**Attachment Q**

# Coastal Storm Erosion

Q1 RPS Modeling of Episodic Coastal Storm Erosion

Q2 Coastal Design Memo

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Q1 RPS Modeling of Episodic Coastal Storm Erosion

Q2 Coastal Design Memo

# Q1 RPS Modeling of Episodic Coastal Storm Erosion

# DOWSES BEACH CABLE LANDING: COASTAL EROSION ANALYSIS

Dowses Beach Cable
Final Report
**Privileged and Confidential**
**Attorney-Client Privileged**
**Attorney Work Product**
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# 1. INTRODUCTION

Epsilon contracted RPS to perform a sediment transport analysis, using a numerical modelling approach, to simulate erosion during episodic storm events. The study is done in support of the AVANGRID Commonwealth Wind (CWW) New England Wind 2 Connector and the proposed cable landing infrastructure in Dowses Beach, MA. The site of interest extends alongside East Bay Road and includes about 0.5 kilometres of the Dowses Beach shoreline (Figure 1-1). The goal of the study was to identify the extent of the erosion that is likely to occur in the future during major storm events with specific return periods and taking into account the projected sea level rise (SLR) over the life of the project. Additionally, wave (radiation) forces along the cable landings were also mapped.

The study uses the two-dimensional hydro-morphodynamic model, XBeach, to simulate the sediment transport and the erosion at the site of interest. The model handles the wave propagation towards the shoreline obliquely, and considers the mixed grain size (sand, gravel, and cobble) of beach sediments. At first, we present the results of the model simulating shoreline profile changes due to superstorm Sandy. Then, we present the results of extreme events simulations (50-, 100-, and 200-year return period event as well as a combine 50- & 100- year return period back-to-back event) associated with selected SLR scenarios.

This study characterizes the vulnerabilities of Dowses Beach to storm-induced erosion and flooding, specifically at the landing location of landing cables 1, 2, and 3 as well as their connection to East bay Road otherwise known as the causeway (Figure 1-1). All illustrations and results of water and bed level elevations are presented relative to the North American Vertical Datum of 1988 (NAVD88).


**Figure 1-1: The study area and cable routes of interest.**

# 2. STUDY AREA

Global climate change is occurring rapidly and features SLR and increased storm frequency that pose profound threats to coastal areas. In 2021 alone, four hurricane paths crossed along the state of Massachusetts (Elsa, Fred, Henri, and Ida); this is more than in the entire past decade (NOAA, n.d), though the storms had weakened to less than hurricane strength by the time they hit the state. Massachusetts' vast and typically low-lying coastline makes it particularly vulnerable to the impacts of climate change (EEA, 2011). Cape Cod has over 580 miles of coastline that are typically sandy, low-lying and vulnerable to flooding and erosion. The Town of Barnstable alone has 104 miles of coastline and has approximately 15 square miles (9,834 acres) of property that is within hurricane inundation zones (Woodard & Curran, 2022). Future inundation on Cape Cod is expected to require that adaptation and resiliency strategies be developed and iteratively implemented over time (e.g., identifying adaptation options for assets).

In coordination with the state of Massachusetts, Woods Hole Group created the Massachusetts Coast Flood Risk Model (MC-FRM) to help predict and plan for flooding and erosion induced by the potential impacts of climate change throughout the Massachusetts coastline. The MC-FRM is a hydrodynamic model that simulates tides, waves, winds, storm surges, SLR, and wave set-up at sufficient resolution to characterize site-specific locations (Woods Hole Group, 2000). MC-FRM dynamically simulates hundreds to thousands of storms, including hurricanes and nor-easters, and projects coastal flooding and inundation resulting from future SLR and storm events. The MC-FRM projects annual exceedance probability of inundation under 2030, 2050, and 2070 conditions for the entire Massachusetts coastline. MC-FCM projections were applied to simulate flooding and erosion proximate to the shoreline and within the existing and future flood zones in the Project area and to support evaluation of the resiliency of the design of onshore cables.

