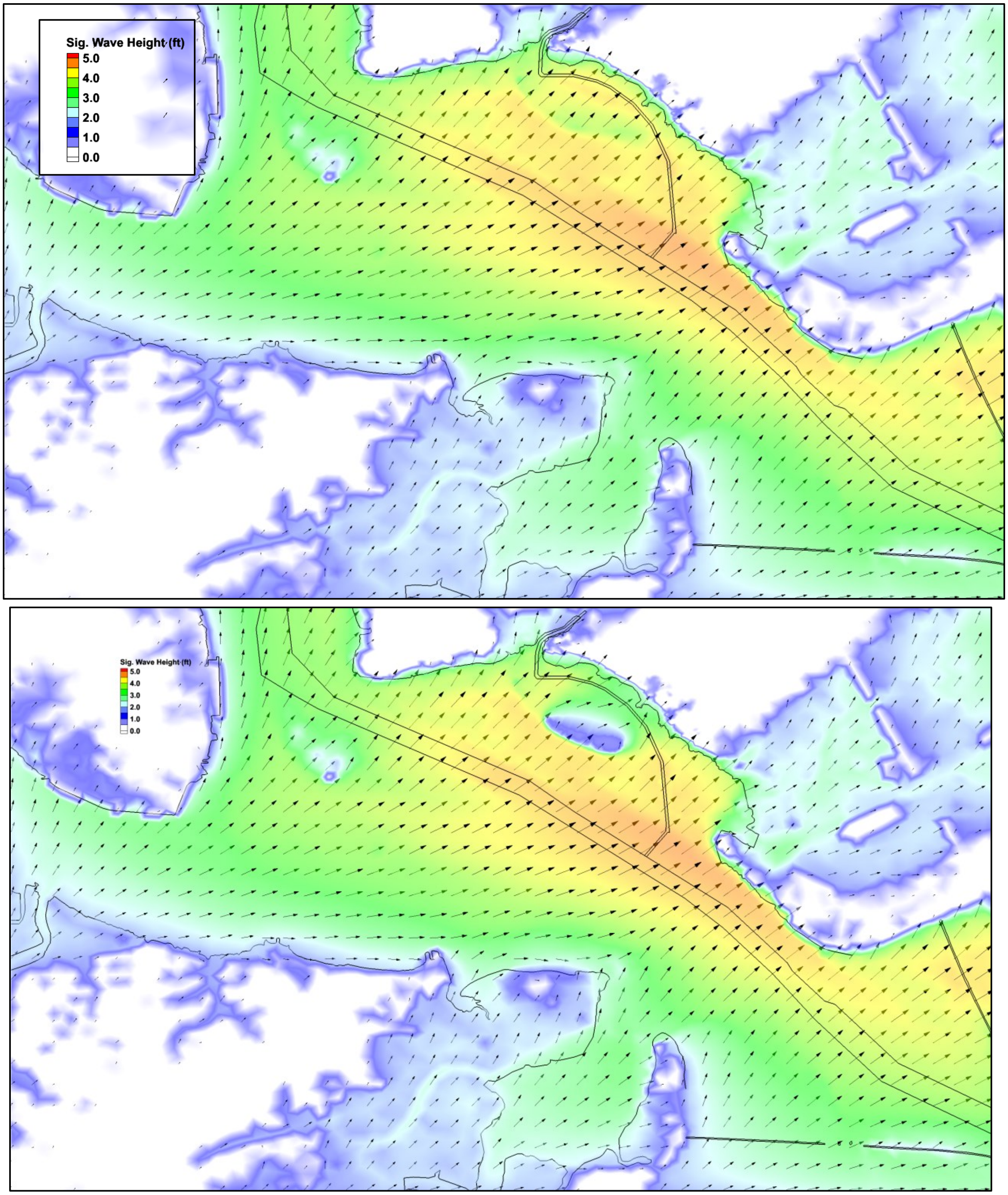
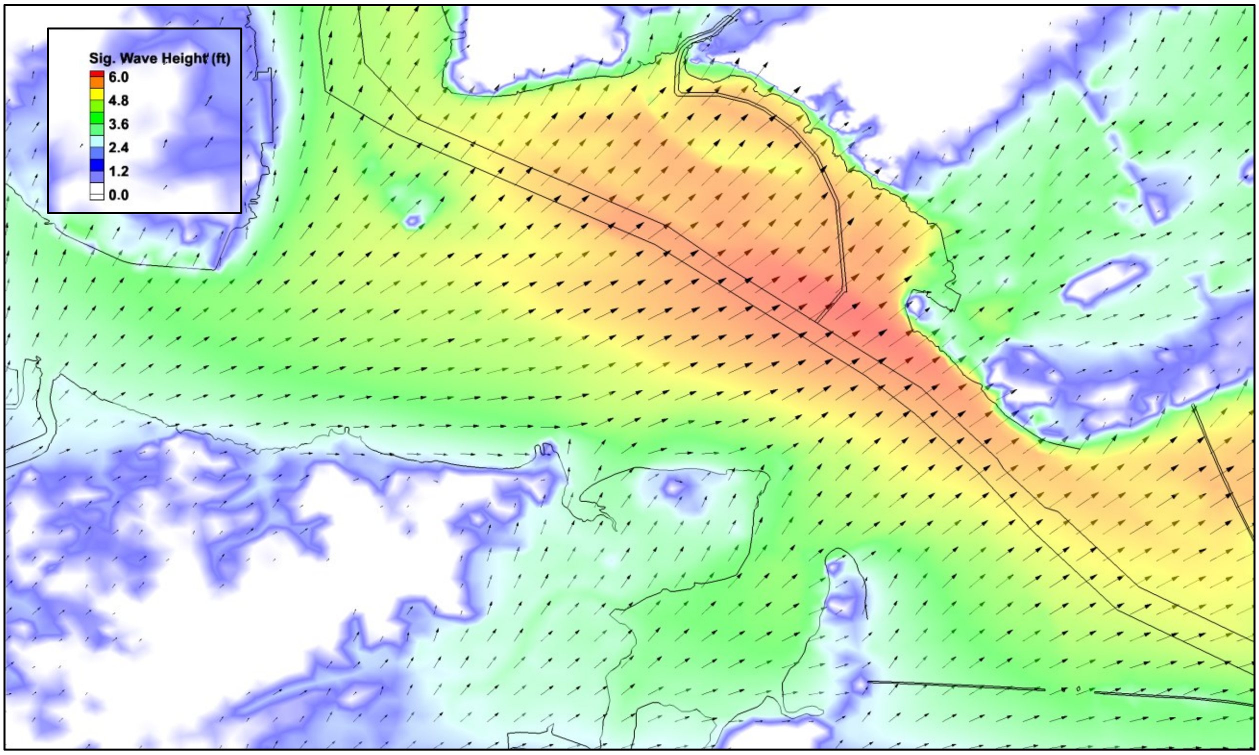


Figure 2-5. 25-year return period event modeled significant wave heights for existing (top) and post-project conditions (bottom)



