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Memorandum

To: Biohabitats, Inc.

From: Moffatt & Nichol

Date: January 2023

Subject: Wave Modeling and Coastal Engineering

Project: Nags Head Estuarine Shoreline Management Plan

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1.0 INTRODUCTION

The following memorandum details the wave modeling and coastal engineering study conducted to support the design of Nags Head Estuarine Shoreline Management Plan project. The purpose of the study was to characterize the water levels and wave climate at the project site (Figure 1) and use statistical analysis of these environmental parameters to inform the design of living shorelines to meet the goals of the shoreline management plan.

With the normal conditions (constant winds with high magnitude on an annual basis) and extreme (infrequently occurring, potentially damaging conditions associated with storm events) wave heights and wave periods determined, various living shoreline types will be considered for their appropriateness.

Figure 1: Project area with locations of water level gage and wind stations

2.0 WATER LEVELS

2.1 Vertical Datums

The vertical datum for this study is the North American Vertical Datum of 1988 (NAVD88). Because this study considers Sea Level Rise (SLR) as a variable, the reference tidal datums (e.g., Mean Sea Level (MSL)) are not static. The tidal datums that are currently reported by NOAA for Duck, NC (NOAA Station 8651370) are generally not applicable for the project, considering that the project is substantially isolated from open ocean tides (due to limited flows through Oregon Inlet and the large size of Albemarle Sound, which absorbs any tidal flows with minimal water level change). However, the MSL reported for Duck, NC may be considered broadly indicative of the relative sea level in the vicinity of the project (Overton, et al. 2015). The Duck tide gauge reports an MSL of -0.42 ft NAVD88, which corresponds to the 1983 to 2001 tidal epoch (i.e., approximately MSL in 1992). This study accounts for the change in sea level between 1992 and 2022 by assuming a combination of the historic rates and the projections reported by NOAA. This results in an increase in all water levels of 6.7 inches (or 0.56 ft) between 1992 and 2022 resulting in an assumed MSL in 2022 of +0.14 ft-NAVD.

2.2 In-situ Water Level Measurements

Water level measurements are available at four Hohonu stations (https://www.hohonu.io/) near the project site. The gage location map is given in Figure 1 and the gage station information is listed in Table 1.

Table 1: Water level gage station information

Source	Station	Start Date	End Date	Frequency
Hohonu	Collington Creek Inn Dock, Kill Devil Hills	01/18/2021	02/15/2022	6-min
Hohonu	Village of Nags Head Golf Links	01/28/2021	02/15/2022	6-min
Hohonu	Hwy 64, Little Bridge, Dare County	04/16/2021	02/15/2022	6-min
Hohonu	Coastal Studies Institute (CSI), Wanchese	03/16/2021	02/15/2022	6-min

Among all the gages, the gage at Nags Head Gold Links was the closest to the project site. However, a large amount of measured data at this gage was of bad quality or had errors. Similar observation of bad quality data was found at the Collington Creek Inn Dock gage. As a result, water level data analysis was not performed at those two gages with the focus instead on the gages at Little Bridge and CSI Wanchese. From Table 1, the measurement periods are short (< 1 year) at those two gages. Thus, the following water level analysis results are only representative of the past year or so instead of a longer-term representation.

The percent of exceedance results referring to NAVD88 for the gages at Little Bridge and CSI Wanchese are shown in Figure 2 and Figure 3, respectively while Table 2 gives the percentage of exceedance values. In general, water level ranges and high water levels are small at both gages with the probability ≥ 1 ft at only 10% at the Little Bridge gage and 5% at the CSI Wanchese gage.

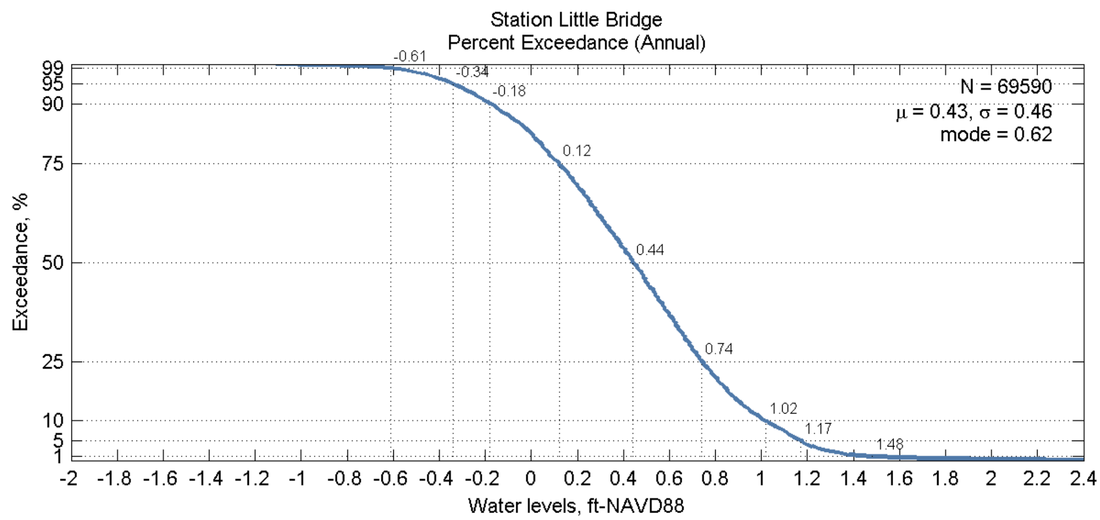


Figure 2: Cumulative exceedance plot for water levels at Little Bridge gage

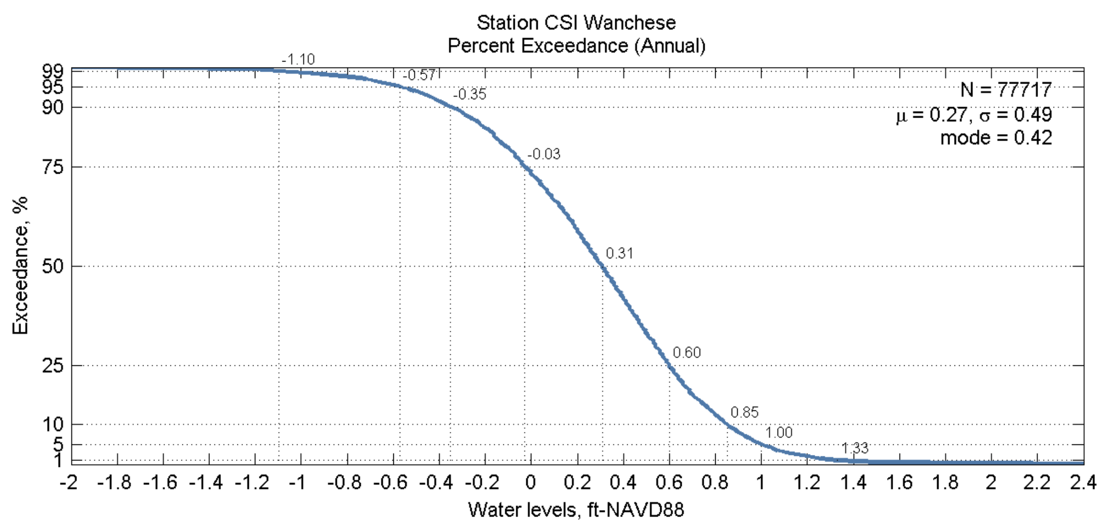


Figure 3: Cumulative percentage of exceedance plot for water levels at CSI Wanchese gage

Table 2: Percentage of exceedance value for water levels at the Little Bridge and CSI gages (ft-NAVD88)

Percentage of Exceedance [%]	Little Bridge	CSI Wanchese
99%	-0.6	-1.1
95%	-0.3	-0.6
90%	-0.2	-0.4
75%	0.1	0.0
50%	0.4	0.3
25%	0.7	0.6
10%	1.0	0.9
5%	1.2	1.0
1%	1.5	1.3

2.3 FEMA Surge Levels

Extreme value analysis cannot be conducted based on gage data due to the short measurement periods. Thus, extreme surge levels from FEMA (https://fris.nc.gov/fris/Home.aspx?ST=NC) are presented in Table 3 to show the surge levels at different return periods. The 10-year surge level from FEMA is 1.7 ft which is 13% and 31% higher than the 1% of exceedance value in little bridge (1.5 ft) and CSI Wanchese (1.3 ft), respectively.

Table 3: Surge levels from FEMA (ft-NAVD88)

Return Period (yr)	Surge Level
10	1.7
25	2.7
50	3.3
100	5.0
500	10.0

2.4 Local Sea Level Rise

While considerable effort is focused on the underlying science for predicting changes in the global mean sea level, the work products produced by these studies are not always in a format that is useful for incorporating to coastal planning and design projects (Hinkel, et al. 2019). In particular, global estimates of mean sea level change are not directly applicable to any specific project; local effects such as vertical land motion can add or subtract from the global rate of sea level change. Additionally, changes to the earth's gravitational field due to melting of polar ice results in significant variability in the distribution of the resulting sea level change, i.e., when ice melts, the sea level does not go up everywhere by the same amount (e.g., Bamber and Riva, 2010, Mitrovica, et al., 2011 and Adhikari, et al., 2019).

Because of the complexity in accounting for local effects, some sea level rise studies account only for the global mean sea level change and the local vertical land motion. That is the procedure followed by the North Carolina Sea Level Rise Assessment Report (Overton, et al. 2015). Some other recent studies have produced sea level rise projections that do include more of the local effects and present results in a very useful format. For example, in addition to producing probabilistic analyses for global mean sea level change, Kopp et al. (2014) and Kopp et al. (2017) provide detailed local probabilistic sea level rise projections for tide gauges (and other output points) throughout the world. These local projections can be used for planning and design, incorporating the local effects of subsidence as well as the expected variation in global sea level change.

The projections labeled “K14” are based on Kopp et al. (2014), which relies on the expert elicitation work of Bamber and Aspinall (2013) for characterizing the contribution to sea level rise from ice sheets. The likely ranges for the K14 projections published in Kopp et al. (2017) present comparable results to other projections. Dr. Robert Kopp is one of the leading scientists contributing to 2017 NOAA Report on Sea Level Rise in the U.S. (Sweet, et al. 2017). This work represents the best available scientific basis for estimating local sea level change at tide gauges around the country. Some states (e.g., Maryland, see Boesch et al. (2018)) have explicitly relied on the K14 results. Other states use the underlying science through reference to the NOAA report or through commission of other studies that use the same methodology (e.g., New York City Panel on Climate Change, see Horton et al. (2015) and Gornitz et al. (2019)).

The K14 projections represent the best available projections for local sea level change in North Carolina and were used for this study. The K14 projections for relative sea level change for Duck, NC are shown in Figure 4 and Figure 5. The local sea level change along the Town of Nags Head’s estuarine shoreline is taken as equal to the local sea level change at the Duck tide gauge. This is reasonable due to the structure of the underlying geologic framework, as outlined in Overton et al. (2015). Nags Head is in the Albemarle Embayment Zone which is the same zone as the Duck tide gauge. The Duck tide gauge is the only long-term tide gauge in this zone, as well as being the closest tide gauge to the project.

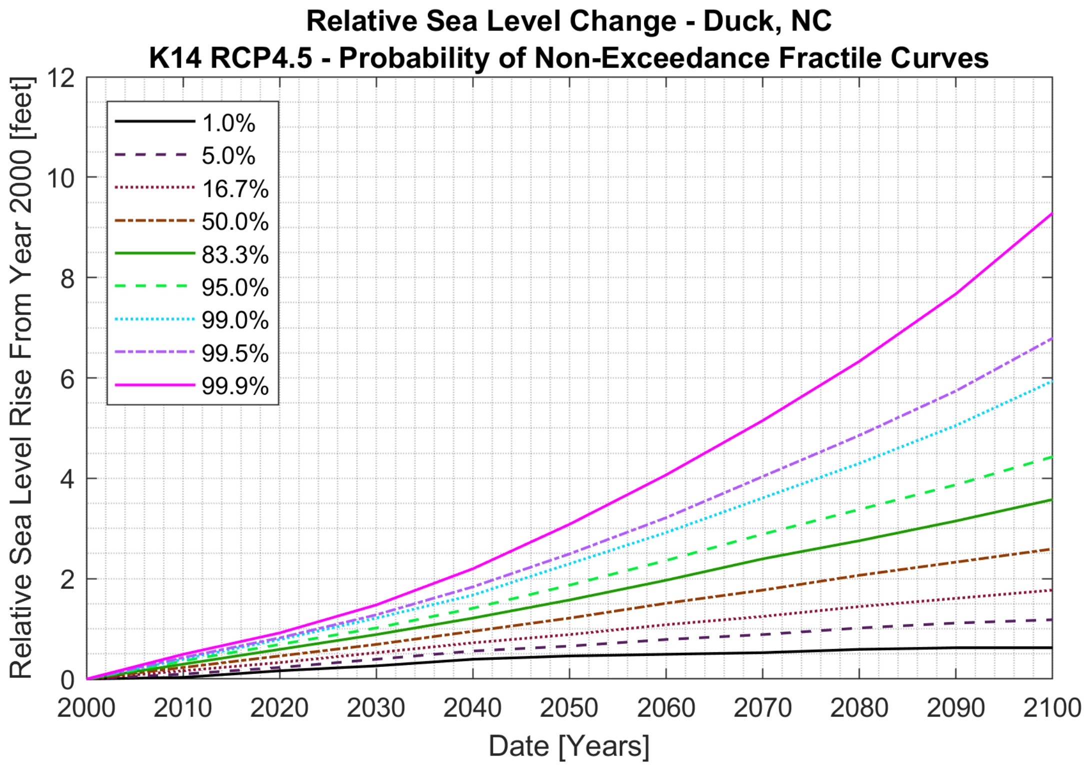


Figure 4: Relative Mean Sea Level Change – Duck, NC (K14 RCP4.5)

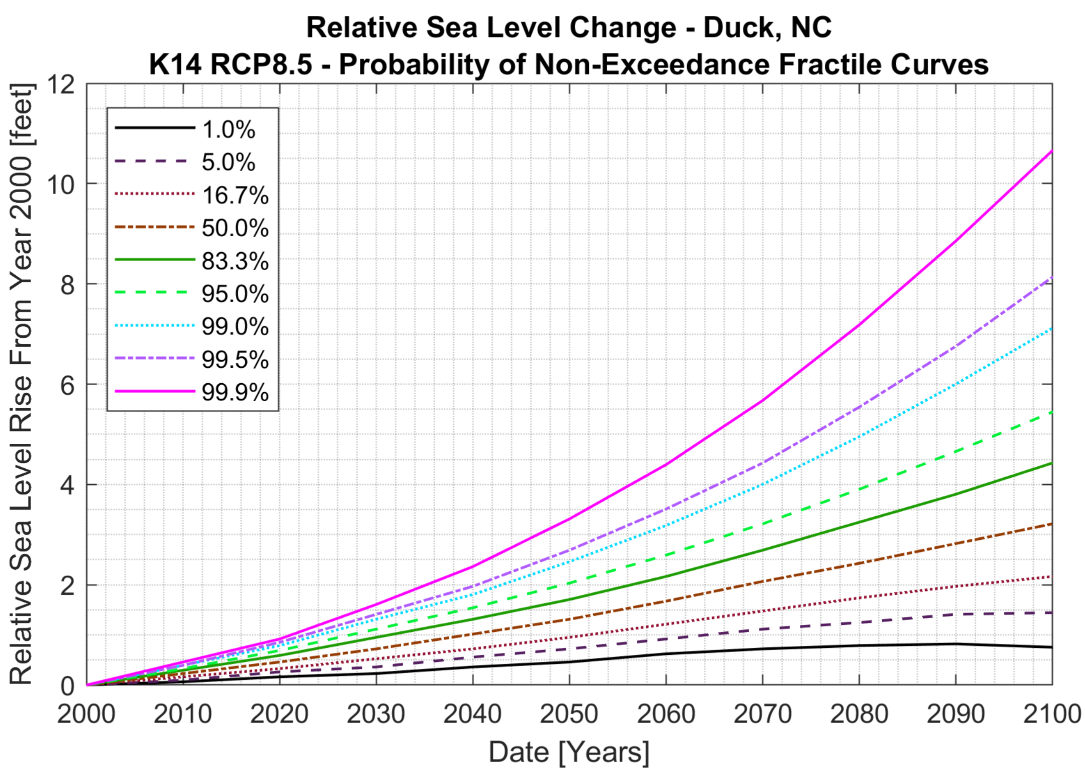


Figure 5: Relative Mean Sea Level Change – Duck, NC (K14 RCP8.5)

3.0 WINDS

3.1 In-situ Wind Measurements

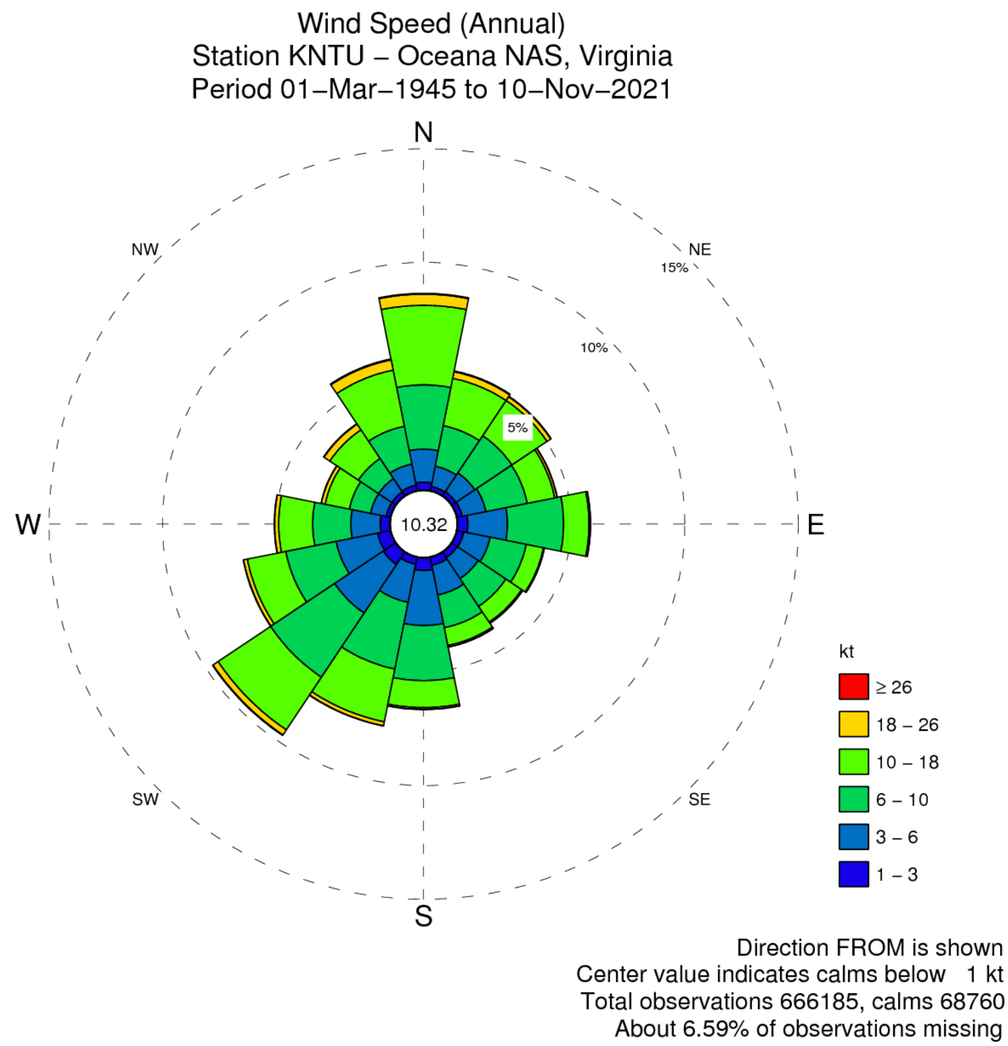
To identify the dominant wind directions with large magnitudes at the project site, wind data were analyzed from two sources - Meteorological Terminal Air Reports (METAR) data located at airports and data from the National Oceanic and Atmospheric Administration's (NOAA) Center for Operational Oceanographic Products and Services (CO-OPS).