Dowses Beach (Figure 1-1) is a sandy residential beach off East Bay Road in Osterville, Barnstable County, Cape Cod, MA. It sits just south of the East Bay inlet which connects East Bay (Centerville River's outlet) to its northwest to Centerville Harbor and Nantucket Sound waters to its east-southeast. Dowses Beach's berm is approximately 300m long and 40m wide to the toe of its dune. Its orientation is on an approximate NE to SW line. At the inlet edge of Dowses Beach there is a jetty protruding into Centerville Harbor. At the beach's opposite (southwestern) edge, the shoreline continues with another narrow and low-lying pathway separating the open Sound waters from a shallow lake called Phinneys Bay. At its highest, the height of the Doses Beach dune is around 3.5m above the North American Vertical Datum of 1988 (NAVD88) but varies considerably; The dune drops to almost berm level toward the southwest near Phinneys Bay. Dowses Beach is connected to the mainland by a causeway with a parking lot, that has been built between East Bay and Phinneys Bay and continuing behind the coastal dune on the beach's landform.

As previously stipulated, the area of Barnstable, MA, is vulnerable to coastal flooding due to waves and surges during storm events, as well as to an increase in the Mean Sea Level (MSL). The south-facing Dowses Beach is open to the Atlantic Ocean, sitting along the track of hurricanes and tropical storms originating from the Gulf of Mexico or the waters of the Atlantic Ocean, as well as Nor'easters originating from Cape Hatteras to New England. The area historically has been strongly impacted by extreme storms such as the April Nor'easter in 2007, Tropical Storm Irene in 2011 (Costa, 2012), superstorm Sandy (2012), and Hurricane Bob (1991). Hurricane Bob caused 15 feet of storm surge in the neighboring area of Buzzards Bay and 6 feet of storm surge in Barnstable's Hyannis Harbor (COB, 2020). As climate change continues to cause more frequent and intense extreme events, it has become exceedingly important to accurately forecast and model these events. The adopted state standard SLR projections are the "High" SLR projections from Resilient MA, which are also used in the MC-FRM model and applied to the XBeach model of Dowses Beach. According to these projections, normal tidal flooding is predicted to inundate a significant portion of the site daily by 2070 (Figure 2-1). The erosion associated from storm events raising water levels above normal tides is expected to become a significant issue (Figure 2-1).

Projected SLR conditions for future decades pose flooding risks to areas that surround East and Phinneys Bays. SLR projections over the next 50 years are projected to inundate shorelines of low-lying elevation (i.e., areas that are not protected by a beaches natural dune system). The barrier inlet located on the northeast edge of East Bay as well as the shorelines encompassing Phinneys Bay are projected to be exposed daily to 1.4 m (4.6 ft) NAVD88 (~0.45 m (1.5 ft) MHHW 83-01) by 2050. The northern area of Dowses Beach features a persistent dune system offering protection from flooding and inundation (MOCZM, 2020).