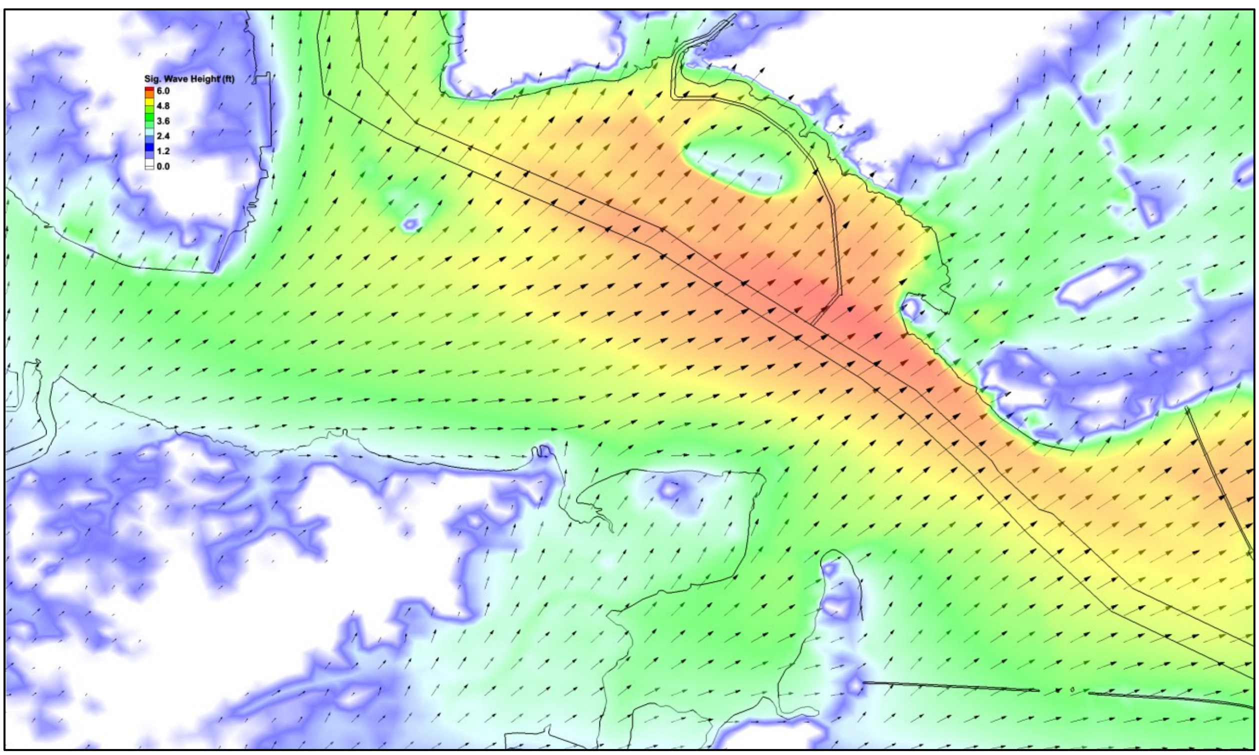


Figure 2-6. 100-year return period event modeled significant wave heights for existing (top) and post-project conditions (bottom)

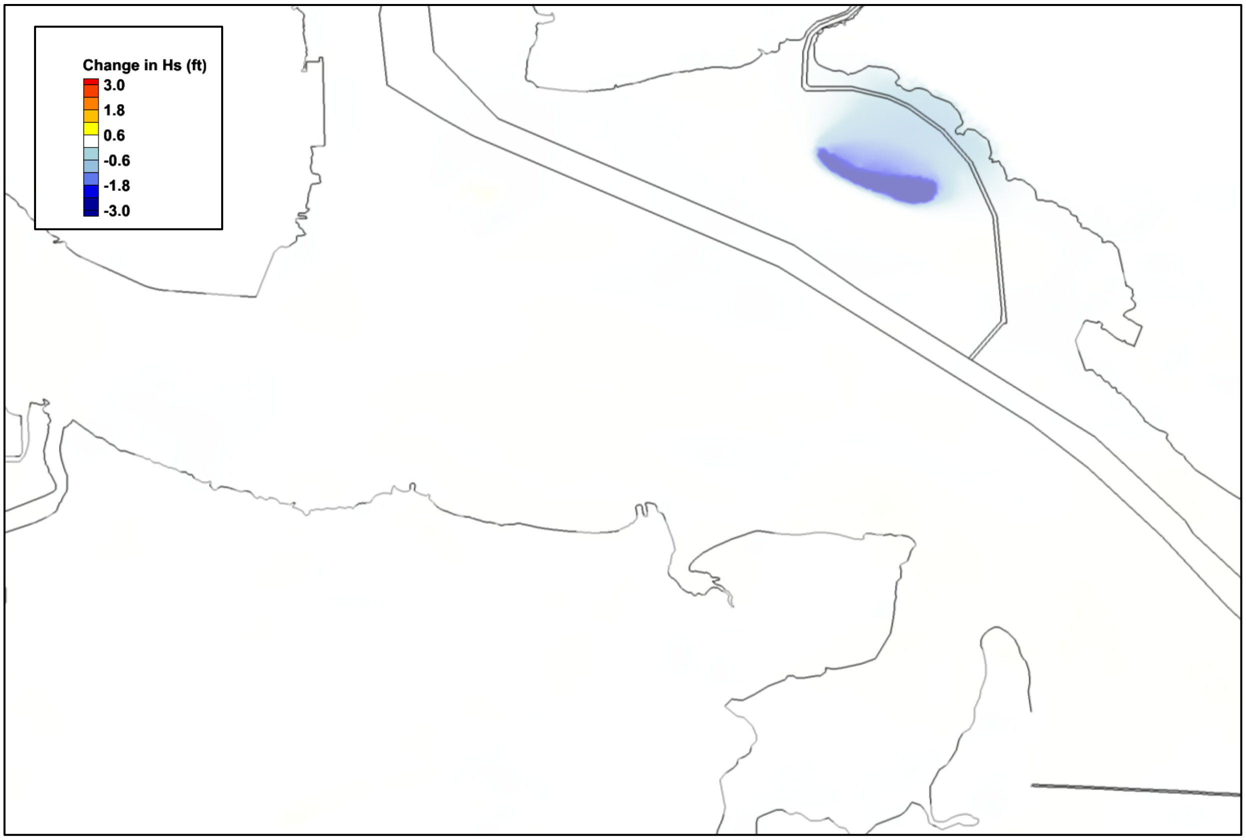


Figure 2-7. Change in modeled significant wave heights - 10-year return period event