The historic records for METAR stations KNTU (Oceana NAS, Virginia), KONX (Currituck, North Carolina), KMQI (Manteo, North Carolina) and KFFA (Kill Devil Hills, North Carolina) were obtained from the Iowa State University's Iowa Environmental Mesonet (https://mesonet.agron.iastate.edu/request/download.phtml). Wind data for NOAA CO-OPS station 8651370 (Duck, NC) were collected from the NOAA CO-OPS website (https://tidesandcurrents.noaa.gov/inventory.html?id=8651370). The station locations are shown in Figure 1. The details of these wind stations are listed in Table 4.

Table 4: Wind data stations

Source	Station	Anemometer elevation (ft)	Period of Record	Frequency	Wind averaging
METAR	KNTU	23.0	03/1945 - present	1 hr	2-min
METAR	KONX	16.1	08/2004 - present	20 min	2-min
METAR	KMQI	13.1	03/1945 - present	1 hr	2-min
METAR	KFFA	13.1	02/2004 - present	20 min	2-min
NOAA	8651370	27.2	10/1995 - present	1 hr	2-min

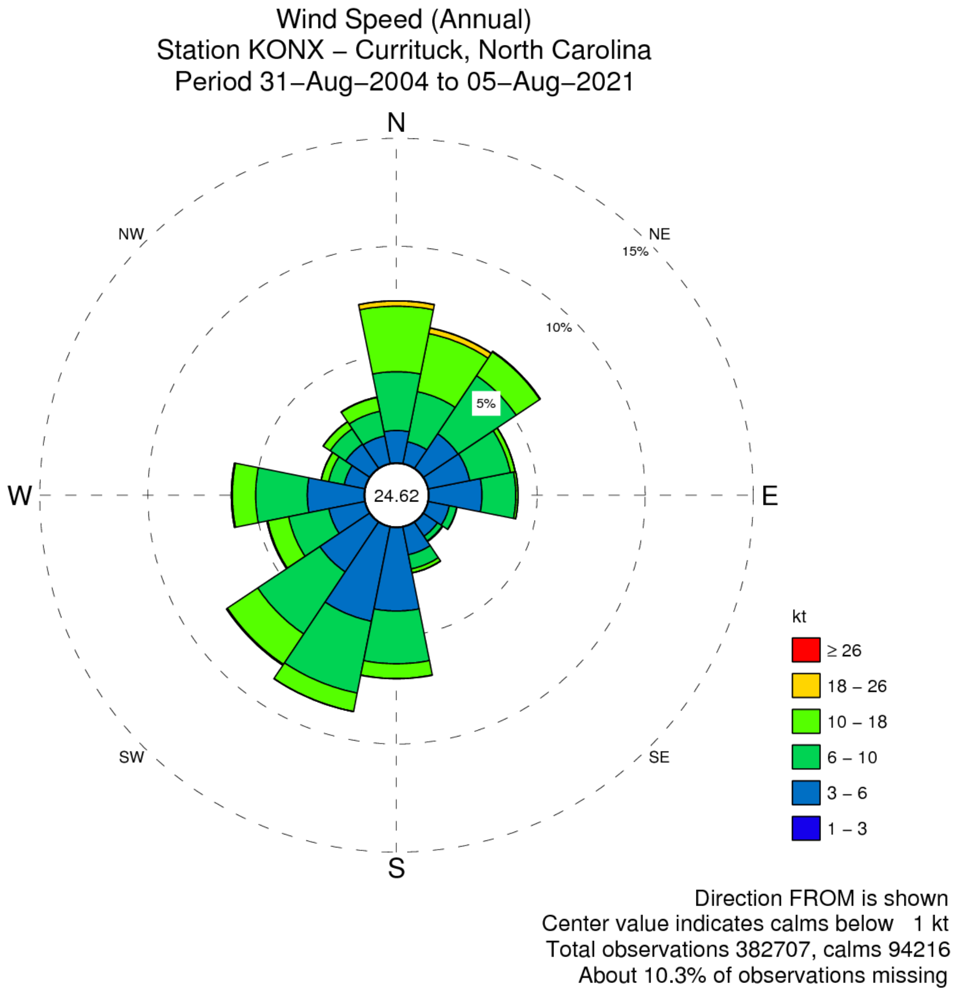
Data analyses were performed for wind measurements at the stations listed in Table 4. The annual wind roses are shown from Figure 6 to Figure 10. Wind data plotted in the wind roses were converted to a standard 10 m (33 ft) elevation using the ISO 19901-1:2005(E) formulation.



Percentage of Occurrence

Wind Speed, kt	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Total	8.64	5.36	5.25	4.50	5.85	3.92	3.75	4.02	6.66	7.56	9.68	6.61	5.08	3.11	3.80	5.90	89.68
≥ 26																	0.26
18 – 26	0.49	0.30	0.19	0.10						0.18	0.27	0.17	0.18	0.17	0.31	0.46	3.12
10 – 18	3.50	2.12	1.86	1.23	1.12	0.77	0.84	0.80	1.19	2.36	2.78	1.72	1.50	1.09	1.51	2.52	26.92
6 – 10	2.83	1.82	1.96	1.86	2.47	1.62	1.47	1.47	2.42	2.99	3.39	2.26	1.68	0.95	1.07	1.69	31.94
3 – 6	1.45	0.91	0.99	1.07	1.75	1.18	1.10	1.33	2.42	1.71	2.56	1.86	1.30	0.70	0.70	0.95	21.98
1 – 3	0.34	0.18	0.21	0.23	0.44	0.30	0.29	0.35	0.55	0.31	0.65	0.57	0.41	0.19	0.19	0.24	5.46

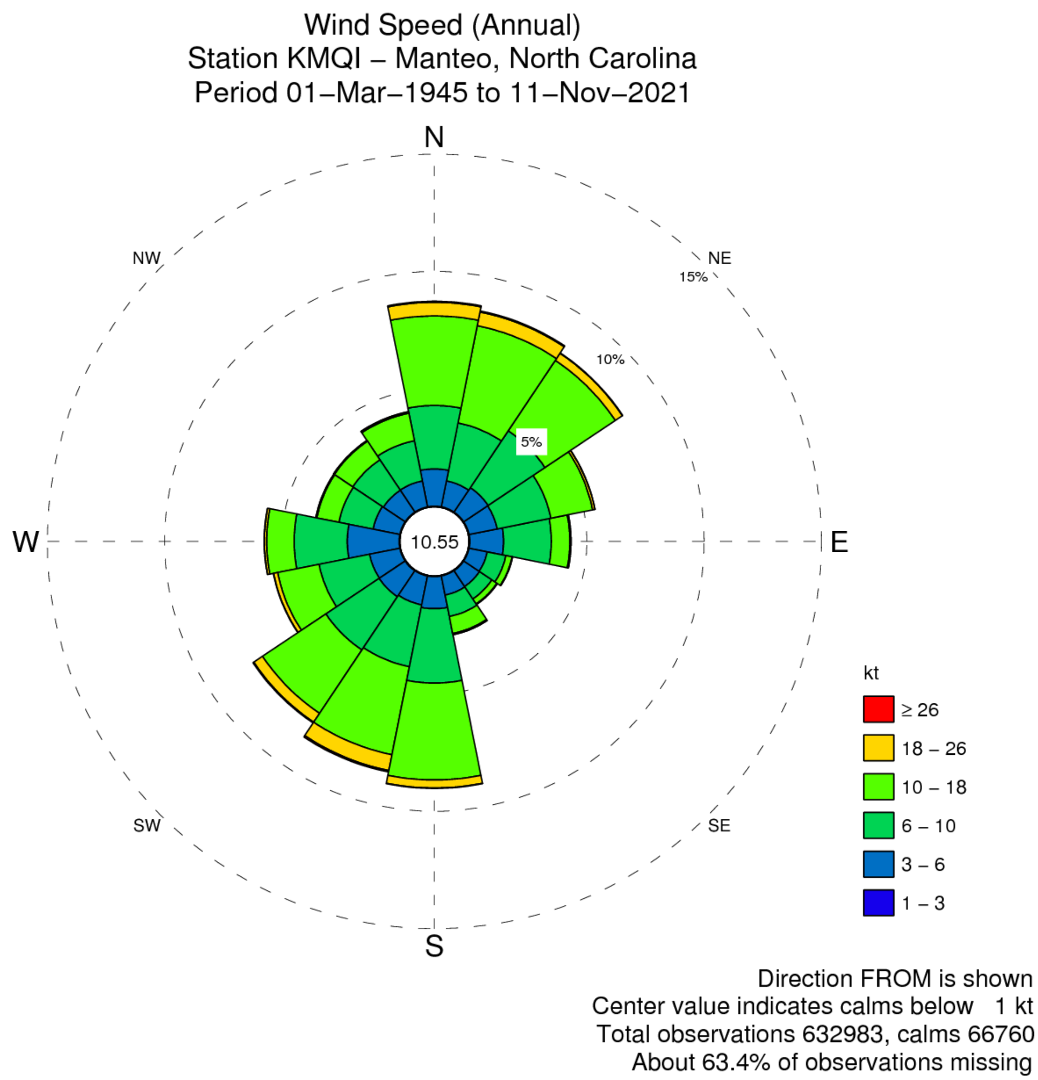
Figure 6: Annual wind speed rose at METAR Station KNTU



Percentage of Occurrence

Wind Speed, kt	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Total	7.49	6.39	6.50	4.10	4.12	1.36	1.08	2.16	6.99	8.70	7.96	4.61	6.14	2.06	2.59	3.13	75.38
≥ 26																	
18 – 26	0.24	0.26															0.74
10 – 18	3.03	2.74	1.32	0.22	0.10			0.18	0.68	0.87	1.69	0.99	1.08	0.35	0.39	0.65	14.33
6 – 10	2.72	2.36	3.23	1.92	1.56	0.35	0.26	0.67	2.44	3.38	3.45	1.90	2.39	0.73	0.85	1.16	29.38
3 – 6	1.49	1.02	1.92	1.95	2.45	0.99	0.78	1.30	3.86	4.44	2.77	1.69	2.63	0.97	1.34	1.29	30.89
1 – 3																	

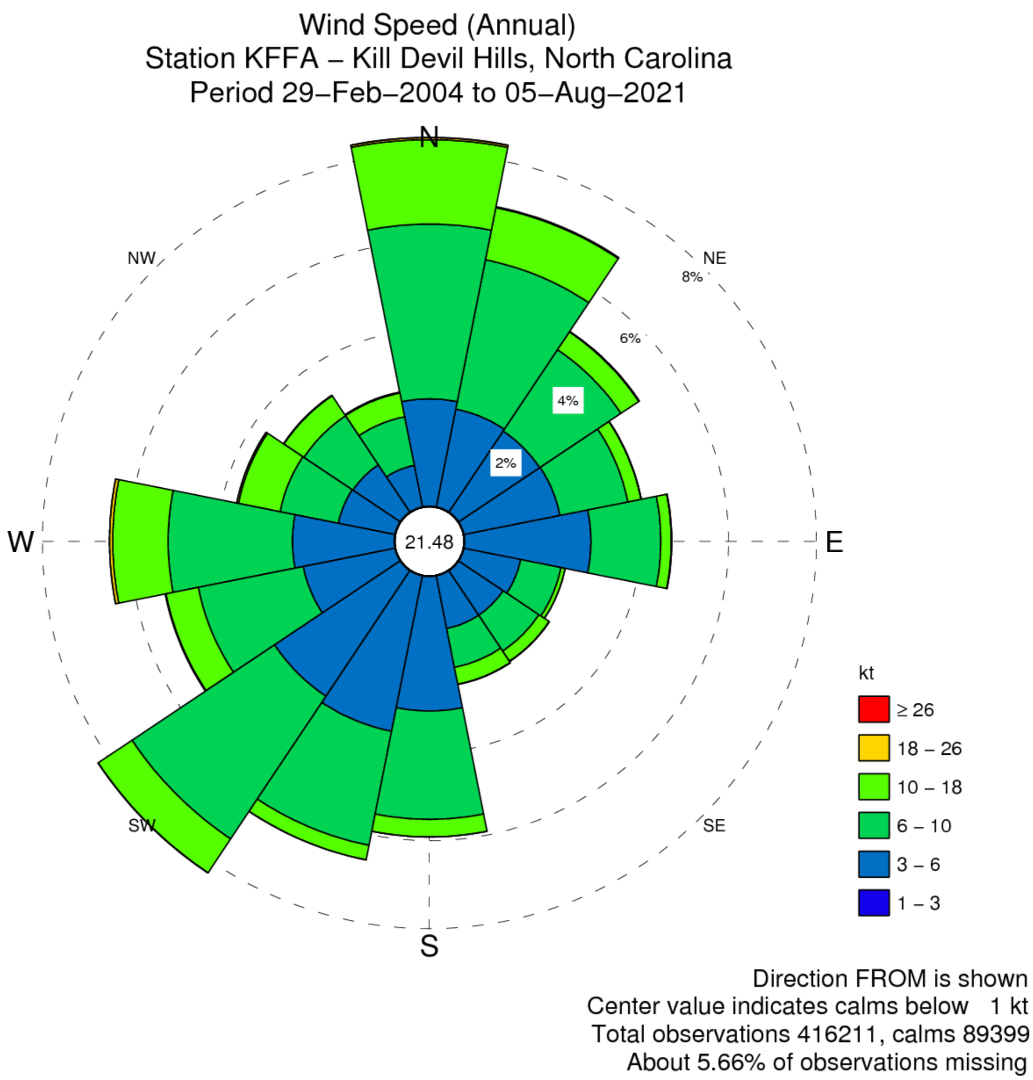
Figure 7: Annual wind speed rose at METAR Station KONX



Percentage of Occurrence

Wind Speed, kt	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Total	8.73	8.51	8.16	5.48	4.32	1.90	1.73	2.55	9.02	8.52	7.80	5.50	5.76	3.66	3.67	4.13	89.45
≥ 26																	0.27
18 – 26	0.58	0.60	0.36	0.10					0.34	0.69	0.45	0.18					3.67
10 – 18	3.82	4.22	3.61	1.82	0.79	0.27	0.26	0.74	4.13	3.82	3.25	1.80	1.17	0.96	0.95	1.20	32.79
6 – 10	2.70	2.52	2.91	2.33	2.04	0.81	0.64	0.93	3.17	2.69	2.73	2.20	2.27	1.49	1.56	1.74	32.71
3 – 6	1.58	1.13	1.25	1.23	1.44	0.79	0.81	0.83	1.37	1.26	1.33	1.32	2.21	1.17	1.12	1.13	19.97
1 – 3																	

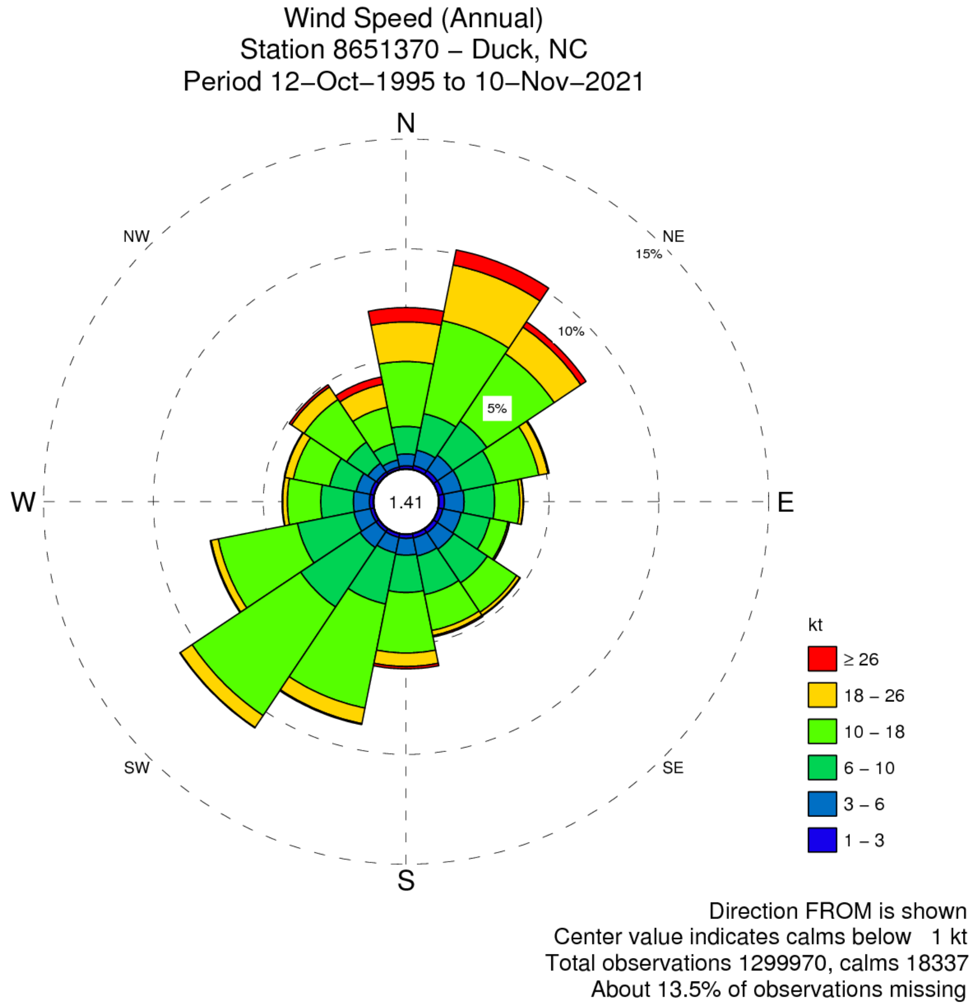
Figure 8: Annual wind speed rose at METAR Station KMQI



Percentage of Occurrence

Wind Speed, kt	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Total	8.38	6.95	4.94	4.11	4.71	2.35	2.48	2.52	5.92	6.58	8.26	5.32	6.47	3.67	3.19	2.66	78.52
≥ 26																	
18 – 26																	0.29
10 – 18	1.92	1.21	0.49	0.31	0.24		0.28	0.39	0.40	0.34	0.93	0.75	1.26	0.96	0.55	0.55	10.65
6 – 10	3.97	3.46	2.22	1.57	1.59	0.93	0.98	0.90	2.46	2.64	3.90	2.43	2.83	1.35	1.34	1.13	33.71
3 – 6	2.44	2.27	2.22	2.23	2.87	1.32	1.22	1.22	3.05	3.60	3.43	2.13	2.31	1.31	1.29	0.96	33.87
1 – 3																	

Figure 9: Annual wind speed rose at METAR Station KFFA



Percentage of Occurrence

Wind Speed, kt	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Total	7.32	10.18	8.34	5.13	3.84	3.31	4.75	4.78	6.11	8.85	10.89	7.59	4.14	4.16	4.89	4.29	98.59
26–	0.64	0.70	0.29						0.11						0.12	0.34	2.54
18–26	1.80	2.58	1.45	0.42	0.15		0.17	0.23	0.61	0.72	0.65	0.34	0.21	0.40	0.69	1.06	11.57
10–18	2.95	4.32	3.68	1.98	1.14	0.84	1.60	1.67	2.76	4.83	5.94	3.68	1.52	1.69	2.33	1.69	42.59
6–10	1.26	1.70	1.88	1.61	1.39	1.34	1.85	1.79	1.70	2.37	3.25	2.62	1.49	1.23	1.16	0.76	27.39
3–6	0.54	0.72	0.84	0.85	0.90	0.85	0.90	0.84	0.77	0.73	0.87	0.77	0.73	0.65	0.48	0.33	11.75
1–3	0.13	0.17	0.20	0.21	0.24	0.20	0.21	0.18	0.17	0.15	0.15	0.15	0.17	0.17	0.13	0.10	2.75

Figure 10: Annual wind speed rose at NOAA Station 8651370

The wind roses show that the wind field at NOAA station 8651370 (Duck, NC) is stronger than other METAR stations, which is expected as the NOAA station is located on the Ocean side while other METAR stations are located on the sound side with less fetch and more friction from land (Figure 1). Among all the METAR stations, KNTU (3.38% > 18 kt) and KMQI (3.94% > 18 kt) have a relatively larger percentage of high wind speed than KFFA (0.29% > 18 kt) and KONX (0.74% > 18 kt). Considering the locations of KNTU and KMQI, KMQI better represents the wind conditions at the project site. Percentage of exceedance values were computed for KMQI for wind directions including SW, WSW, W, WNW, NW with long fetches to the project site which potentially cause larger wave conditions, and the results are presented in Table 5..