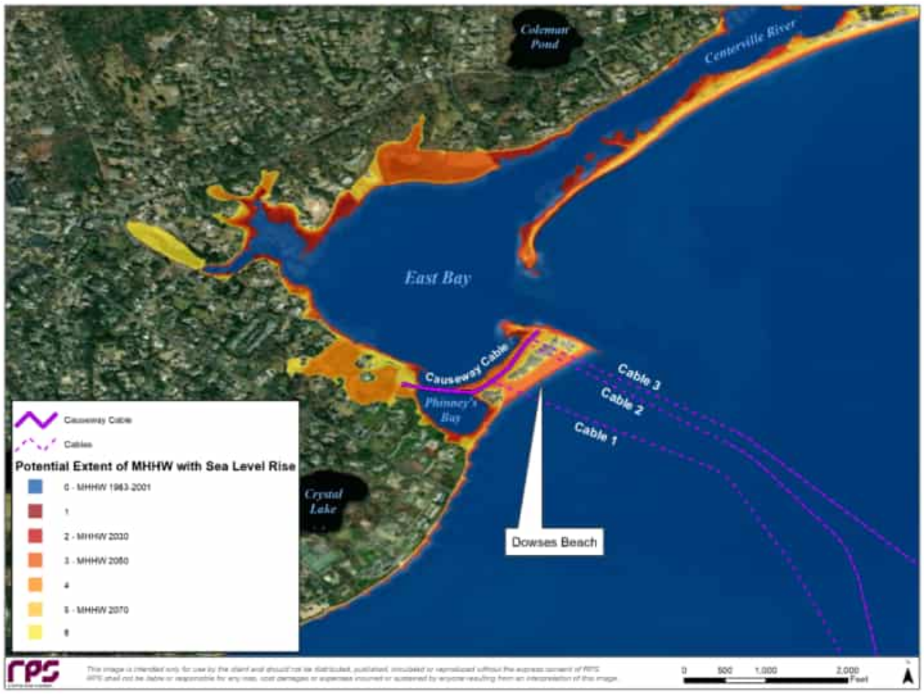


**Figure 2-1: Extent of normal daily tidal flooding under future sea level rise scenarios [projected Mean Higher High Water, in feet] (adopted by MOCZM, 2020)**

# 3. SEDIMENT TRANSPORT MODELING

RPS group modeled coastal erosion that would ensue in the Dowses Beach area after various extreme events. The erosion was modeled using the 2D hydro-morphodynamic numerical model XBeach (Roelvink et al., 2009). XBeach couples a hydrodynamic and a morphodynamic model, combining a phase average wave module based on the wave action equation, a flow module based on the shallow water equation, a sediment transport module, and a morphodynamic module assessing the induced changes in coastal morphology.

The model uses the local bathymetry and sea-state in initial and boundary conditions, respectively. The offshore boundary sea-state is defined with the significant wave height, peak period, dominant wave direction and water level, resulting from the astronomical tidal level and tidal residual (storm surge). These variables are used by the wave and flow modules to simulate the waves and currents in the domain, which are passed to the sediment transport module to simulate the sediment transport and ultimately the changes in bed level to predict a new morphology at the site after the event (Roelvink et al., 2009). This process is iterated over time to simulate the relevant processes occurring over the course of a storm event (Figure 3-1).

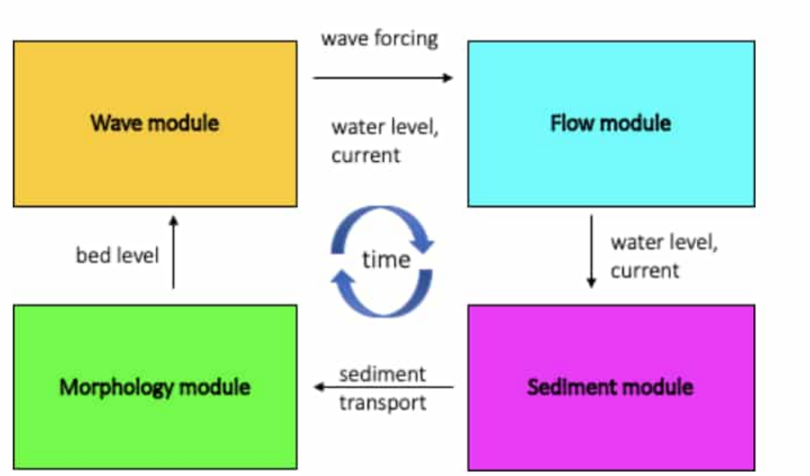


**Figure 3-1: Diagram of XBeach's embedded modules (top) from Roelvink et al., 2010.**

XBeach has been favoured in recent years for its ability in modelling nearshore responses to hurricanes and extreme events, as it accounts for wave breaking, surf and swash zone processes, dune erosion, overwashing, and breaching. XBeach has three different modes: Stationary, Surfbeat, and Non-Hydrostatic (Roelvink et al., 2010, Figure 3-1). RPS utilized XBeach in Surfbeat mode to model extreme events at the study area. "Surfbeat" refers to infragravity waves or long waves with long period of oscillations around the mean water level. These slow oscillations are strongly associated to foreshore erosion (Schaffer & Svendsen, 1988). The Surfbeat mode was indeed designed to resolve these particularly energetic and erosive long waves. The XBeach model in Surfbeat mode has been validated during extreme events showing good accuracy; in particular, in sandy dissipative beaches (de Vet et al., 2015).