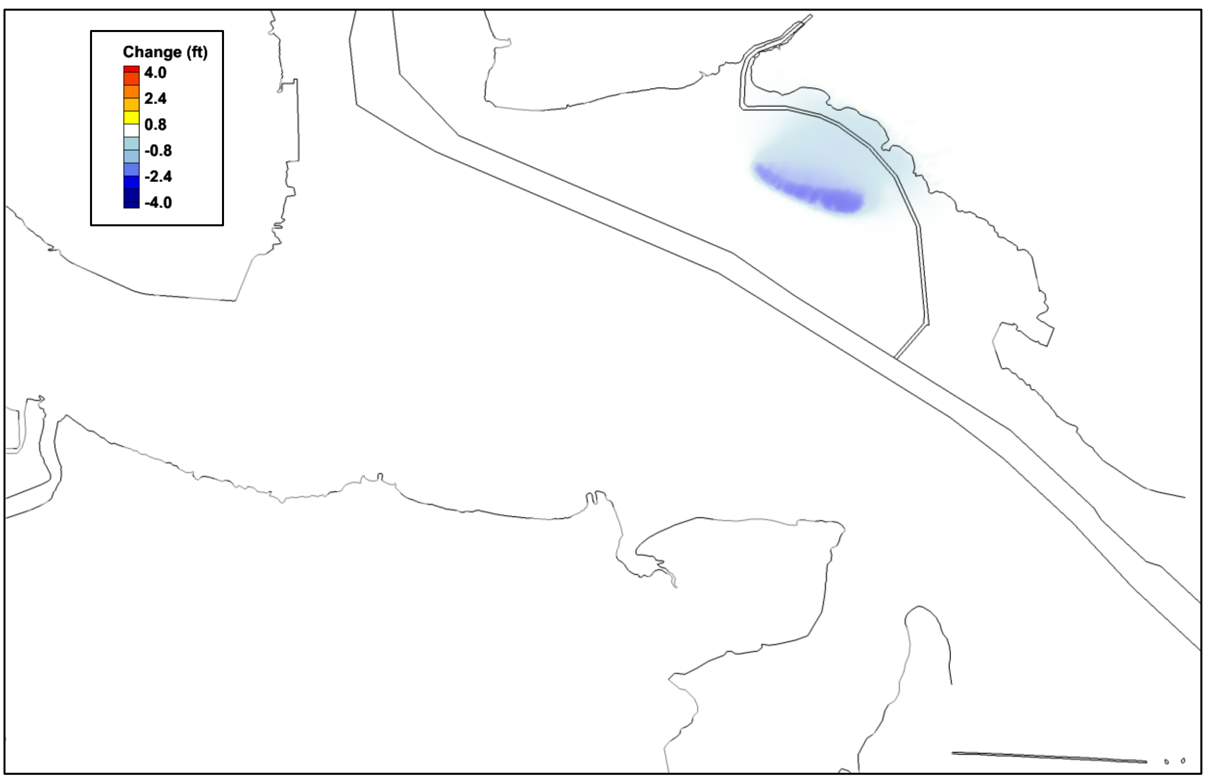


Figure 2-8. Change in modeled significant wave heights - 25-year return period event

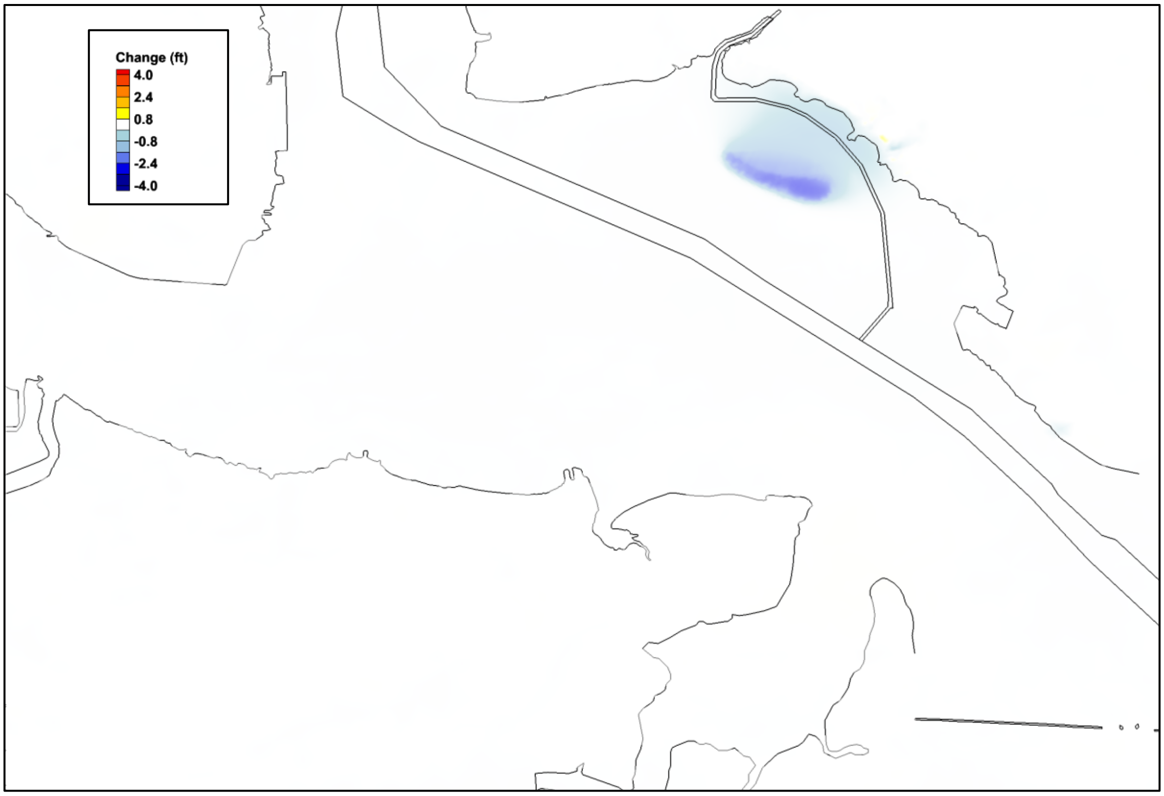


Figure 2-9. Change in modeled significant wave heights - 100-year return period event

Table 2-5 for the dock structures. No wave height table is provided for the residential structure locations because the results do not show a significant reduction in wave heights at these locations. The wave heights at the residential structure locations are zero for the 10 and 25-year return period events because the locations were not inundated for those extreme events. For the 100-year return period events, most points showed zero wave heights (i.e., not inundated), except for a few points (H14, H15 and H16). However, even at these few points there is only very shallow flooding during the 100-year return period event. The maximum wave heights at these locations are restricted by depth-limited wave breaking. As a result, the maximum waves reaching the residential structures are not reduced by the restoration project. Therefore, the modeling of 10, 25 and 100-year return period events does not show a benefit related to wave height reductions reaching residential structures, but it does show reductions in wave heights reaching the dock structures.