Table 5: Percentage of exceedance value for wind speeds (knots) at KMQI for different directions

Dir From	75%	50%	25%	10%	5%	1%
SW	7	9	13	16	18	23
WSW	6	8	11	14	16	21
W	5	6	9	12	14	19
WNW	5	7	10	13	14	18
NW	5	7	10	12	14	18

3.2 Historical Storm Events

A total number of 68 hurricanes and their physical parameters were collected from NOAA Historical Hurricane Tracks (https://coast.noaa.gov/hurricanes/) for hurricanes passing near the project area in the last 100 years. Detailed information including the maximum sustained wind speeds, minimum sea level pressure, and Radius of Maximum Wind (RMW) for each hurricane is listed in Table 6. The maximum sustained wind speeds for hurricanes are the highest surface winds occurring within the circulation of the system, which are observed or estimated at the standard meteorological height of 10 m (33 ft) in an unobstructed exposure. Minimum central pressure is the estimated lowest surface pressure in the hurricane. This represents the pressure at the center of circulation reduced to sea level. Radius of Maximum Wind is the distance between the maximum wind and the storm center, and it is noted, though, that RMW usually is not well tracked.

All these parameters are time and spatial varying with a spatial resolution of 0.1° (~6.2 mile) and a time resolution of 3-hour. Values listed in Table 6 are representative values when the hurricane center is close to the project site to provide a general picture of each hurricane's size and intensity. A time-varying wind field was generated based on the collected hurricane track information, which is discussed in Section 5.1.3.

Table 6: Hurricane information

Hurricane	Max sustained wind speeds (kt)	Min sea level pressure (mb)	Radius of Max. Wind (nautical mile)
KYLE2020	20	1013	60
FAY2020	40	1005	50
DORIAN2019	85	956	25
UNNAMED2017	40	1004	50
MATTHEW2016	55	990	70
JULIA2016	25	1011	40
HERMINE2016	60	995	50
BONNIE2016	25	1005	15
CLAUDETTE2015	25	1010	30
ANA2015	30	1012	60
ARTHUR2014	85	973	20
BERYL2012	45	994	75
IRENE2011	65	950	45
GABRIELLE2007	40	1007	35
BARRY2007	40	992	*
ALBERTO2006	35	1002	120
CHARLEY2004	60	1000	*
BONNIE2004	25	1008	31
ALEX2004	85	972	*
ISABEL2003	85	958	45
KYLE2002	40	1009	30
ALLISON2001	25	1009	*
HELENE2000	40	1008	*
FLOYD1999	70	967	*
EARL1998	50	998	*
BONNIE1998	65	983	*
DANNY1997	40	1000	*
JOSEPHINE1996	45	986	*
ARTHUR1996	35	1005	*
ALLISON1995	40	992	*
EMILY1993	100	960	*
DANIELLE1992	55	1001	*
BOB1991	100	950	*
CHARLEY1986	65	988	*
GLORIA1985	90	942	*
DIANA1984	50	1000	*

Hurricane	Max sustained wind speeds (kt)	Min sea level pressure (mb)	Radius of Max. Wind (nautical mile)
UNNAMED1982	60	992	*
DENNIS1981	60	997	*
BOB1979	20	1012	*
AGNES1972	45	986 x	*
DORIA1971	55	989	*
UNNAMED1970	30	1011	*
ALMA1970	25	1003	*
GLADYS1968	70	983	*
ABBY1968	25	1006 x	*
DORIA1967	35	1000 x	*
DORA1964	60	998	*
CLEO1964	40	999	*
UNNAMED1964	25	1010 x	*
UNNAMED1963	50	1002	*
ALMA1962	65	990 x	*
UNNAMED1962	55	998	*
DONNA1960	85	960	*
BRENDA1960	50	993	*
CINDY1959	40	1002 x	*
UNNAMED1956	45	999 x	*
FLOSSY1956	50	1009	*
IONE1955	65	955 x	*
CONNIE1955	85	962	*
CAROL1954	100	960 x	*
BARBARA1953	75	980 x	*
UNNAMED1946	45	1000 x	*
UNNAMED1944	105	940	*
UNNAMED1937	60	996	*
UNNAMED1936	85	965	*
UNNAMED1933	90	952	*
UNNAMED1933	80	963	*
UNNAMED1924	60	1000 x	*

x: Pressure is not available in the model domain, and interpolation using adjacent points are used.
**: Radius of Maximum Wind is not available for the specific hurricane, and RMW= 27 nmile is assumed.*

4.0 HISTORICAL SHORELINE EROSION

The USGS Digital Shoreline Analysis System (DSAS) software was used to evaluate the shoreline erosion rates along the estuarine shoreline of Nags Head based on historic shorelines and recent shoreline measurements by East Carolina University. DSAS allows analysts to calculate rate-of-change statistics from multiple historical shoreline positions as related to a common, inland baseline. The reliability of parameters such as "end point rate," the distance the shoreline has moved per year over a time interval depends on a nuanced examination of the source data and correction of outliers or errors. For example, software can compare the current (orange) and historic shoreline (white) as shown in the figure at left, but if the digitization methods are not consistent, there may be some misleading overlaps where previous analysts were more or less meticulous in defining the shoreline. Sch areas require correction by hand for problem sites. That level of data cleaning is underway at East Carolina University, but the simple preliminary DSAS performed provides a useful interim tool for grouping sites according to erosion rates.

Figure 11: Current and historical shoreline erosion

5.0 MODEL SETUP

5.1 HD and Wave Model

A MIKE 21 hydrodynamic model (hereinafter referred to as HD model) and a MIKE 21 spectrum wave model (hereinafter referred to as SW model) were developed to simulate hydrodynamic and wave conditions in the Pamlico Sound and at the project site. MIKE 21 is a modeling suite developed by DHI (Danish Hydraulic Institute). The model can predict time dependent flow and wave parameters at each point in the computational domain. The model can be forced with either constant or time dependent boundary conditions, which in general may include tide, river discharges, wind, and other parameters. The model utilizes a flexible mesh.

Winds were the only external force driving the model simulation, and two groups of wind conditions were simulated in HD and SW model:

- Constant winds in various directions based on exceedance values (10%, 5% and 1%) presented in Table 5
- 65 storm events as listed in Table 6

The model domain, model grid and bathymetry were the same for both HD and SW model, and SW was run concurrently with the HD model using the same wind fields for each storm event or each constant wind conditions.

5.1.1 Model Grid and Bathymetry

The model domain included most of the Pamlico Sound, Albemarle Sound, and Currituck Sound. The grid cell sizes were varying throughout the domain. In most of the sounds, the resolution was coarse with an element size of about 16,000 ft. In the area near the Nags Head, the element size was approximately 60 ft. The overall grid is shown in Figure 11, and Figure 12 shows model grid near Nags Head.

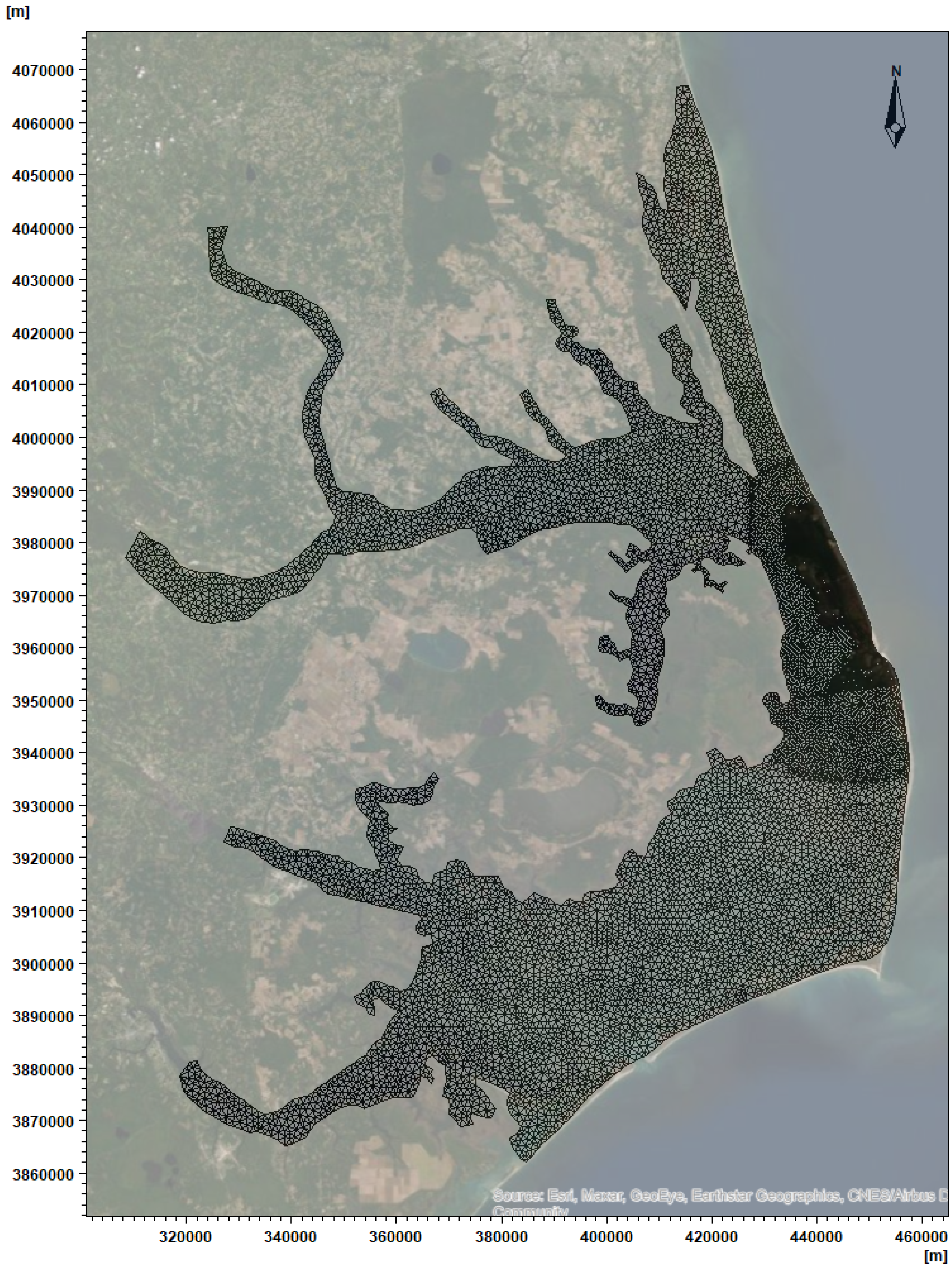


Figure 12: Model grid

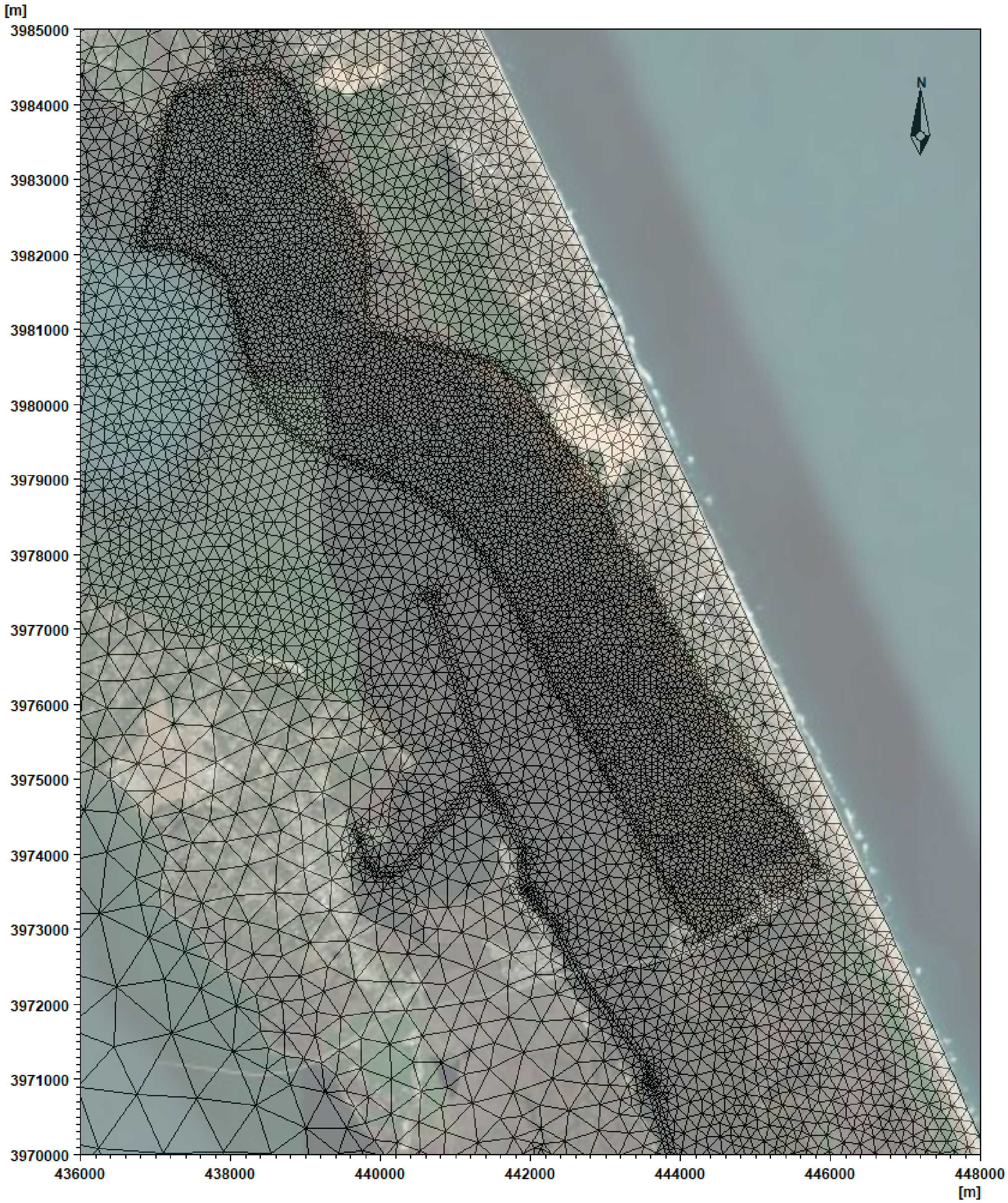


Figure 13: Model grid near Nags Head

Bathymetry were combined using the data listed below.

- Navigation channel survey data from United States Army Corps of Engineers (USACE) (https://navigation.usace.army.mil/Survey/Hydro)
- Navigational charts from C-MAP by Jeppesen
- Bathymetric surveys conducted by the Coastal Studies Institute (CSI), around the Nags Head shoreline in December 2021
- LiDAR data from North Carolina statewide LiDAR collection managed by North Carolina Division of Emergency Management (NCEM) (https://sdd.nc.gov/)

Horizontally, the four datasets were converted to UTM18 meters. Vertical reference was converted to NAVD88 in meters. The overall model bathymetry is shown in Figure 13, and Figure 14 shows the bathymetry near Nags Head. For presentation purposes, the bathymetry shown here are in feet.