The XBeach model is a process-based model which is sensitive to few parameters, in particular the wave skewness and asymmetry. The wave skewness and asymmetry influence the stokes advection velocity ($u_a$) which accounts for non-linear effects on sediment transport, formulated as,

$$u_a = \left(f_{sk}(S_k) - f_{as}(A_k)\right)u_{RMS}$$

where the advection velocity is a function of wave skewness and asymmetry ($S_k$ and $A_k$ , respectively), root mean square velocity ($u_{RMS}$), and calibration factors ($f_{sk}$ and $f_{as}$). The user-defined input value for the XBeach model, FACUA, is a dimensionless variable that combines the two calibration factors ($f_{sk}$ and $f_{as}$) into the sediment transport equation (Roelvink, 2010). FACUA can range from 0.1 to 0.3, with 0.1 being the default value. Previous XBeach studies (Schambach et al., 2018 and de Vet et al., 2015) that have calibrated the model with pre- and post-storm erosional data have noted that the default FACUA value in XBeach overestimates sediment transport. The studies show that a higher FACUA value tends to represent sediment transport more accurately during storm events. However, since wave skewness and asymmetry are highly dependent on site-specific bathymetry, the FACUA parameter should be calibrated for each location where XBeach is applied. As there was no historic field data available (per Epsilon's communications) at this site, the parameters were defined to align with the most reliable literature. However, in addition, a sensitivity analysis was performed to assess likely responses, for a range of FACUA values, and provide an indication of the confidence interval one might expect in the morphological response.

## 3.1 Model Input

### 3.1.1 Bathymetry, topography and land coverage

Site specific bathymetric data was required as the input for XBeach's morphodynamic model. National Oceanic and Atmospheric Administration LiDAR data (NOAA 2023) in combination with topographic LiDAR data provided from AVANGRID were utilized to create the bathymetry input for XBeach. The modeling domain and associated bathymetry extended from the Dowses Beach study area to the offshore closure depth of about 7 m at its eastern boundary based on the local wave climate and Dean's formulation (Figure 3-2) (Dean, 2002). The offshore closure depth refers to the water depth where sediment, once transported offshore by wave action past this point, will no longer be returned naturally back to the beach, which is a direct result of the extreme wave climate on the beach profile (Nicholls et al.,1998). Based on the Beach's location with reference to the Atlantic Ocean and Centerville Harbor, storm induced wave action is shown to propagate towards Dowses Beach from the south to southeast.

To optimize computational time while maximizing the resolution closer to the cable landing sites, the computational domain was kept quite small and grid cell resolution was made to be 5 m in easting and northing.