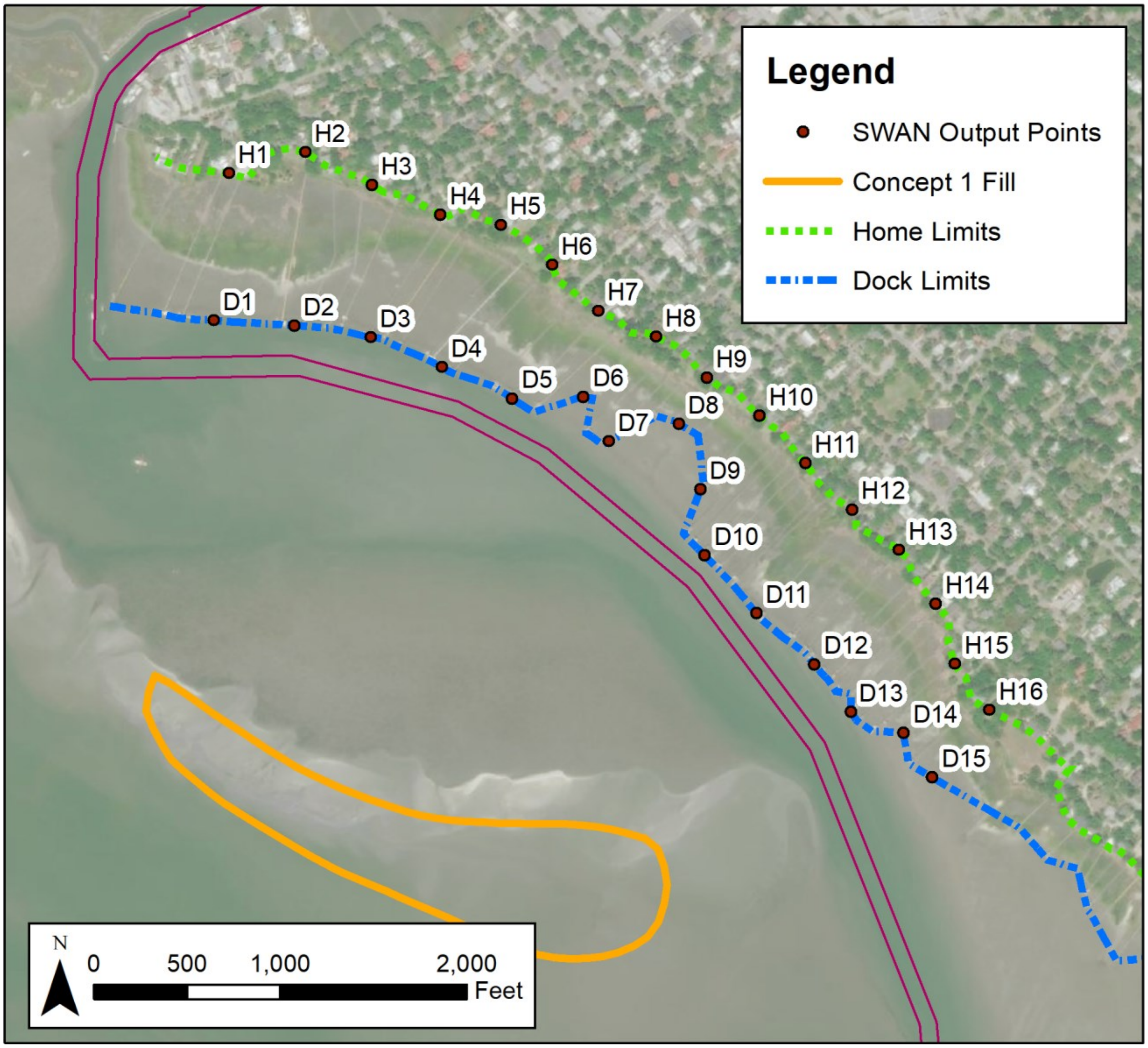


Figure 2-10. Model output points along outer limits of homes and docks

Table 2-5. Modeled changes in significant wave height at selected output locations

	10-yr return period event			25-yr return period event			100-yr return period event		
Location	Existing (ft)	Post-project (ft)	Change (ft)	Existing (ft)	Post-project (ft)	Change (ft)	Existing (ft)	Post-project (ft)	Change (ft)
D1	3.0	2.9	-0.1	3.7	3.5	-0.2	4.9	4.7	-0.2
D2	3.2	3.0	-0.2	3.8	3.6	-0.2	5.1	4.8	-0.3
D3	3.3	2.9	-0.4	3.9	3.5	-0.4	5.2	4.7	-0.5
D4	3.3	2.7	-0.5	3.9	3.3	-0.6	5.2	4.5	-0.7
D5	3.3	2.6	-0.7	4.0	3.2	-0.8	5.2	4.4	-0.9
D6	3.1	2.4	-0.7	3.8	3.0	-0.8	5.1	4.2	-0.8
D7	3.2	2.4	-0.8	3.9	2.9	-0.9	5.1	4.1	-1.0
D8	3.0	2.3	-0.7	3.7	2.9	-0.8	4.9	4.1	-0.9
D9	3.1	2.2	-0.8	3.8	2.8	-1.0	5.0	3.9	-1.1
D10	3.2	2.3	-1.0	3.9	2.8	-1.1	5.2	4.0	-1.3
D11	3.2	2.3	-0.9	3.9	2.9	-1.1	5.2	4.0	-1.2
D12	3.1	2.4	-0.8	3.8	2.9	-0.9	5.1	4.1	-1.0
D13	3.1	2.5	-0.6	3.8	3.1	-0.7	5.0	4.2	-0.8
D14	3.1	2.6	-0.5	3.7	3.2	-0.6	4.9	4.3	-0.6
D15	3.1	2.7	-0.4	3.7	3.3	-0.4	4.9	4.5	-0.5

3 Storm Damage Reduction Estimate

Given the wave heights modeled by WEC, FNI estimated the reduction in storm damages to structures along the shoreline in the vicinity of Crab Bank. See Appendix A for the complete details of the FNI analysis.

In summary, FNI developed an inventory of docks along the shoreline and compared existing dock elevations to the estimated extreme SWEL plus wave crest elevations. FNI used published wave damage curves for coastal structures for the purpose of estimating the percent damage to the docks that would occur for each storm scenario.

The results demonstrate modest but significant reductions for the 10-year return period event, for which FNI estimates a damage reduction benefit totaling approximately $1.6 million. Because of the higher water levels and wave heights that occur during the 25-year return period event, FNI estimates a near total loss of the dock structures, and the damage reduction is smaller (about $0.4 million). Given the even higher water levels and wave heights associated with the 100-year return period event, the benefits of the restoration project for that scenario are negligible.

These estimates could be higher or lower based on uncertainty in the various assumptions used in this analysis including estimated water levels, structure replacement costs, structure elevations, construction quality, and applicability of the depth-damage curves. Nonetheless, the analyses provided herein provide a reasonable approximation of the coastal storm damage reduction economic benefits that can be expected upon completion of the of the Crab Bank restoration project.

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Appendix A. FNI Crab Bank Benefits Assessment

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PROJECT:	WEN21559 – Audubon Society Wave Barrier Benefits Assessment
DATE:	September 1, 2021
CC:	Joel Tillery, PE Katie Jones, EIT

1.00 INTRODUCTION

This technical memorandum (TM) was prepared for Water Environment Consultants, LLC (WEC) to document the methods and results of an economic benefit assessment for the Crab Bank Seabird Sanctuary. As part of the Charleston Harbor Post 45 Harbor Deepening Project, the US Army Corps of Engineers (USACE) proposes to restore Crab Bank through the strategic placement of dredged fill to raise and expand the area. In addition to the ecological benefits of this restoration, fill placement has the potential to reduce leeward wave heights, reducing the risk of damage to existing docks and infrastructure along the Mount Pleasant shoreline (see Exhibit 2). Audubon South Carolina is studying the economic benefits of this restoration project, and as part of that assessment, Audubon needs an estimate of the benefits attributable to storm wave damage reduction resulting from the project.