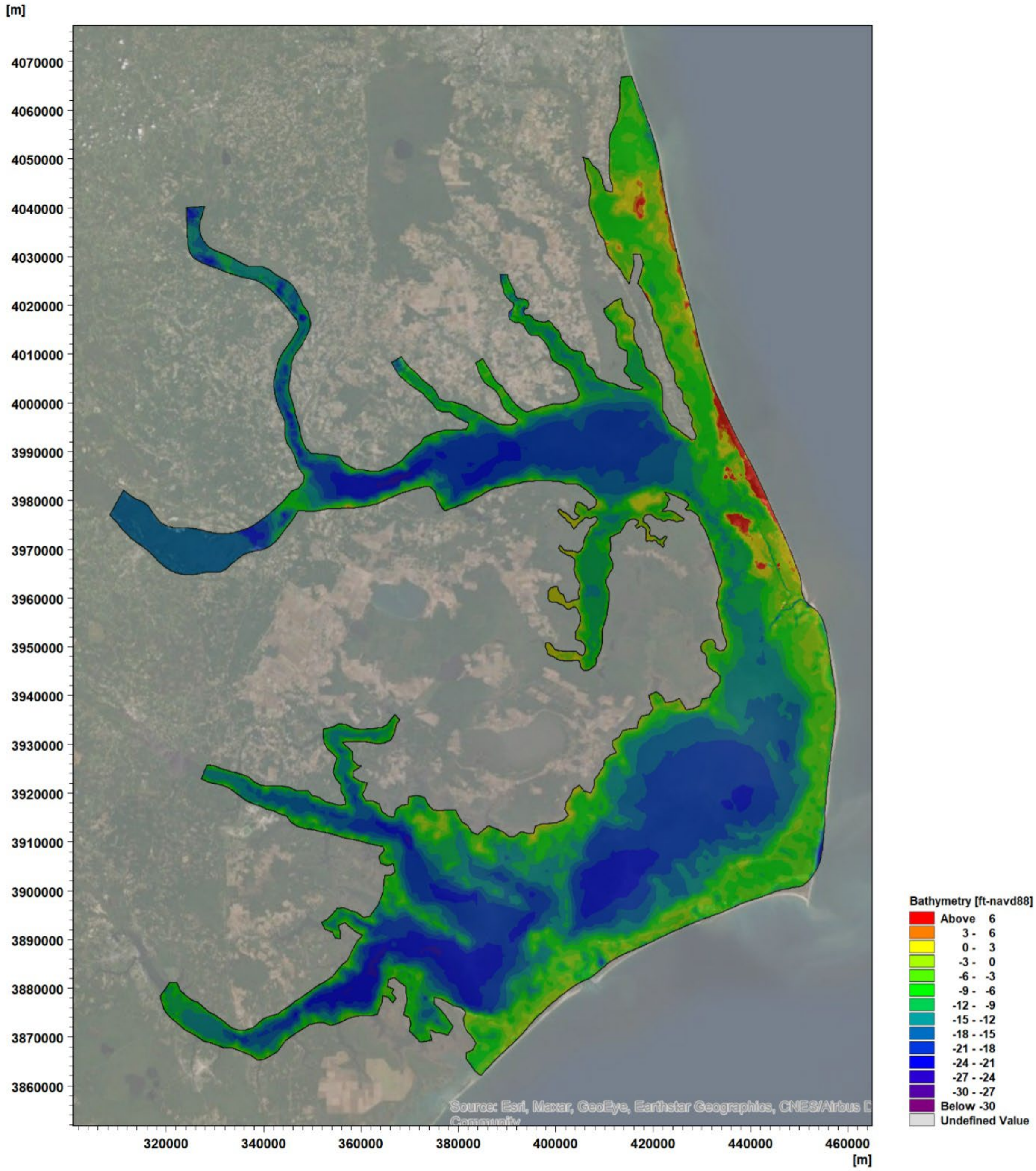


Figure 14: Model bathymetry

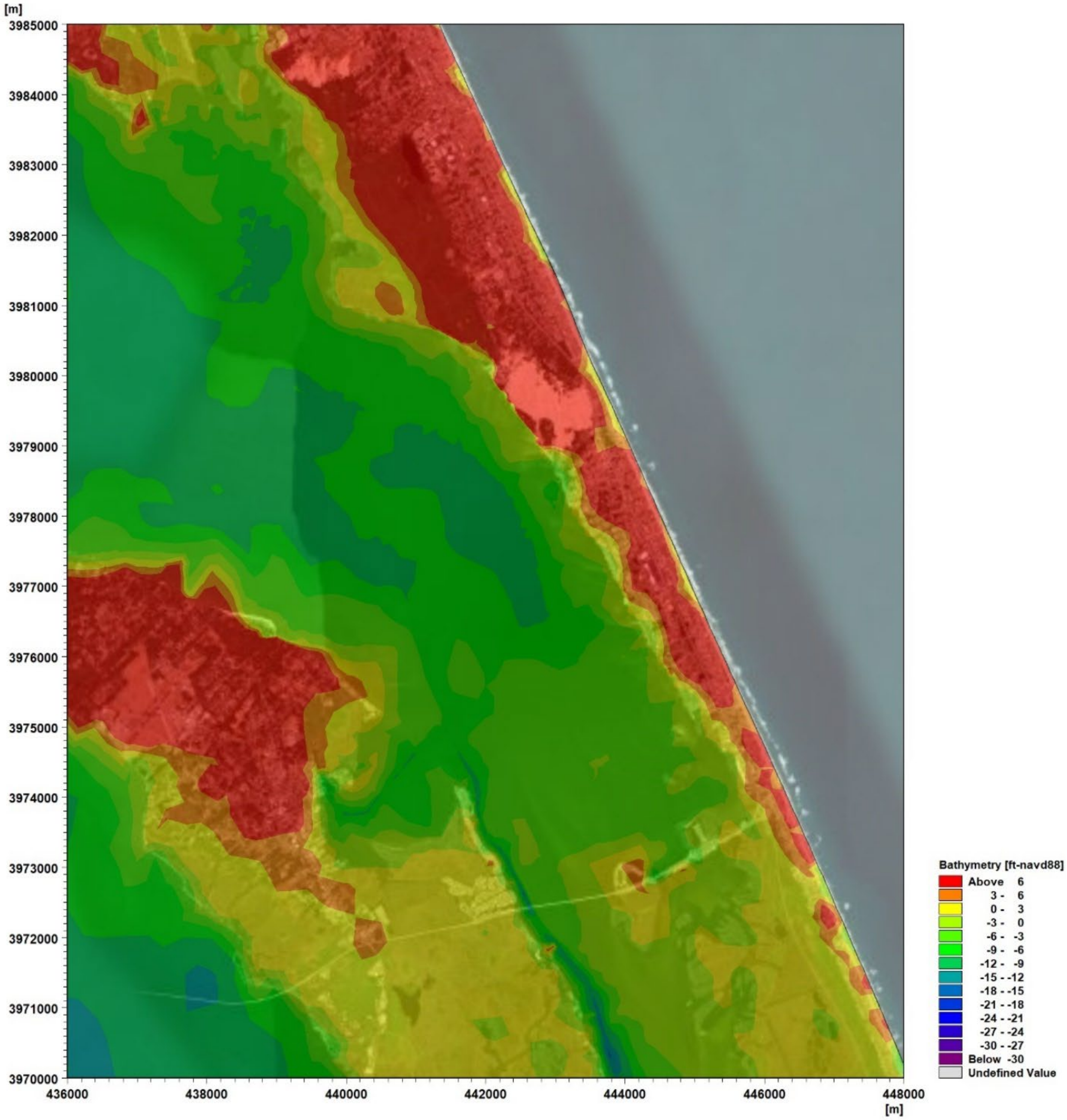


Figure 15: Bathymetry near the Alligator River Bridge

5.1.2 Normal Conditions

Normal conditions were simulated using constant wind conditions based on exceedance values (10%, 5% and 1%) presented in Table 5, with a total of 15 cases (3 exceedance values × 5 wind directions). The model was run for 24 hours for each wind case to reach steady state.

5.1.3 Storm Events

For storm events, wind fields varying in time and space were applied in the model for each storm event. Wind fields were generated using the data presented in Table 6. An example of the wind fields for Hurricane Dorian 2019 is shown in Figure 15, and similar storm generation processes were conducted for the other storm events.

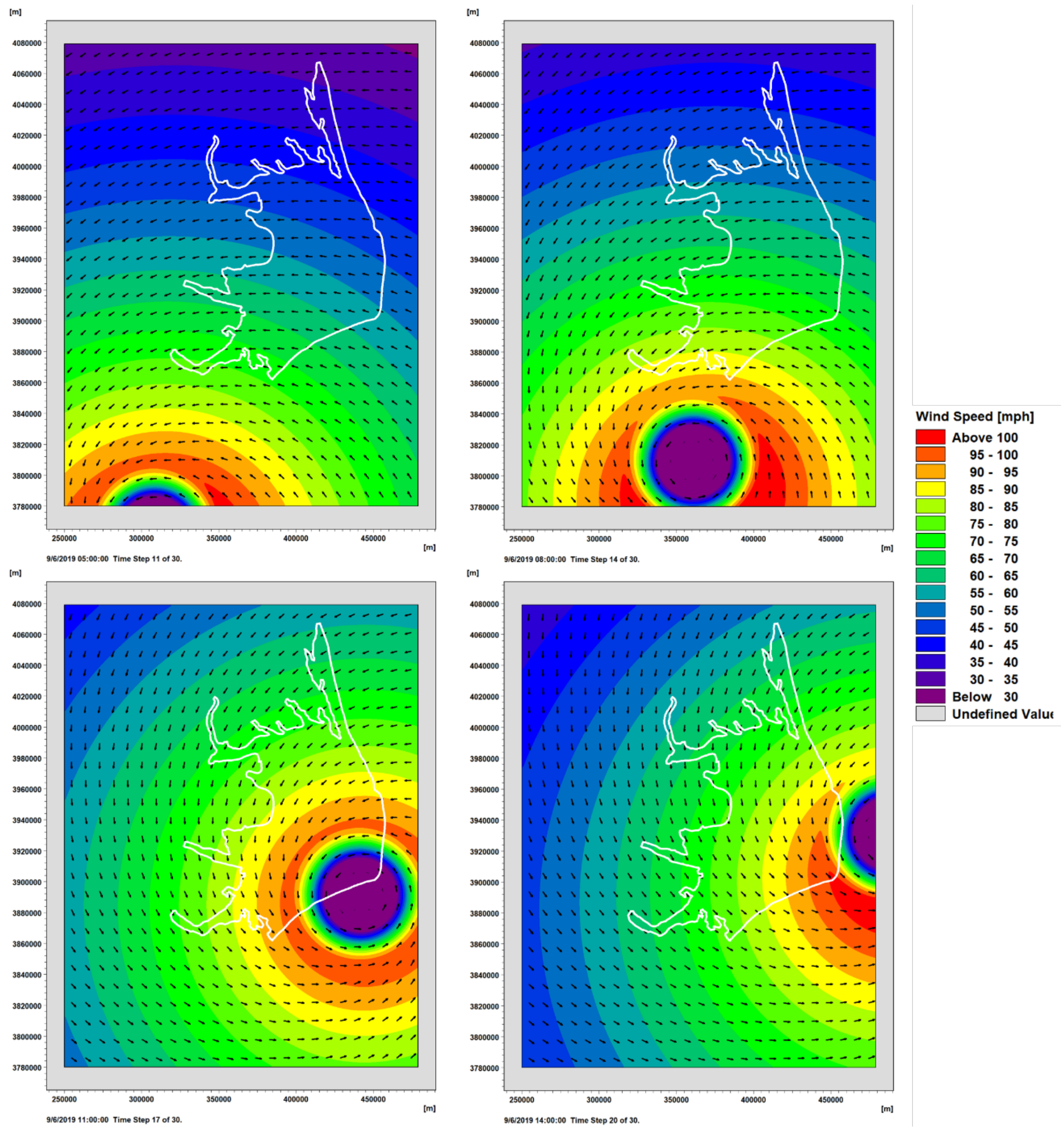


Figure 16: Example of wind field - Hurricane Dorian 2019 passing by the Pamlico Sound (white line)

6.0 MODEL RESULTS

After running all the wind conditions including constant winds and storm events listed for the HD and SW models, results were extracted at locations along the Nags Head shoreline shown in Figure 16 for statistical analysis.

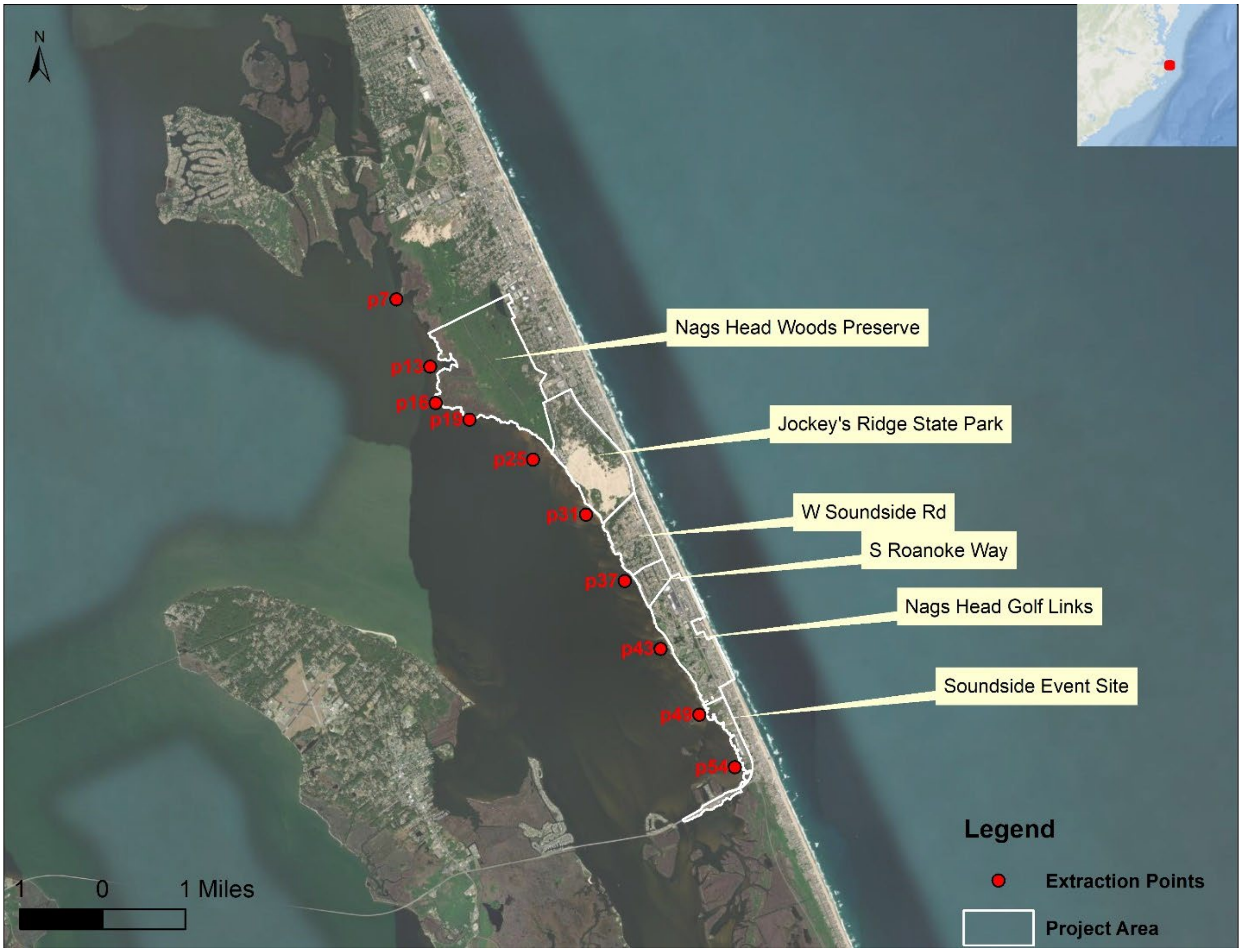


Figure 17: Extraction points of model results along the Nags Head shoreline

6.1 Existing Conditions – without SLR

6.1.1 Normal Conditions

Significant Wave Heights (Hs) and Peak Wave Periods (Tp) at the extraction points (Figure 16) are listed in Table 7, Table 8 and Table 9 for the 10%, 5% and 1% wind exceedance values, respectively. In general, Hs and Tp increase with the smaller exceedance value, but the differences are small. For the 10% wind exceedance value, Hs ranges from 0.1 ft – 0.9 ft and Tp ranges from 1.8 s – 2.3 s. For the 5% wind exceedance value, Hs ranges from 0.1 ft – 0.9 ft and Tp ranges from 1.8 s – 2.4 s. For the 1% wind exceedance value, Hs ranges from 0.1 ft – 1.1 ft and Tp ranges from 1.8 s to 2.6 s.

Among all the extraction points, points located north of Jockey's Ridge State Park (p7, p13, p16, p25) experience higher Hs than those points south of the park (p31, p37, p43, p49, p54), except at p19 where wave energy is partially reduced by the protruded shoreline shape. Hs >0.5 ft is observed in those points north of Jockey's Ridge State Park (p7, p13, p16, p25), while Hs <0.5 ft is observed in those points south of the park for all three exceedance values. Differences in Tp are small among all those points, with values of 2.0 s – 2.5 s observed for most of the points.

Two-Dimension maps for Hs and Tp under the normal conditions are presented in the Appendix.

Table 7: Hs and Tp for the 10% wind exceedance value

Wind Dir	SW		WSW		W		WNW		NW	
	Hs(ft)	Tp(s)	Hs(ft)	Tp(s)	Hs(ft)	Tp(s)	Hs(ft)	Tp(s)	Hs(ft)	Tp(s)
p7	0.9	2.2	0.8	2.2	0.6	2.0	0.4	2.0	0.2	2.0
p13	0.7	2.3	0.7	2.2	0.7	2.1	0.7	2.1	0.5	2.0
p16	0.7	2.3	0.6	2.2	0.6	2.2	0.5	2.2	0.4	2.1
p19	0.2	2.2	0.2	2.2	0.1	2.2	0.1	2.3	0.1	2.2
p25	0.8	2.1	0.6	2.2	0.5	2.2	0.5	2.2	0.4	2.2
p31	0.2	2.2	0.1	2.2	0.1	2.2	0.1	2.3	0.1	2.3
p37	0.2	2.1	0.2	2.2	0.2	2.2	0.1	2.3	0.1	2.2
p43	0.2	2.1	0.4	2.1	0.4	2.2	0.4	2.2	0.3	2.2
p49	0.1	2.1	0.2	1.8	0.2	2.0	0.2	2.1	0.2	2.0
p54	0.1	2.1	0.1	2.1	0.1	2.0	0.1	2.0	0.1	2.0

Table 8: Hs and Tp for the 5% wind exceedance value

Wind Dir	SW		WSW		W		WNW		NW	
	Hs(ft)	Tp(s)	Hs(ft)	Tp(s)	Hs(ft)	Tp(s)	Hs(ft)	Tp(s)	Hs(ft)	Tp(s)
p7	0.9	2.3	0.8	2.2	0.6	2.1	0.5	2.0	0.3	2.0
p13	0.7	2.4	0.7	2.3	0.7	2.2	0.7	2.2	0.6	2.1
p16	0.7	2.4	0.6	2.4	0.6	2.3	0.5	2.2	0.5	2.2
p19	0.2	2.4	0.2	2.3	0.1	2.3	0.1	2.3	0.1	2.3
p25	0.8	2.2	0.6	2.2	0.6	2.2	0.5	2.2	0.4	2.2
p31	0.2	2.1	0.1	2.4	0.1	2.4	0.1	2.4	0.1	2.3
p37	0.2	2.1	0.2	2.2	0.2	2.3	0.1	2.4	0.1	2.3
p43	0.2	2.1	0.4	2.1	0.4	2.2	0.4	2.2	0.3	2.2
p49	0.1	2.1	0.2	1.8	0.2	2.0	0.2	2.1	0.2	2.1
p54	0.1	2.2	0.1	1.8	0.1	2.0	0.1	2.0	0.1	2.0

Table 9: Hs and Tp for the 1% wind exceedance value

Wind Dir	SW		WSW		W		WNW		NW	
	Hs(ft)	Tp(s)	Hs(ft)	Tp(s)	Hs(ft)	Tp(s)	Hs(ft)	Tp(s)	Hs(ft)	Tp(s)
p7	1.1	2.4	0.9	2.3	0.8	2.2	0.6	2.1	0.4	2.0
p13	0.8	2.6	0.8	2.5	0.8	2.4	0.8	2.2	0.7	2.1
p16	0.9	2.5	0.8	2.5	0.7	2.5	0.6	2.4	0.5	2.3
p19	0.3	2.5	0.3	2.5	0.2	2.5	0.1	2.5	0.1	2.5
p25	1.0	2.4	0.8	2.4	0.7	2.4	0.6	2.4	0.5	2.3
p31	0.3	2.2	0.2	2.4	0.1	2.5	0.1	2.5	0.1	2.5
p37	0.3	2.2	0.3	2.4	0.2	2.4	0.2	2.5	0.1	2.5
p43	0.4	1.8	0.5	2.2	0.5	2.3	0.4	2.3	0.4	2.4
p49	0.2	1.8	0.4	1.8	0.3	2.0	0.3	2.1	0.2	2.1
p54	0.1	2.2	0.2	1.8	0.2	1.8	0.2	1.8	0.2	1.8

6.1.2 Storm Events

For the storm event results, extreme value analysis using the "Peak Over Threshold" (POT) approach was performed at the extraction points along the Nags Head Shoreline (Figure 16) for significant wave height (Hs) and peak wave period (Tp), and the results are presented in this section. Examples of extreme value analysis for point p7 are shown in Figure 17 and Figure 18, and results for the other points are calculated similarly.