2.00 METHODS

WEC utilized the Delft University of Technology Simulating Waves Nearshore (SWAN) model to estimate wave conditions along the Mount Pleasant shoreline adjacent to Crab Bank, both for existing conditions and with project conditions, for storm events with a 10 percent annual exceedance probability (AEP) (10-year return period), a 4-percent AEP (25-year), and a 1-percent AEP (100-year). WEC indicated that results of SWAN modeling showed that significant wave height reduction was observed at the docks and piers on the shoreline behind Crab Bank, but not at the residential structures inland of those docks and piers. Therefore, the analysis focused on assessing damage to dock and pier structures behind Crab Bank. SWAN model results, including significant wave heights (H_s), wave period (T_p), and wave direction, and still water level (SWL), and depth were provided to FNI at 31 nodes within the model domain. FNI used this data to compare the water levels (wave heights plus SWL) for the range of storms with the elevations of docks and piers for both existing conditions and with project conditions.

Pile-supported structures such as bridges and elevated buildings typically experience significant damage as storm waves produce vertical uplift forces on decks (Gutierrez, Cresanti, & Jeffrey, June 2006). Uplift was found to be the dominant failure mode for pile-supported wharves and piers exposed to storm surge and waves examined for shear and flexural failure of dowelled deck-pile connections (Balomenos & Padgett, 2018). Therefore, FNI sought information for wave damage relationships to pile-supported structures, especially those that would reflect the major failure mode for piers. The Institute for Water Resources (IWR) and Federal Emergency Management Agency (FEMA) are the principal agencies that develop standard structural damage estimating methods. Damages to existing docks and boardwalks in the vicinity of Crab Bank were estimated based on curves developed by IWR produced for the North Atlantic Coast Comprehensive Study (NACCS) (US Army Corps of Engineers, 2015) that associate the height of the wave crest relative to the finished floor elevation (FFE) to physical damage. These represented the closest match for wave-to-damage relationships that FNI could readily find to apply to pier-type structures. The FFE-damage curves were developed for a variety of residential and commercial structures, including damage related to wave crest elevation of pile-supported structures. Of the available curves, *Prototype 7A: Building on Open Pile Foundation, Wave Damage – Structure* [reference Figure 111, (US Army Corps of Engineers, 2015)] was the one that most closely resembled the expected progression of damage, shown in **Figure 1**. In the context for using the curve for pier structures, the FFE would represent the deck elevation. As wave height relative to FFE increases, the damage as a percent of the structure value also increases. Notably, the steepness of the curve between -3 and +2 feet relative to the FFE mimics the incipient and major damage that occurs as wave crests begin to impact decks from below, then through the deck elevation, as would be expected in an uplift damage situation. Therefore, it was selected to estimate damage to dock and pier structures.

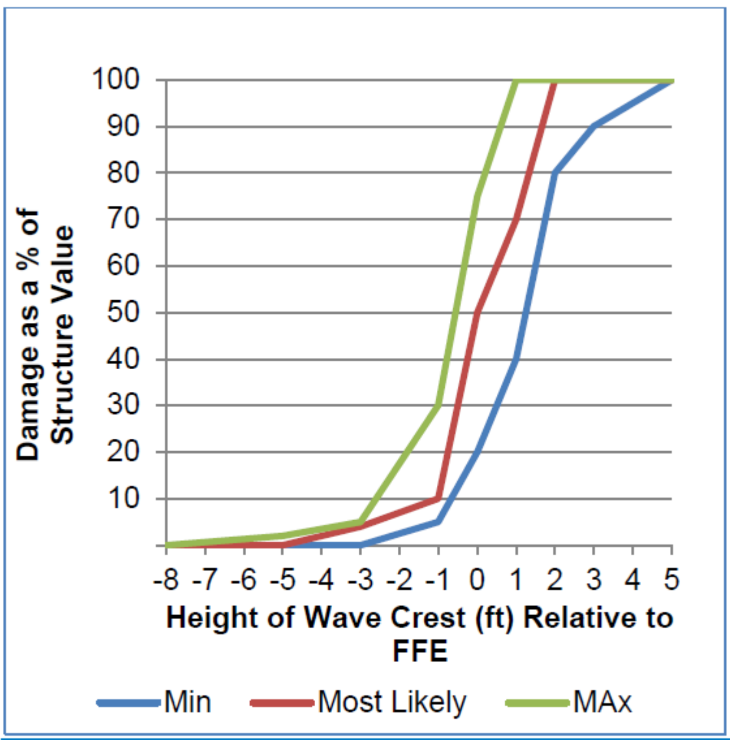

Figure 111. Prototype 7A: Building on Open Pile Foundation, Wave Damage - Structure

Figure 1: Wave Damage Curve for Building on Open Pile (Source: USACE 2015)

Typical dock and pier construction behind Crab Bank is shown in Bing Maps Birdseye imagery in **Figure 2** and **Figure 3**.

Figure 2: Typical Dock and Pier Construction behind Crab Bank (Source: Microsoft Bing Maps)

Figure 3: Closeup of Typical Dock and Pier Construction behind Crab Bank (Source: Microsoft Bing Maps)

For this analysis, the value of each structure was based on replacement costs for docks (cost per square foot) and piers (cost per linear feet). The difference between the simulated wave crest and dock / pier elevations and the associated damages were calculated for both existing conditions and with project conditions, the difference between the two representing the economic benefits.

The following subsections provide additional details of the methods used to estimate the benefits to existing structures:

Elevation Data. South Carolina Light Detection and Ranging (LiDAR) data for Charleston County was downloaded from the National Oceanic and Atmospheric Administration (NOAA) Digital Coast products and used within ESRI ArcGIS Pro to visualize and evaluate point elevations on piers and docks. The vertical datum of the elevation data was North American Vertical Datum of 1988 (NAVD88). USACE Clean Water Act (CWA) Section 404 permit information provided by the Charleston District was obtained and reviewed for selected dock and pier elevations contained in permit drawings. Elevations for four docks were discernible from permit information and used to gauge the accuracy of LiDAR over docks and piers. The NOAA Tides and Gauges station datums for the nearest gauge, Charleston, Cooper River Entrance (Station ID 8665530) was used to convert permit elevations from Mean Low Water (MLW) or Mean High Water (MHW) to NAVD88. From the available permit elevations, LiDAR data indicated prevailingly accurate values where return signal density was thicker and able to capture more of the pier or dock surface area. For example, the pier structure for Permit SAC-2016-1414 listed 5.5 feet NAVD88 for the bottom chord of the pier and the LiDAR showed 5.7 feet, which accounting for typical deck board thicknesses of 2 inches would make it very close at 5.67 feet NAVD88. Therefore, LiDAR values on docks and piers was reviewed and a representative value selected and assigned for each dock structure. Docks varied enough in indicated elevation that assigning individual dock elevations was justified for more accurate damage estimation.

Dock and Pier Inventory. Existing docks and piers were inventoried from satellite imagery along with pier length and dock area. Dock and pier elevations (NAVD88 datum) were obtained from LAS point cloud data obtained through NOAA's Digital Coast products. Dock and pier elevations estimated from the point cloud data compared favorably with the dock head grade based on terrain elevation as well as dock permits.

Dock and Pier Construction Costs. Previous and internal recreational feasibility studies were reviewed to determine a cost to rebuild the analyzed structures (BayLand Consultants & Designers, Inc. 2017; Edward J. Bloustein School of Planning and Public Policy and Center for Urban Environmental Sustainability at Rutgers, the State University of New Jersey 2015). Additionally, a Preliminary Opinion of Probable Construction Cost (OPCC) from a recent 2020 FNI project to design a new fishing pier at Martin Dies, Jr. State Park in Texas was consulted. The values found in these past studies were indexed for inflation using the US Army Corps of Engineers Civil Works Construction Cost Index System Yearly Cost Indices and corrected for state cost of living (USACE, 2021). The average of the corrected replacement costs were found to be $93.37 per square foot ($/SF).

A bulk of the cost information came from public facility or commercial piers which reflect a cost of construction and robustness expected to be higher than smaller residential docks, ranging from $82 to $115/SF for the piers. Many residential home improvement, contractor and material supplier websites cite a range for piled docks typically between $20 to $40/SF, and as high as $60/SF, recognizing that soils and construction in coastal storm vulnerable areas could drive costs higher (Smith, 2020; HomeAdvisor, 2021; CraftJack, 2021; CostOwl.com, 2021). However, aerials indicate docks behind Crab Bank, with long pier lengths (>200 feet) to span the fronting marsh, include some appearing to have composite decks, more substantial hand railing and deck construction, and potentially concrete pilings. After considering typical residential dock construction unit prices, the level and finish of construction of some of the Crab Bank docks, and the cost data reviewed, the low end of the cost data reviewed, $82/SF for the Martin Dies pier, was selected as an appropriate unit cost to avoid over or understating costs and benefits. This unit rate strikes a balance between the unit cost of typical residential pier / dock structures and higher end, more robust commercial grade dock / marine facilities. The unit cost was used along with the dock and pier area data from GIS to assign costs to each dock in the inventory.

Damage Estimation Procedure. The following procedure was used to estimate damages to dock and pier structures using the SWAN information and elevation data.

- Existing and with project wave heights at SWAN model nodes for the 10-percent, 4-percent, and 1-percent AEP were interpolated to rasters using ArcGIS Pro 3D Analyst.

- Wave heights for each storm were extracted from the interpolated rasters to points representing the existing docks and piers. SWL corresponding to each storm (5.4 feet,6.8 feet, and 9.8 feet for the 10-percent, 4-percent, and 1-percent AEP, respectively) were added to the extracted wave heights. This shown in Exhibit 3.

- Microsoft Excel spreadsheets were used to set up wave-damage calculations using the exported dock elevation and wave data, and the NACCS wave elevation-damage curve.

- Wave heights relative to FFE were calculated as the difference wave heights and dock / pier elevations. The corresponding percent damage was computed using the wave-damage curve. Wave-damage curves specific to docks and piers are not readily available; therefore, curves for buildings on open pile foundation were assumed to approximate the damage characteristics. As shown Exhibit 1, there are three curves reflecting the “minimum,” “most-likely,” and “maximum” damage that is likely to occur for a given wave height relative to FFE. Initial results using all three curves showed near or 100 percent damage at the 10 percent event with the “most-likely” and “maximum” range curves. This was deemed not realistic given damage seen in aerials following different storms. These curves essentially also did not produce benefit because the damage started at low wave crest elevations in both without and with-proposed restoration damages with little damage reduction calculated. For this analysis, the “minimum” curve was used assuming that piers and docks are designed and constructed in consideration of potential wave impacts.

- The difference between the damages for each structure under existing vs. with project conditions was calculated as the benefit and then summed to estimate the total project economic benefits.

Event damages were not converted to annual expected damages (AED) based on the probability of event occurrence during a given year because the results showed 100 percent damage at the 10-percent AEP, and would therefore not result in a useful calculation. This is further discussed in Section 3.00 Results.

3.00 RESULTS

A total of 27 structures were inventoried with an average replacement cost of approximately $417,615 for a total replacement cost of $11.3M. **Table 1** summarizes the results of the damage estimate, showing minimums, maximums, and averages of damage and the damage reduction benefit for existing and proposed restoration conditions under the three return periods. The bottom row lists the total damages and benefits for all 27 structures. As shown in Column A, wave heights plus SWL for each of the events simulated exceed the dock and pier elevations obtained based on the LiDAR data. This results in average percent of structure value damages (Column B) for the 10-year event approaching an average of 77 percent, and a near total loss at the 25-year and the 100-year event with 96.5 and 99.6 averages, respectively. The reduction in wave heights resulting from the restoration of Crab Bank yield modest reductions in percent damage with an average of approximately 64 percent damage for the 10-year event, reducing damages (Column C) from $8.6 million to $7 million, an average reduction of 13 percent providing a total of $1.55 million in benefits (Column D) for the 10-year single event. The benefits for the 25-year are significantly smaller at an average reduction of 4 percent, and approximately $400,000 in total benefits. The benefits of the restoration for the 100-year event are negligible if not zero. **Table *2*** summarizes the stillwater elevations (SWEL) and wave heights produced by the SWAN modeling along with the damage summary.

As mentioned above, the results indicate an average percent of structure value damage of 77 percent during the 10-year event, which may be somewhat high, but within reason for use in a reconnaissance-level of damage estimate. Hurricane Matthew in October 2016 made its South Carolina landfall as a Category 1 Hurricane at Cape Romain National Wildlife Refuge, about 17 miles north of Charleston, producing large surge flooding and the third highest water level ever recorded at the downtown Charleston tidal gauge (National Weather Service, 2021). It produced wind gusts in Charleston Harbor of 75 miles per hour (mph), similar to the 10-year wind gust of 77 mph from American Society of Civil Engineers' (ASCE) ASCE-7 Hazard Tool (American Society of Civil Engineers, 2018). Because the storm eye track skirted up the South Carolina coast, it impacted the south shoreline of the harbor and not the docks behind Crab Bank. **Figure 4** and **Figure 5** show Google Earth aerial imagery before and after Hurricane Matthew, showing piers east of the James Island Yacht Club suffering damage. Visually, approximately 5 of 9 piers experienced significant damage. **Figure *6*** provides a typical close-in view, showing that the decking is almost completely gone, but most pier piles and caps remain.