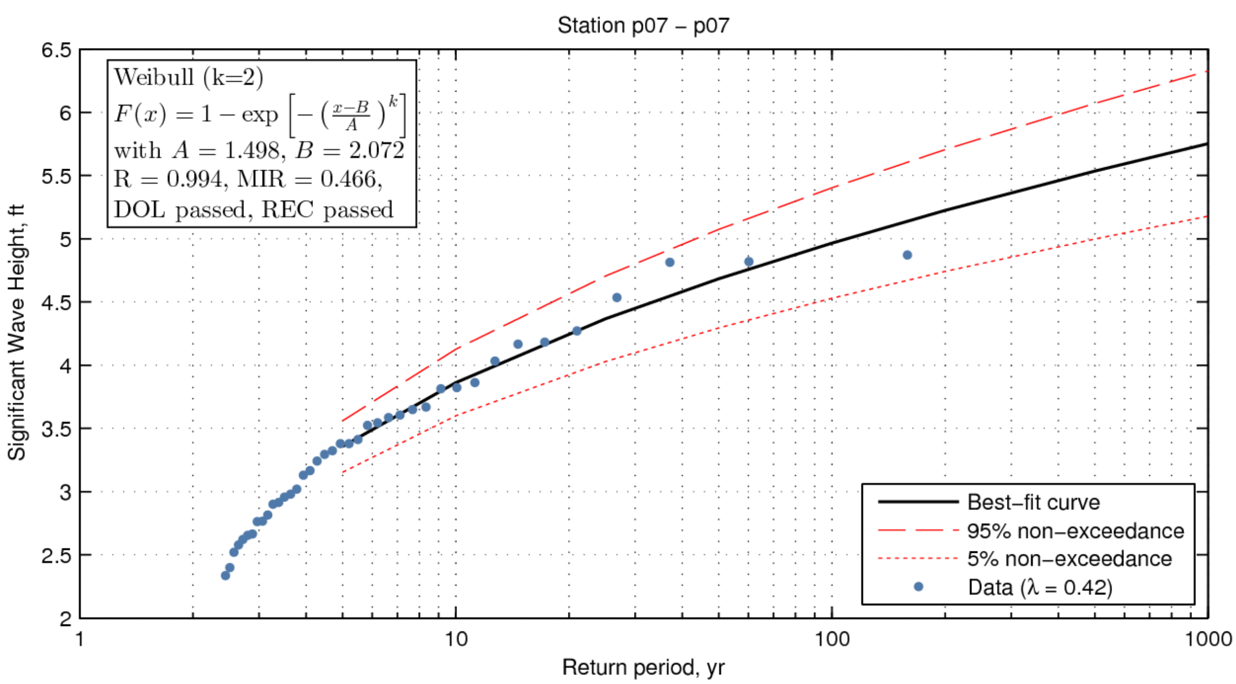


Figure 18: Extreme Value Analysis of Hs at point p7

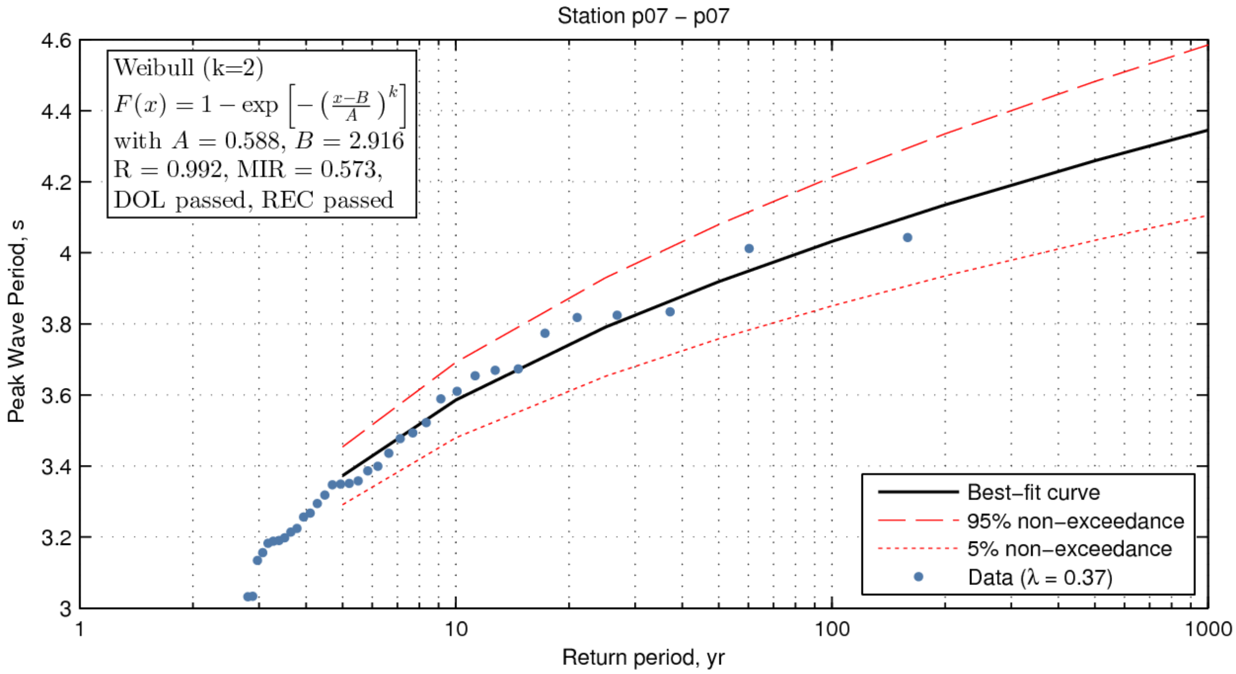


Figure 19: Extreme Value Analysis of Tp at point p7

Table 10 lists the Hs and Tp results at the extraction points for the 5-year and 10-year storm events, while Figure 19 and Figure 20 show the results using colored dots with satellite imagery. From Table 10, Hs ranges from 1.5 ft – 3.4 ft for a 5-year event and from 2.0 ft – 3.9 ft for a 10-year event. Hs at points north of Jockey's Ridge State Park are generally higher than those points south of the park except at p19, which agrees with the observations during normal conditions discussed above. Tp ranges from 2.8 s – 3.8 s for a 5-year event and from 3.1 s – 4.0 ft for a 10-year event. The largest Tp are at two points just south of the Jockey's Ridge State Park (p31, p37) where Tp is ≥ 3.7 s for a 5-year event and ≥ 4.0 s for a 10-year event.

Table 10: Hs and Tp for 5-year and 10-year storm event

	5-year		10-year	
	Hs(ft)	Tp(s)	Hs(ft)	Tp(s)
p7	3.4	3.1	3.9	3.5
p13	2.9	3.3	3.4	3.8
p16	2.4	3.5	2.9	3.9
p19	1.5	3.5	2.0	3.9
p25	3.1	3.2	3.6	3.7
p31	1.6	3.7	2.1	4.0
p37	1.8	3.8	2.3	4.0
p43	2.8	3.3	3.3	3.6
p49	2.6	2.9	3.1	3.1

	5-year		10-year	
p54	2.3	2.8	2.8	3.1

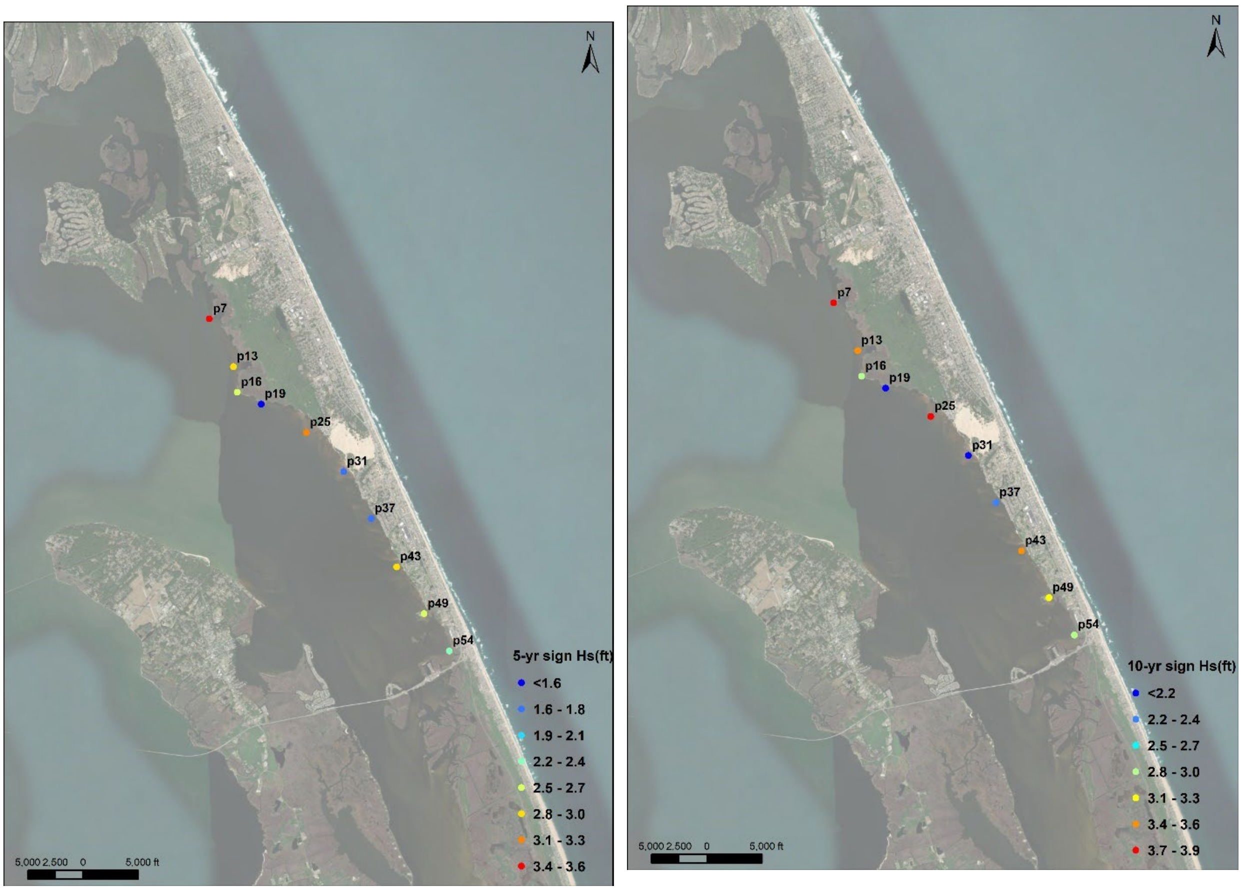


Figure 20: Significant Wave Height (Hs) for 5-year(left) and 10-year(right) return period

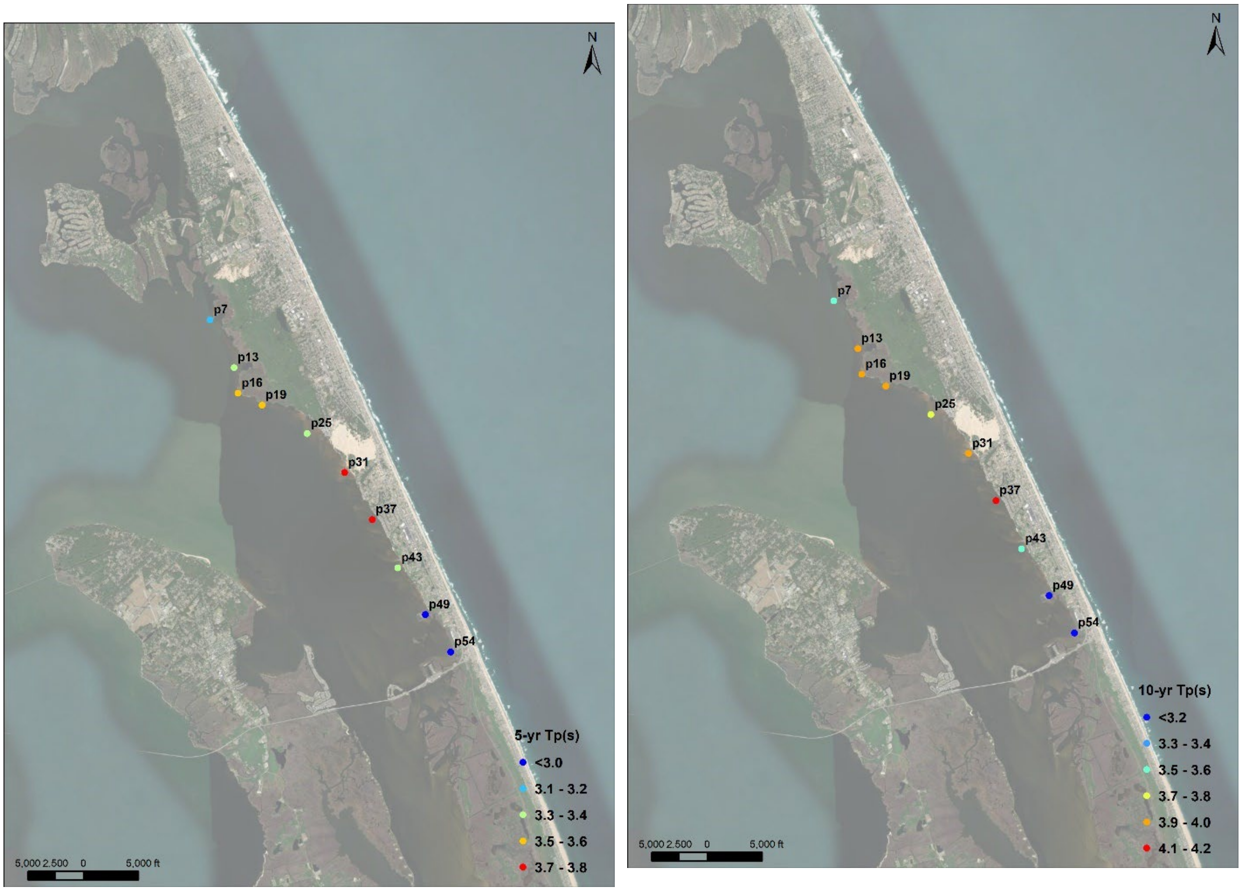


Figure 21: Peak Wave Period (Tp) for 5-year(left) and 10-year(right) return period

7.0 LIVING SHORELINE DESIGN

7.1 Marsh Erosion Thresholds

Previous work has been performed for the shorelines in Coastal Alabama examining the wave climates associated with the presence or absence of stable marsh shorelines. Generally, marsh shorelines occur where exposed to lower wave heights, while shorelines with higher wave heights show eroding marsh or lack vegetation completely. Figure 21 (Roland & Douglass, 2005) shows the computed thresholds for the presence or absence of spartina alterniflora marshes along the shorelines in Coastal Alabama.

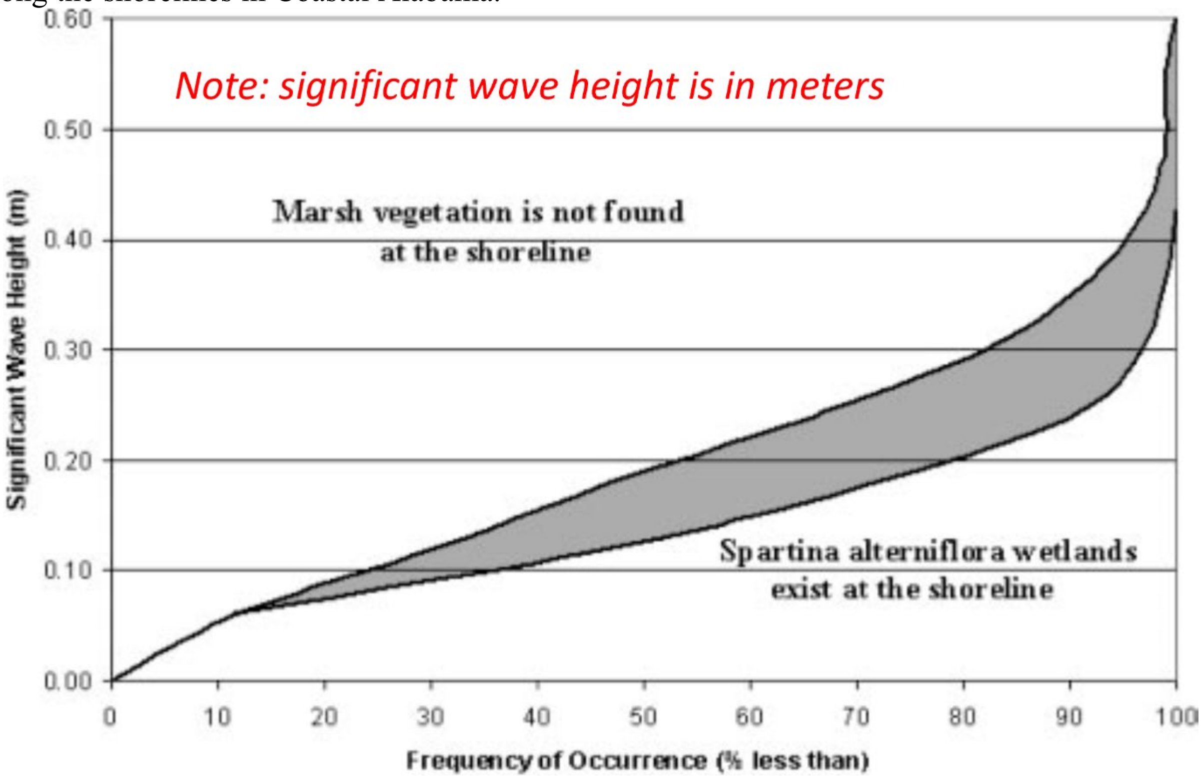


Figure 22: Threshold wave cumulative frequencies for the presences or absence of Spartina alterniflora wetlands in Coastal Alabama (Roland & Douglass, 2005), the intermediate grey area indicates Hs at which eroding wetlands occurred

With results for the current wave climate available from the wave modeling study, the model results were compared to the Roland and Douglass thresholds to see if marshes can survive under normal conditions. Figure 22 plots the computed significant wave height against the wetland presence/absence thresholds. The computed wave climate places most points along the Nags Head shoreline under the wetland's threshold with only p7 in the most northern part experiencing wetland erosion. However, other points are <0.6 ft below the wetland erosion threshold (green line in Figure 22) and those points (p13, p16, p25) north of Jockey's Ridge State Park are only <0.2 ft below the wetland erosion threshold, which is within the model's margin of error. In addition, it is noted that the study from Roland & Douglass, 2005 was focused on shorelines in Alabama, and those threshold curves may be different along the Nags Head shoreline.

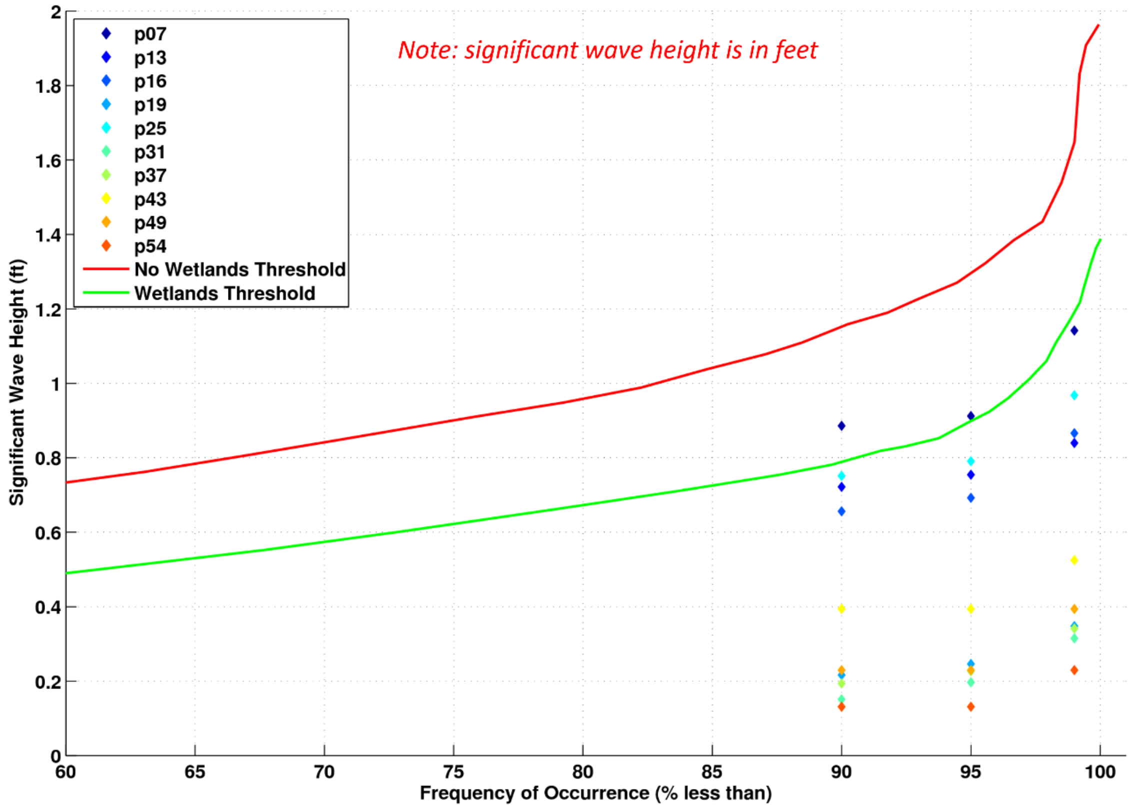


Figure 23: Plot of computed wave cumulative frequency (blue line) compared to the wetland's thresholds established in Roland and Douglass, 2005 (Roland & Douglass, 2005). The figure zooms into the 60th percentile and higher waves for better visualization.

Other recent work has focused on modeling the response of a marsh shoreline to varying wave conditions. The model of Mariotti and Fagherazzi correlates the rate of marsh edge retreat with the wave power over a certain threshold value for stability, ranging from 3 to 15 watts/meter depending on vegetation (Mariotti & Fagherazzi, 2010). Additional work by Trosclair, 2013 in Lake Borgne, Louisiana used the methods of Mariotti and Fagherazzi to model edge erosion during cold fronts (Trosclair, 2013). In this work, the critical wave power of 15 watts/meter is computed to correspond to a significant wave height of approximately 15 cm (or 0.5 ft). Higher wave heights produce more wave power, so wave heights above this threshold would erode the marsh edge at a rate proportional to the difference over the threshold value. Table 11 lists the Hs under normal conditions (wind exceedance value of 10%, 5% and 1%) and storm events (5-year and 10-year events). To be conservative, maximum Hs is considered among all the wind directions for normal conditions. It can be seen that Hs at points (p7, p13, p16, p25) north of north of Jockey's Ridge State Park are > 0.5ft under both normal conditions and storm events, while the other points have Hs > 0.5 ft only under storm events.

Table 11: Summary of Hs at extraction points (for normal condition, the maximum of all wind directions are considered)

	10%	5%	1%	5-year	10-yr
p07	0.9	0.9	1.1	3.4	3.9
p13	0.7	0.8	0.8	2.9	3.4
p16	0.7	0.7	0.9	2.4	2.9
p19	0.2	0.2	0.3	1.5	2.0
p25	0.8	0.8	1.0	3.1	3.6
p31	0.2	0.2	0.3	1.6	2.1
p37	0.2	0.2	0.3	1.8	2.3
p43	0.4	0.4	0.5	2.8	3.3
p49	0.2	0.2	0.4	2.6	3.1
p54	0.1	0.1	0.2	2.3	2.8

If a breakwater is sized such that the transmitted wave height for a particular environmental scenario is less than approximately 0.5 ft, then it is assumed that the marsh shoreline will not be significantly damaged.

7.2 Wave Transmission

7.2.1 Modeling wave transmission across the breakwater

Wave transmission across breakwaters is difficult to model numerically because of the complex physics of waves shoaling, breaking, traveling across the crest, and reforming in the lee. There is also a contribution of transmission through the pores of rubble mounds. The most reliable method of determining transmission is physical modeling in a laboratory, which is outside the scope of this project.

7.2.2 Empirical prediction formulae for wave transmission

Extensive physical modeling of rubble mounds has been conducted over the past few decades and data have been collated, analyzed, and used to produce empirical prediction formula. These formula are derived from the pool of data and account for the influence of the major parameters of the incident wave conditions and breakwater geometry.

The current authoritative guidance on wave transmission over and/or past a structure is the recently revised *EurOtop – Manual on wave overtopping of sea defences and related structures* (Van der Meer, et al., Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application., 2017), supported jointly by the U.K. Environment Agency and Rijkswaterstaat, the Netherlands Expertise Network on Flood Protection. Since its conception in 1999, guidance by EurOtop has been incorporated into worldwide engineering publications related to breakwater design; see CIRIA / CUR / CETMEF Rock Manual (2007), British Standard 6349 (2000), US Army Corps Coastal Engineering Manual, and International Organization for Standardization TC98. Alternative tools offered by EurOtop – the Neural Network and PC Overtopping – are useful for structures with unique or complex configurations and sea states. A simple rubble mound breakwater, such as for this project, does not necessitate the use of these tools and will be well covered by the empirical formulae.

7.2.3 Equation 4.8 – wave transmission across rubble mounds

The equation for predicting wave transmission across rubble mound structures is given below, taken directly from Chapter 4.2.5 of EurOtop. This equation is applicable to narrow rubble mound structures, where crest breadth B / wave height H_{m0} < 10, and is valid for negative freeboards (i.e., when the structure is submerged). Indeed, many tests were conducted specifically to investigate overtopping and transmission at low to negative freeboards. This equation is the exact same as Equation 5.66 in the Rock Manual. It is noted that porosity is not included as a variable in the equation. This is because the equation is applicable specifically to rubble mounds and the typical range of porosity within this class of structure does not change enough to exert significant influence on transmission.

$$K_t = -0.4\frac{R_c}{H_{m0}} + 0.64\left(\frac{B}{H_{m0}}\right)^{-0.31} \times \left(1 - \exp\left(-0.5\xi_{op}\right)\right)\ for\ 0.075 \le K_t \le 0.8$$

$where,$
$K_t = tranmission\ coefficient$
$R_c = crest\ freeboard\ [m]$
$H_{m0} = significant\ wave\ height, spectrally\ derived\ [m]$
$B = crest\ breadth$
$\xi_{op} = surf\ similarity\ parameter$

7.3 Transmission Results

Using the equation for transmission over low-crested, rubble-mound structures detailed above, the transmission coefficient and resulting transmitted wave height were computed for all design environmental scenarios for varying breakwater crest dimensions. The crest dimension exerts the most influence on transmission, while crest breadth and slope are less influential and chosen more for constructability. A typical crest breadth of 10 ft with a foreslope of 1:3 (vertical: horizontal) is assumed, and the crest elevation is varied for +1 ft, +1.5 ft, and +3.0 ft (all relative to NAVD88). Note that these alternatives are not all necessarily considered for design but are useful in demonstrating the influence of crest level on the level of protection. Figure 23 gives a schematic of the breakwater dimensions relative to the wave transmission computations.

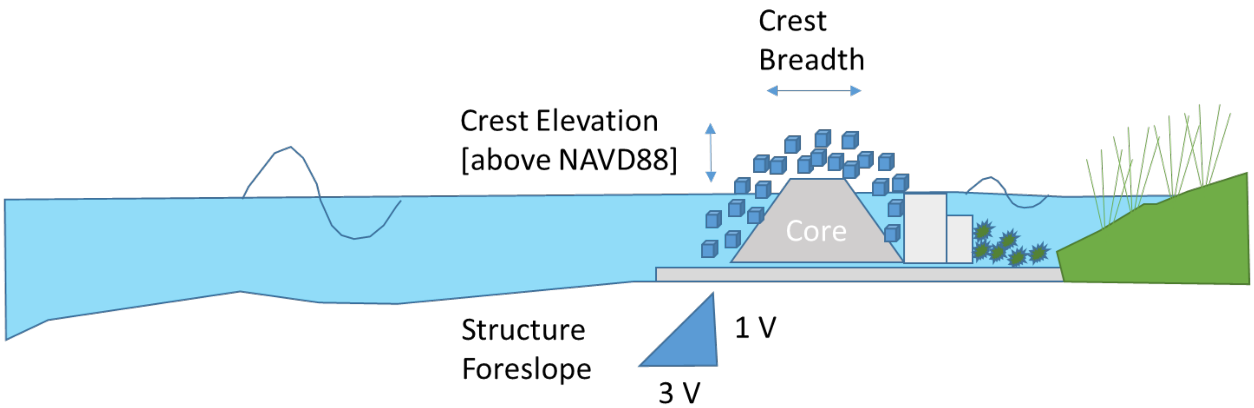


Figure 24: Schematic of breakwater dimensions for computing wave transmission

Table 12 to Table 16 show the results of the wave transmission calculations of points along the Nags Head shoreline for various environmental scenarios and crest elevation alternatives. Where transmitted wave heights are greater than 0.5 ft, it is expected that the protected marsh restoration feature could experience erosion. Table 12 to Table 14 indicate that a breakwater crest elevation of 1 ft is large enough to reduce the transmitted wave height below 0.5 ft under normal conditions. Table 15 to Table 16 indicated that a breakwater crest elevation of 3 ft is large enough to reduce the transmitted wave height below 0.5 ft under 5-year and 10-year storm events.

Table 12: Wave transmission results for 10% exceedance value

Type	Water Level (ft-NAVD88)	Significant Wave Height (ft-NAVD88)	Crest Elevation (ft-NAVD88)	1.0	1.5	3.0
			Peak Wave Period (s)	Transmitted Wave Height (ft)		
p07	1.0	0.9	2.2	0.2	0.0	0.0
p13	1.0	0.7	2.3	0.1	0.0	0.0
p16	1.0	0.7	2.3	0.1	0.0	0.0
p19	1.0	0.2	2.3	0.0	0.0	0.0
p25	1.0	0.8	2.2	0.1	0.0	0.0
p31	1.0	0.2	2.3	0.0	0.0	0.0
p37	1.0	0.2	2.3	0.0	0.0	0.0
p43	1.0	0.4	2.2	0.1	0.0	0.0
p49	1.0	0.2	2.3	0.0	0.0	0.0
p54	1.0	0.1	2.1	0.0	0.0	0.0

Table 13: Wave transmission results for 5% exceedance value

Type	Water Level (ft-NAVD88)	Significant Wave Height (ft-NAVD88)	Crest Elevation (ft-NAVD88)	1.0	1.5	3.0
			Peak Wave Period (s)	Transmitted Wave Height (ft)		
p07	1.2	0.9	2.3	0.3	0.1	0.0
p13	1.2	0.8	2.4	0.2	0.0	0.0
p16	1.2	0.7	2.4	0.2	0.0	0.0
p19	1.2	0.2	2.4	0.1	0.0	0.0
p25	1.2	0.8	2.3	0.2	0.0	0.0
p31	1.2	0.2	2.4	0.1	0.0	0.0
p37	1.2	0.2	2.4	0.1	0.0	0.0
p43	1.2	0.4	2.2	0.2	0.0	0.0
p49	1.2	0.2	2.1	0.1	0.0	0.0
p54	1.0	0.1	2.1	0.0	0.0	0.0

Table 14: Wave transmission results for 1% exceedance value

Type	Water Level (ft-NAVD88)	Significant Wave Height (ft-NAVD88)	Crest Elevation (ft-NAVD88)	1.0	1.5	3.0
			Peak Wave Period (s)	Transmitted Wave Height (ft)		
p07	1.5	1.1	2.4	0.4	0.2	0.0
p13	1.5	0.8	2.6	0.4	0.2	0.0
p16	1.5	0.9	2.5	0.4	0.2	0.0
p19	1.5	0.3	2.5	0.3	0.1	0.0
p25	1.5	1.0	2.4	0.4	0.2	0.0
p31	1.5	0.3	2.5	0.3	0.1	0.0
p37	1.5	0.3	2.5	0.3	0.1	0.0
p43	1.5	0.5	2.4	0.3	0.1	0.0
p49	1.5	0.4	2.1	0.3	0.1	0.0
p54	1.5	0.2	2.2	0.2	0.1	0.0

Table 15: Wave transmission results for 5-year event

Type	Water Level (ft-NAVD88)	Significant Wave Height (ft-NAVD88)	Crest Elevation (ft-NAVD88)	1.0	1.5	3.0
			Peak Wave Period (s)	Transmitted Wave Height (ft)		
p07	1.6	3.4	3.1	1.0	0.8	0.2
p13	1.6	2.9	3.3	0.9	0.7	0.1
p16	1.6	2.4	3.5	0.8	0.6	0.0
p19	1.6	1.5	3.5	0.6	0.4	0.0
p25	1.6	3.1	3.2	0.9	0.7	0.1
p31	1.6	1.6	3.7	0.6	0.4	0.0
p37	1.6	1.8	3.8	0.7	0.5	0.0
p43	1.6	2.8	3.3	0.9	0.7	0.1
p49	1.6	2.6	2.9	0.8	0.6	0.0
p54	1.6	2.3	2.8	0.7	0.5	0.0

Table 16: Wave transmission results for 10-year event

Type	Water Level (ft-NAVD88)	Significant Wave Height (ft-NAVD88)	Crest Elevation (ft-NAVD88)	1.0	1.5	3.0
			Peak Wave Period (s)	Transmitted Wave Height (ft)		
p07	1.7	3.9	3.5	1.2	1.0	0.4
p13	1.7	3.4	3.8	1.1	0.9	0.3
p16	1.7	2.9	3.9	1.0	0.8	0.2
p19	1.7	2.0	3.9	0.8	0.6	0.0
p25	1.7	3.6	3.7	1.2	1.0	0.4
p31	1.7	2.1	4.0	0.8	0.6	0.0
p37	1.7	2.3	4.0	0.9	0.7	0.1
p43	1.7	3.3	3.6	1.1	0.9	0.3
p49	1.7	3.1	3.1	1.0	0.8	0.2
p54	1.7	2.8	3.1	0.9	0.7	0.1