Another recent storm, Hurricane Harvey, made landfall on August 2017 at Rockport, Texas as a Category 4, moving inland approximately 90 miles dissipating to a tropical storm before turning back out through Matagorda Bay, and passing Palacios, Texas along its way (Consortium of Universities for the Advancement of Hydrologic Science, Inc., undated). Palacios reported maximum sustained winds of 49.5 mph and maximum gusts of 69 mph, from the South-Southeast during the initial inland path (National Weather Service, 2017). The 10-year gust value from the ASCE-7 Hazard Tool is 79 mph (American Society of Civil Engineers, 2018) which is about 15% higher, but generally near the range of the event. **Figure 7** and **Figure 8** show the piers at Grassy Point at Palacios before and after the hurricane passed. Visually, approximately 9 out of 13 piers were damaged significantly. **Figure 9** provides a close-in view, which similar to Charleston, shows that most of the decking is completely gone, but most pier piles and caps remain. The Palacios area was selected for review, because landfall at Rockport as a Category 4 likely made too severe an event to compare to 10-year event severity. Interestingly, before and after aerials show pier damage was more extensive at Rockport with almost all showing damage and most showing significant deck damage and more missing piles. This would be similar to the near total damage observed at the 25 and 100-year events when applying the NACCS curves.

Table 1: Summary of Estimated Damages and Damage Reduction Benefits

VALUE	DOCK ELEVATIONS (ft NAVD88)	(A) SWL+WAVE CREST RELATIVE TO DOCK ELEVATION						(B) % DAMAGE OF TOTAL STRUCTURE VALUE						(C) DAMAGE						(D) DAMAGE REDUCTION BENEFIT		
		EXISTING			PROPOSED RESTORATION			EXISTING			PROPOSED RESTORATION			EXISTING			PROPOSED RESTORATION			EXISTING - PROPOSED RESTORATION		
		10 YEAR	25 YEAR	100 YEAR	10 YEAR	25 YEAR	100 YEAR	10 YEAR	25 YEAR	100 YEAR	10 YEAR	25 YEAR	100 YEAR	10 YEAR	25 YEAR	100 YEAR	10 YEAR	25 YEAR	100 YEAR	10 YEAR	25 YEAR	100 YEAR
MIN	4.7	0.70	2.70	7.00	0.20	2.20	6.40	34.0	86.0	99.6	24.0	81.0	99.6	$ 144,769	$ 160,211	$ 160,211	$ 110,897	$ 155,225	$ 160,211	$ 9,651	$ 3,862	
MAX	7.9	3.50	5.50	9.70	2.70	4.80	9.00	92.0	99.6	99.6	86.0	99.0	99.6	$ 572,893	$ 641,125	$ 664,075	$ 553,582	$ 637,263	$ 664,075	$ 147,075	$ 29,825	
AVG	6.2	2.37	4.43	8.65	1.71	3.69	7.84	76.8	96.5	99.6	63.8	92.8	99.6	$ 317,429	$ 401,530	$ 415,945	$ 259,873	$ 386,449	$ 415,945	$ 57,556	$ 15,081	$ -
													TOTAL	**$8,570,596**	**$10,841,318**	**$11,230,524**	**$7,016,584**	**$10,434,121**	**$11,230,524**	**$1,554,012**	**$407,197**	**$ -**

Table 2: Summary Statistics for Wave Heights, Elevations, and Percent Damage

Parameter	Condition	Event Return Period (Year)	Mean
SWEL (ft NAVD88)*	Existing and Proposed Restoration	10	5.4
		25	6.8
		100	9.8
WAVE HEIGHTS (ft)	Existing	10	3.09
		25	3.76
		100	4.99
	Proposed Restoration	10	2.45
		25	3.01
		100	4.15
WAVE HEIGHT REDUCTIONS (ft)	Existing – Proposed Restoration	10	0.64
		25	0.75
		100	0.84
SWEL+WAVE CREST RELATIVE TO DOCK (ft NAVD88)	Existing	10	2.37
		25	4.43
		100	8.65
	Proposed Restoration	10	1.71
		25	3.69
		100	7.84
% DAMAGE OF TOTAL STRUCTURE VALUE	Existing	10	77.80
		25	96.51
		100	99.60
	Proposed Restoration	10	63.81
		25	92.78
		100	99.60

*Stillwater elevations (SWEL) provided by WEC; proposed restoration does not change SWEL.

Figure 4: Aerial Image of South Shore of Charleston Harbor, October 2015 before Hurricane Matthew (Source: Google Earth and Image © 2021 Maxar Technologies). Note yellow arrows at intact piers.

Figure 5: Aerial Image of South Shore of Charleston Harbor, October 2016 after Hurricane Matthew (Source: Google Earth and Image © 2021 Maxar Technologies). Note yellow arrows at damaged piers.

Figure 6: Close-in View of Post-Hurricane Matthew Pier Damage

Figure 7: Aerial Image of Grassy Point at Palacios, Texas November 2014 before Hurricane Harvey (Source: Google Earth and Image © 2021 Maxar Technologies). Note yellow arrows at intact piers.

Figure 8: Aerial Image of Grassy Point at Palacios, Texas December 2018 after Hurricane Harvey (Source: Google Earth and Image © 2021 Maxar Technologies). Note yellow arrows at damaged piers.

Figure 9: Close-in View of Post-Hurricane Harvey Pier Damage

Since hurricane severity and probability at a given location depends on many storm parameters such as central pressure, storm track, and radius to maximum winds, this would require Joint Probability Method (JPM) analysis to truly assign a probability from hurricane-generated waves, which is beyond the scope of this estimate. Wave damage severity in this context is probably most influenced by surge, sustained winds and track. From the Hurricanes Matthew and Harvey examples, events with winds around the wind 10-year return period values do show the potential to generate waves that significantly damage most docks in an area, tearing most of the decking, but typically leaving most piles and caps in place. From the Martin Dies fishing pier estimate reviewed, piles potentially comprise approximately 30 percent of the pier and dock cost. Thus the bulk of the remaining 70 percent would be comprised of decking costs (pile caps, stringers, deck and rail). The damage observed in the hurricane aerials would then be consistent with the 77 percent damage that the application of the NACCS curves resulted with the SWAN data for the 10-year event.

However, this rudimentary review indicates that not every dock will experience significant damage. This can be attributed to differences in construction robustness and age between piers, especially deck to stringer or stringer to cap connections. Curves developed or modified to account for these differences would have to account for different construction types or techniques related to resisting uplift. Thus, with not all piers being significantly damaged, less damage may be expected in actual storms for more frequent return periods. This reveals limitations of using these curves, built for residential structures and buildings on piles, which may experience more uniformly severe damage once they get exposed to the most severe uplift forces around the FFE. However, the curve progression, where major damage is experienced as stillwater elevations and wave crests approach and pass through the deck elevation appears consistent with literature on the major causes of pier failure.