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9.0 APPENDIX

9.1 Existing Conditions – without SLR

9.1.1 Normal Conditions

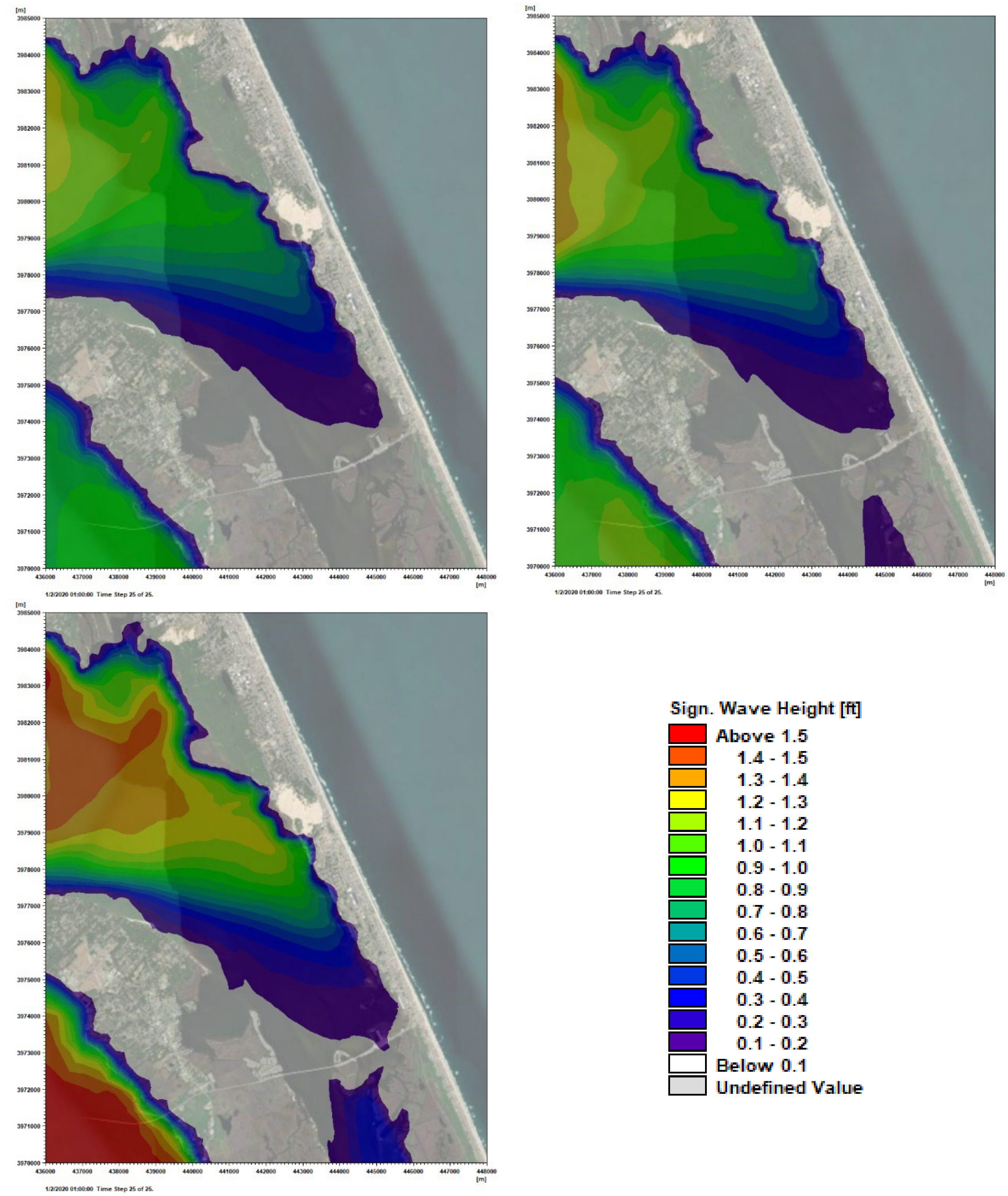

Figure 25: Significant Wave Height (Hs) for SW wind direction and exceedance value of 10% - 16 kt (upper left), 5% - 18 kt (upper right) and 1% - 23 kt (lower left)

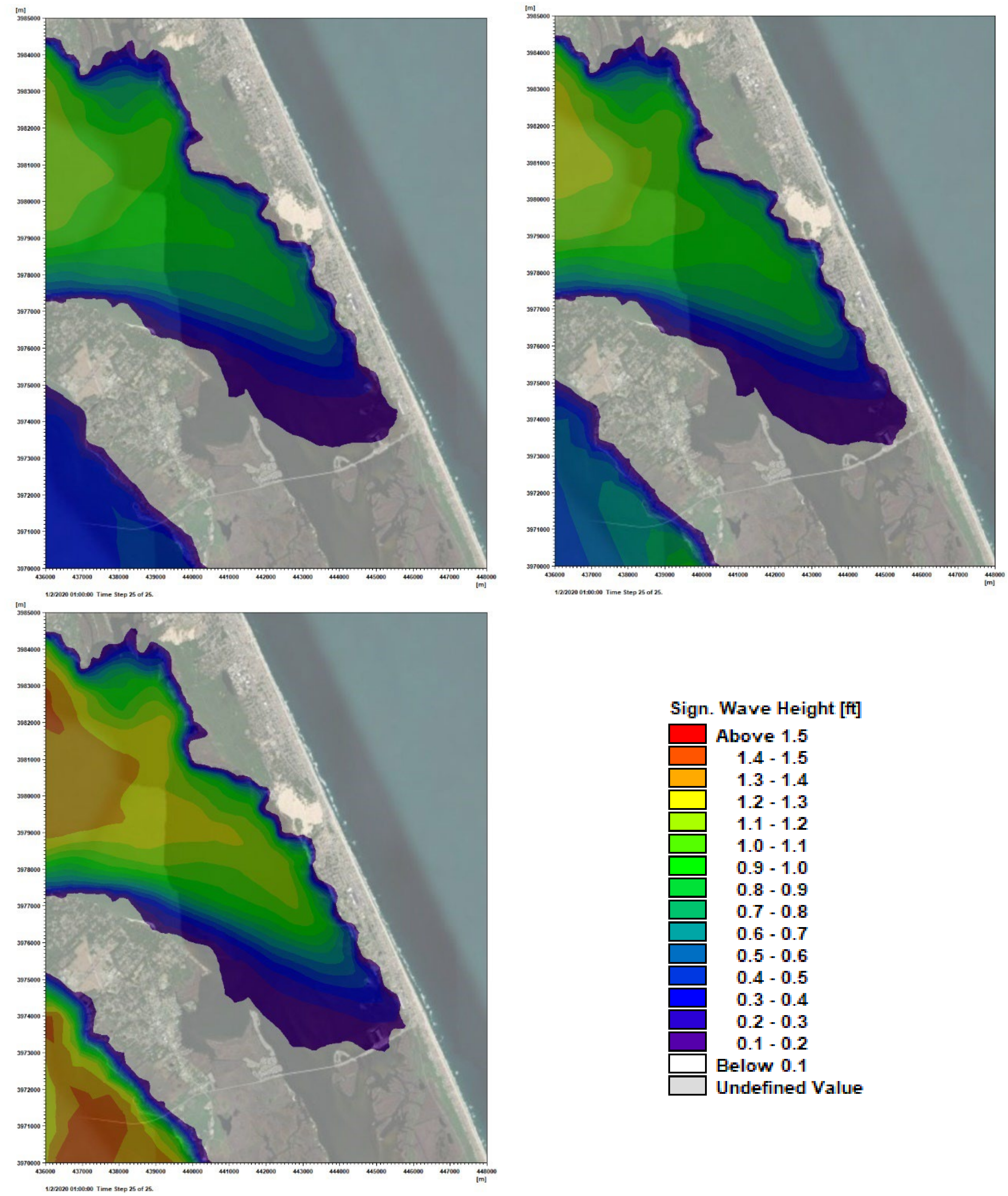

Figure 26: Significant Wave Height (Hs) for WSW wind direction and exceedance value of 10% - 16 kt (upper left), 5% - 18 kt (upper right) and 1% - 23 kt (lower left)

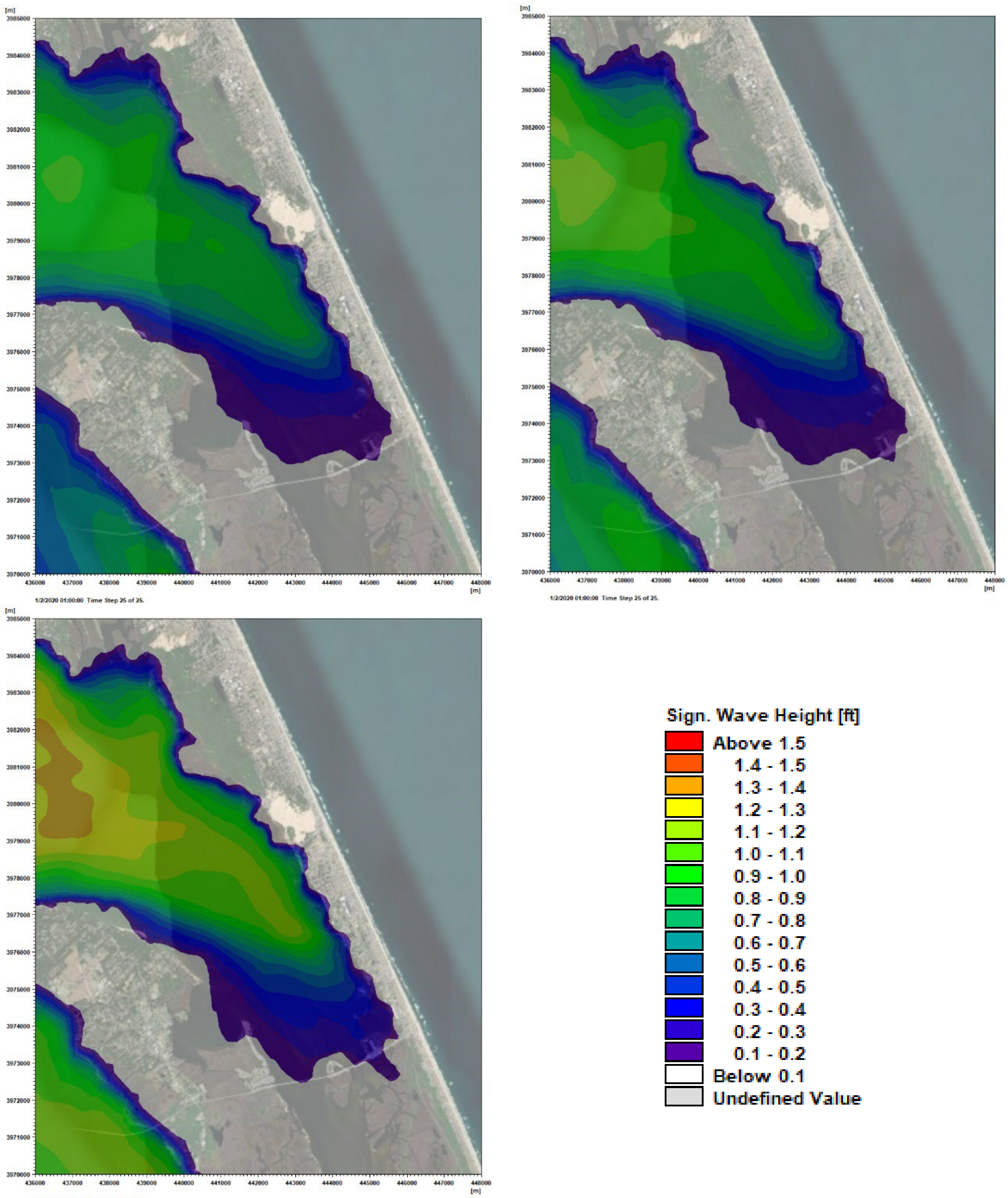

Figure 27: Significant Wave Height (Hs) for W wind direction and exceedance value of 10% - 16 kt (upper left), 5% - 18 kt (upper right) and 1% - 23 kt (lower left)

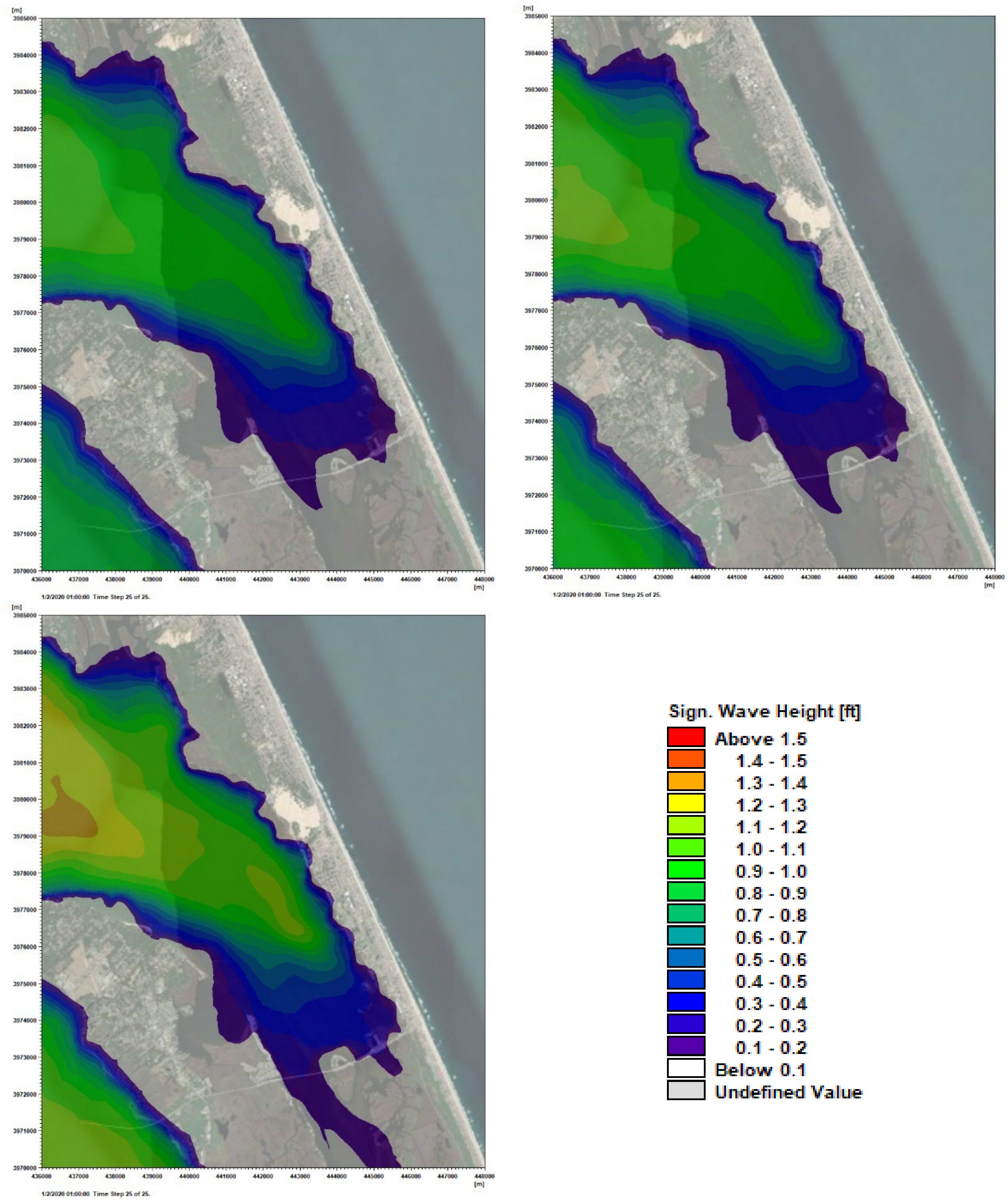

Figure 28: Significant Wave Height (Hs) for WNW wind direction and exceedance value of 10% - 16 kt (upper left), 5% - 18 kt (upper right) and 1% - 23 kt (lower left)

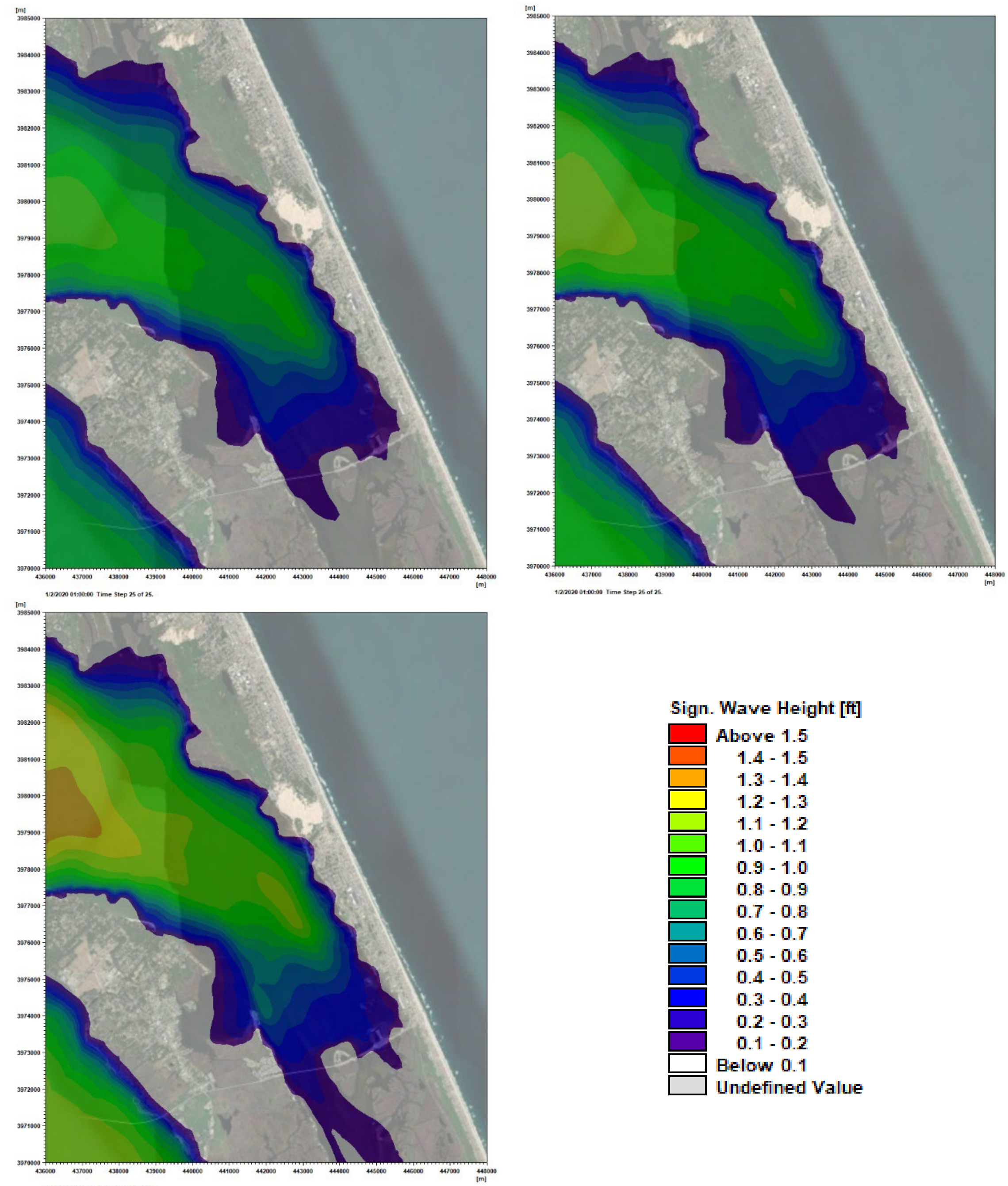

Figure 29: Significant Wave Height (Hs) for NW wind direction and exceedance value of 10% - 16 kt (upper left), 5% - 18 kt (upper right) and 1% - 23 kt (lower left)