4.00 SUMMARY AND CONCLUSION

FNI computed economic benefits to dock and pier structures that are likely to be protected by the Crab Bank Sanctuary. A geospatial and spreadsheet analysis was conducted to inventory docks/ piers, and compare existing dock elevations to predicted water and wave crest levels to apply published wave damage curves for coastal structures for the purpose of estimating the percent damage. The results demonstrated modest but significant reductions for the 10-year return period event, minor benefit at the less frequent 25-year event, and no benefit at the 100-year event. These estimates could be higher or lower based on various assumptions used in this analysis including estimated water levels (see WEC documentation for model description and assumptions), structure replacement costs, structure elevations, construction quality, and applicability of the depth-damage curves. The methods and results documented herein are believed to provide a good approximation of the coastal storm damage reduction economic benefits that can be expected upon restoration of Crab Bank.

5.00 REFERENCES

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Attachment A - Exhibits

Exhibit 1. Wave Height Damage Curve for Buildings on Open Pile Foundation

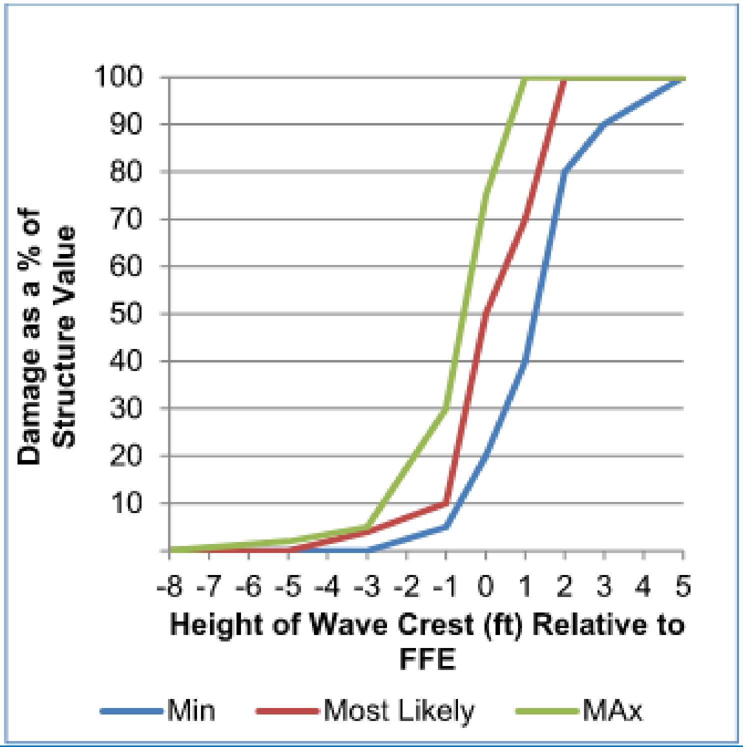

Figure 111. Prototype 7A: Building on Open Pile Foundation, Wave Damage - Structure

Table 95. Prototype 7A: Building on Open Pile Foundation, Wave Damage - Structure

Wave Crest	Min	Most Likely	Max
-8	0	0	0
-5	0	0	2
-3	0	4	5
-1	5	10	30
0	20	50	75
1	40	70	100
2	80	100	100
3	90	100	100
5	100	100	100

FN PROJECT NO. WEN21669
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DATUM & COORDINATE SYSTEM NAD83 UTM 17N
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AUDUBON SOUTH CAROLINA
Crab Bank Benefits Assessment

Crab Bank and Benefited Structures

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EXHIBIT
2

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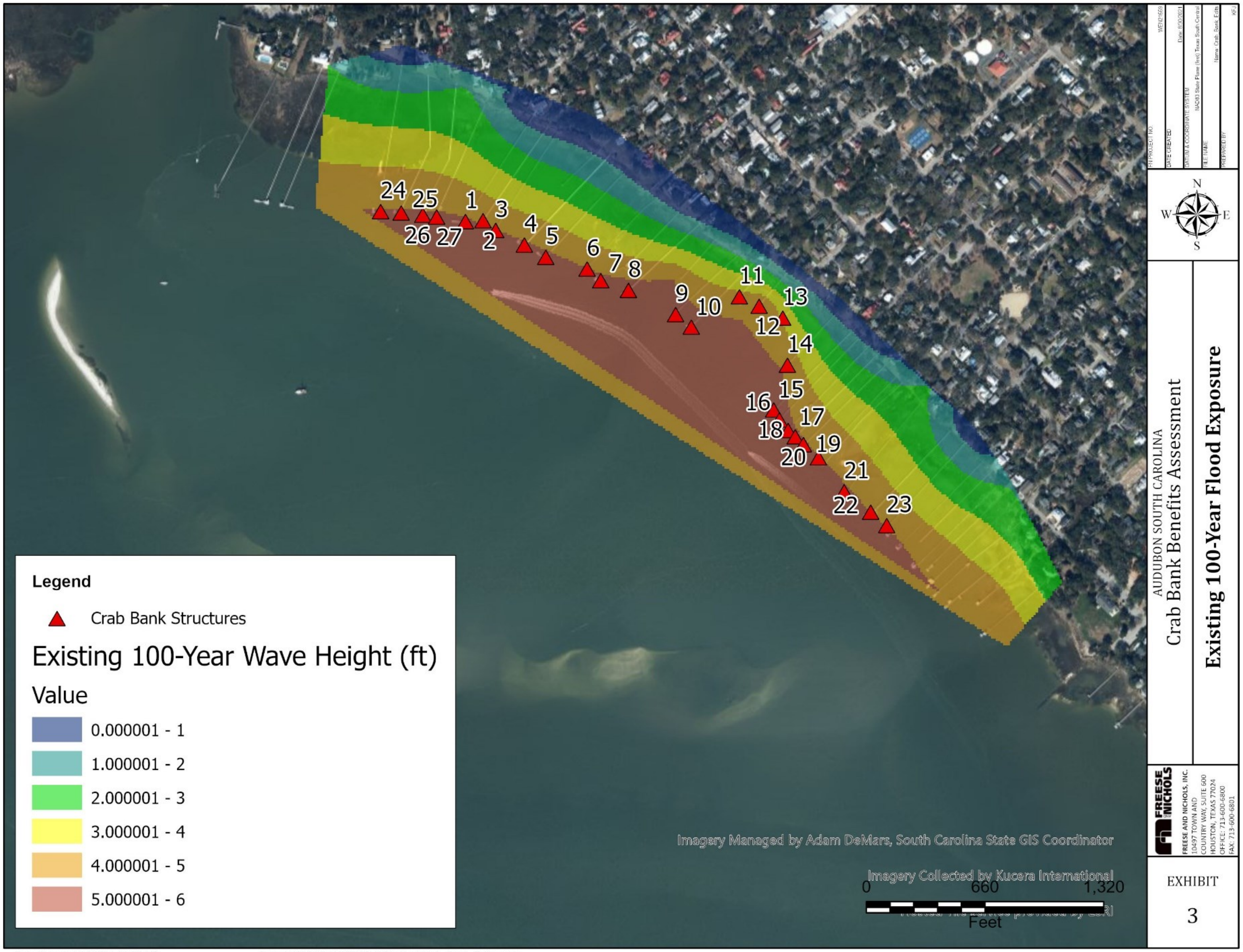

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