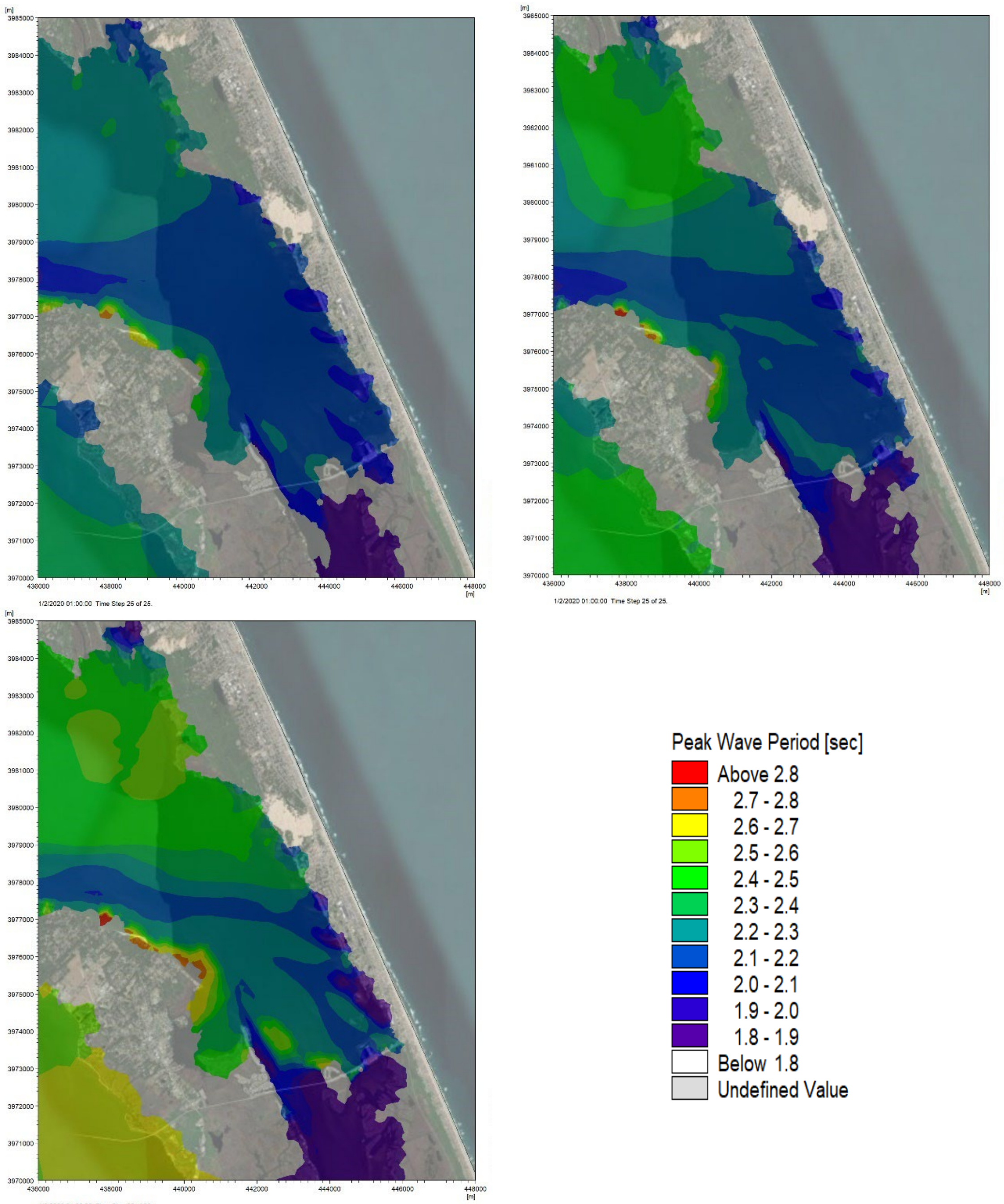

Figure 30: Significant Wave Height (Tp) for SW wind direction and exceedance value of 10% - 16 kt (upper left), 5% - 18 kt (upper right) and 1% - 23 kt (lower left)

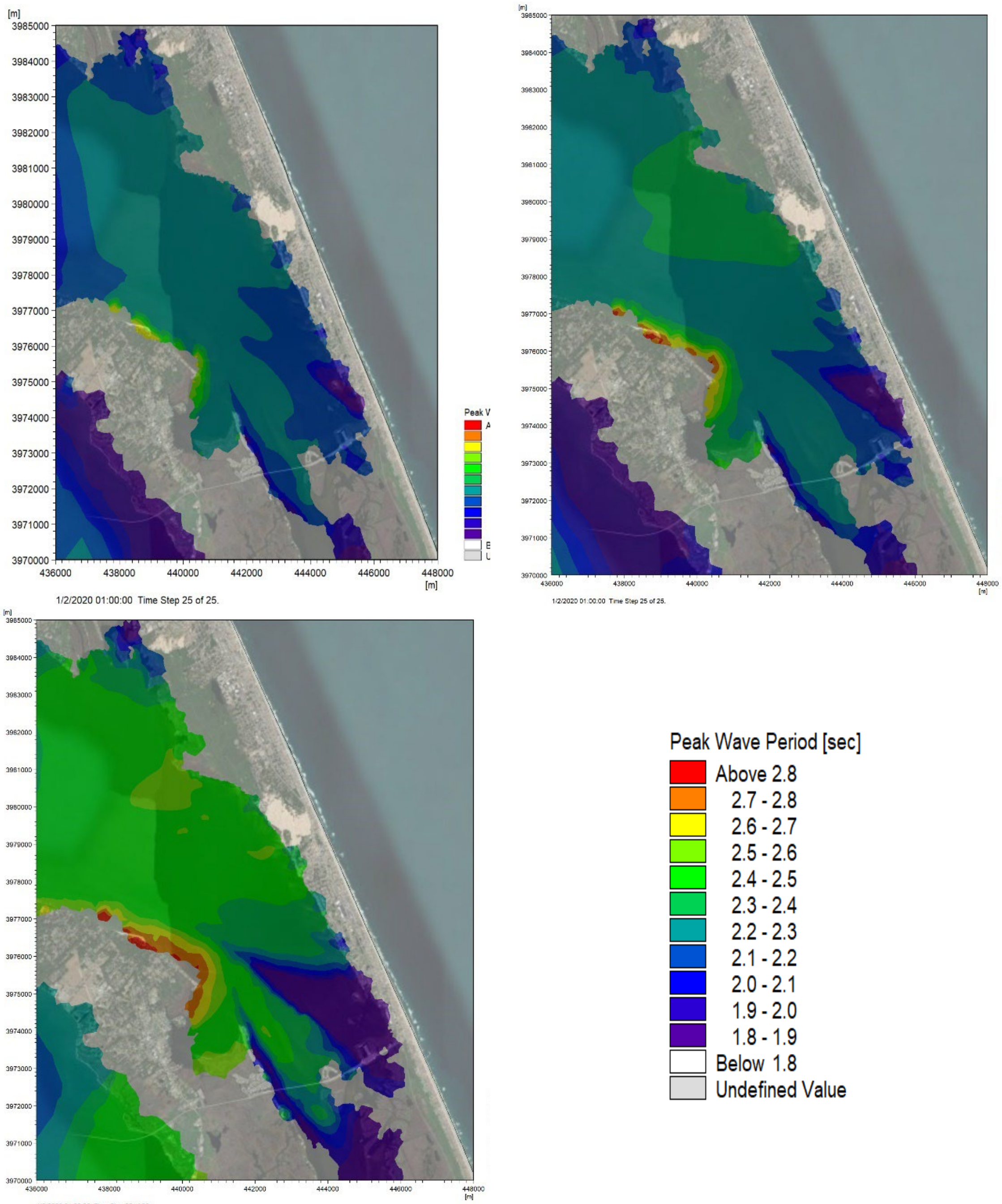

Figure 31: Significant Wave Height (Tp) for WSW wind direction and exceedance value of 10% - 16 kt (upper left), 5% - 18 kt (upper right) and 1% - 23 kt (lower left)

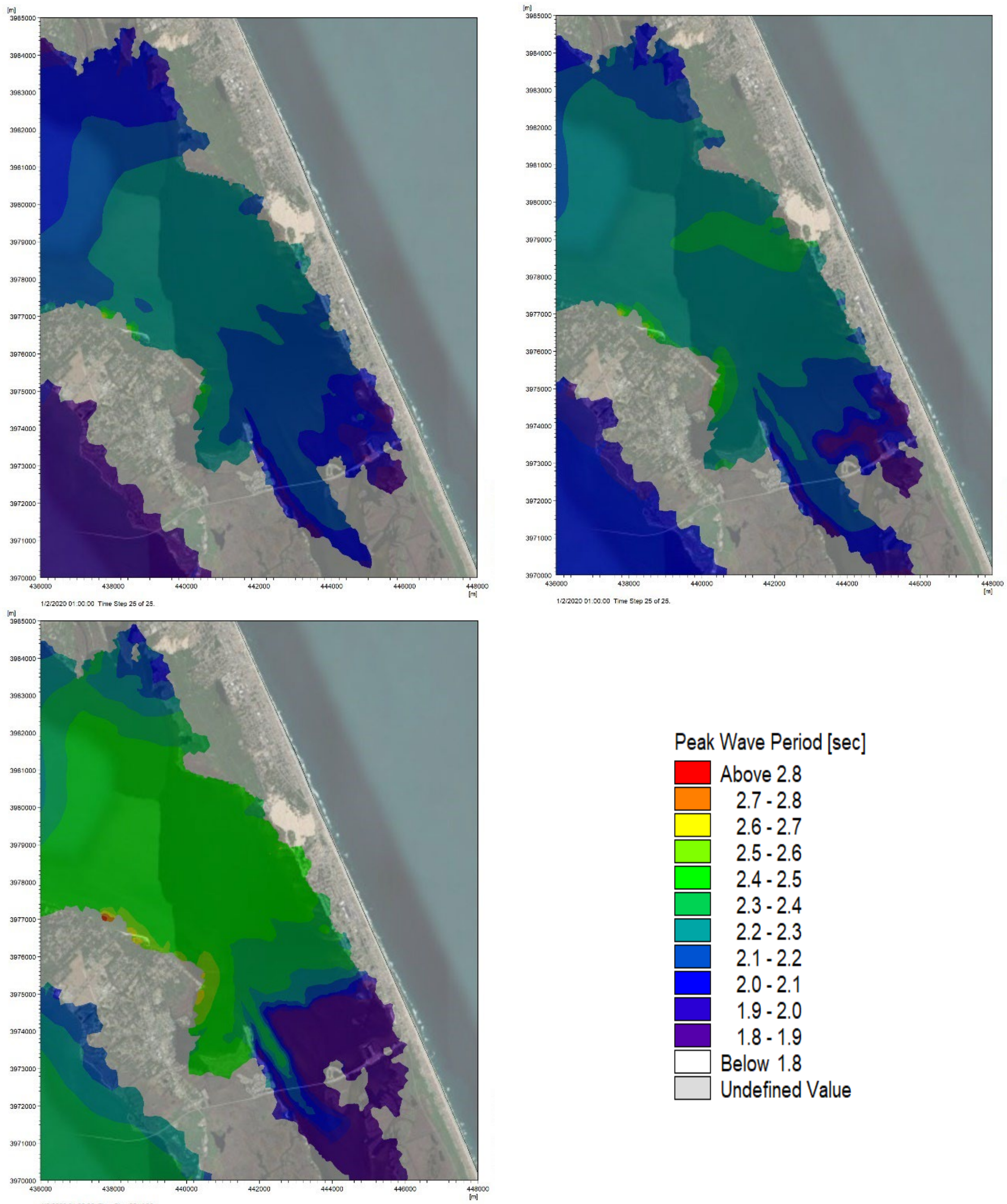

Figure 32: Significant Wave Height (Tp) for W wind direction and exceedance value of 10% - 16 kt (upper left), 5% - 18 kt (upper right) and 1% - 23 kt (lower left)

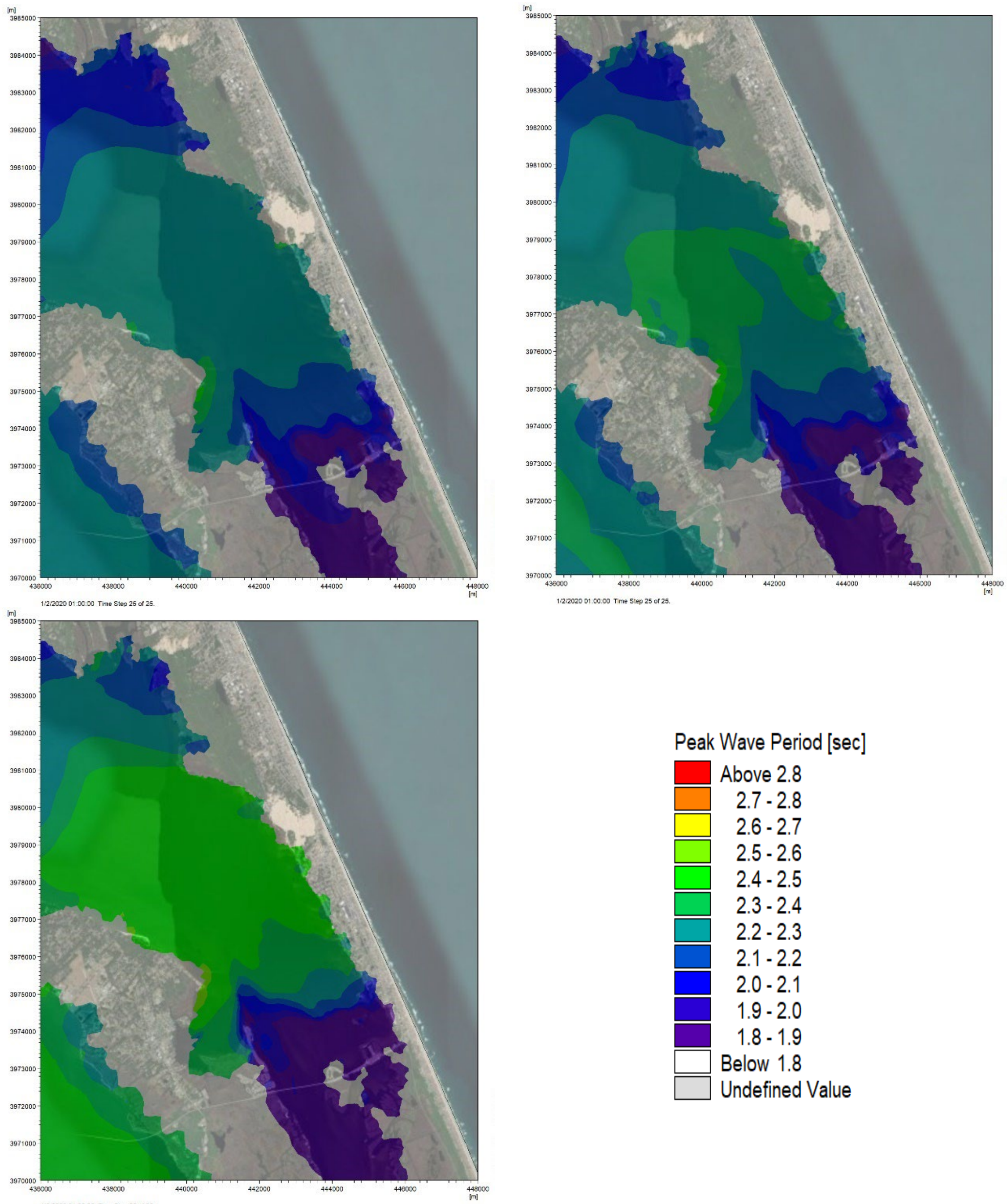

Figure 33: Significant Wave Height (Tp) for WNW wind direction and exceedance value of 10% - 16 kt (upper left), 5% - 18 kt (upper right) and 1% - 23 kt (lower left)

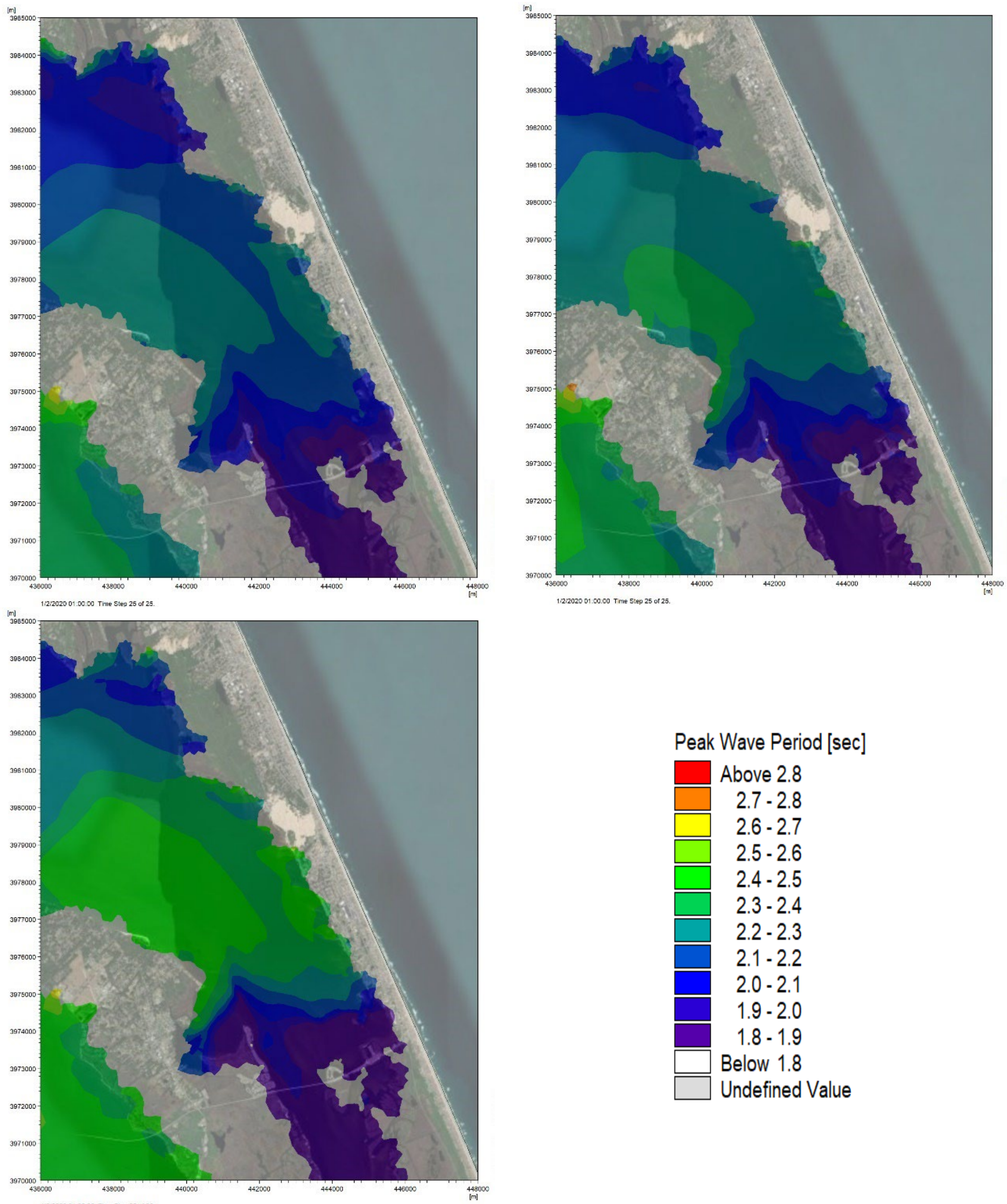

Figure 34: Significant Wave Height (Tp) for NW wind direction and exceedance value of 10% - 16 kt (upper left), 5% - 18 kt (upper right) and 1% - 23 kt (lower left)