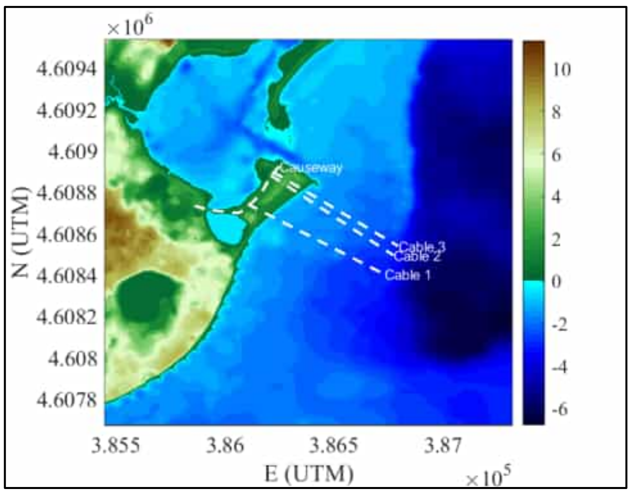


**Figure 3-2: XBeach modelling domain, bathymetry and cable locations.**

The morphodynamic model is shown to perform more accurately if a description of the land coverage is included in the model. This is defined through a roughness coefficient characteristic of the land coverage and directly related to a friction coefficient. Indeed, the bottom friction affects the sediment transport by modulating the velocity of the flow, which can cause either accretion (sediment particles settle out of the flow and accumulate), or erosion of the bottom layer and increased sediment transport, when the friction increases or decreases, respectively. For example, sediment transport will vary for sandy beaches compared to dense woodland areas. Each material (e.g., sand, asphalt, shrubs, etc.) has a specific roughness value associated to a specific friction, Manning coefficient (Table 3-1). XBeach accounts for the geospatial distribution of Manning coefficient when modelling sediment transport. Bed friction data of the area is extracted from the National Land Cover Database (Figure 3-3) and interpolated on the computational grid (Figure 3-4).

It should be noted that to provide conservative results, the Causeway, which connects East Bay Rd, all proposed landing cable routes, and the parking area, located behind the dune, were assumed erodible areas, which could breach or be washed away in the event of a severe storm. In addition, it was assumed that over the next few decades there would be no change in the shoreline naturally or due to maintenance (such as beach nourishments), and the only difference between decades would be sea level rise and any projected changes in storm intensity.

**Table 3-1: Manning Coefficients associated with specific land use types. (USACE Hydrologic Engineering Center 2023)**

| Area | Manning Coefficient (*n*) |
|---|---|
| Mixed Forest | 0.12 |
| Developed Open Space | 0.035 |
| Woody Wetland | 0.07 |
| Developed High Density | 0.15 |
| Barren Land Rock / Sand /Clay | 0.03 |
| Coarse Sand | 0.25-0.035 |
| Cobble | 0.03-0.05 |
| Boulder | 0.04-0.07 |

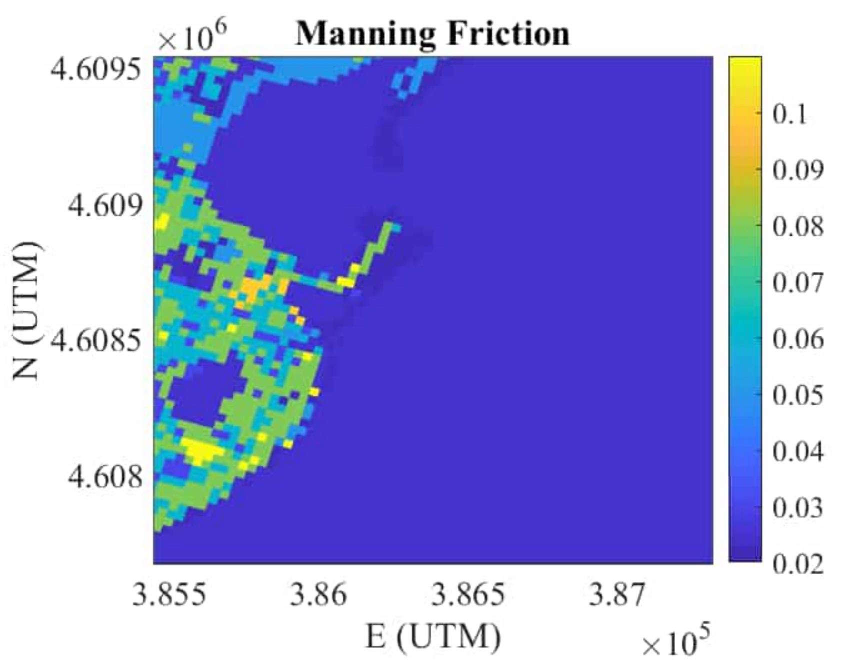


**Figure 3-3: Values of the Manning coefficient associated with land cover from the National Land Cover Database (NLCD) at 30m resolution (as used in USACE, 2023).**

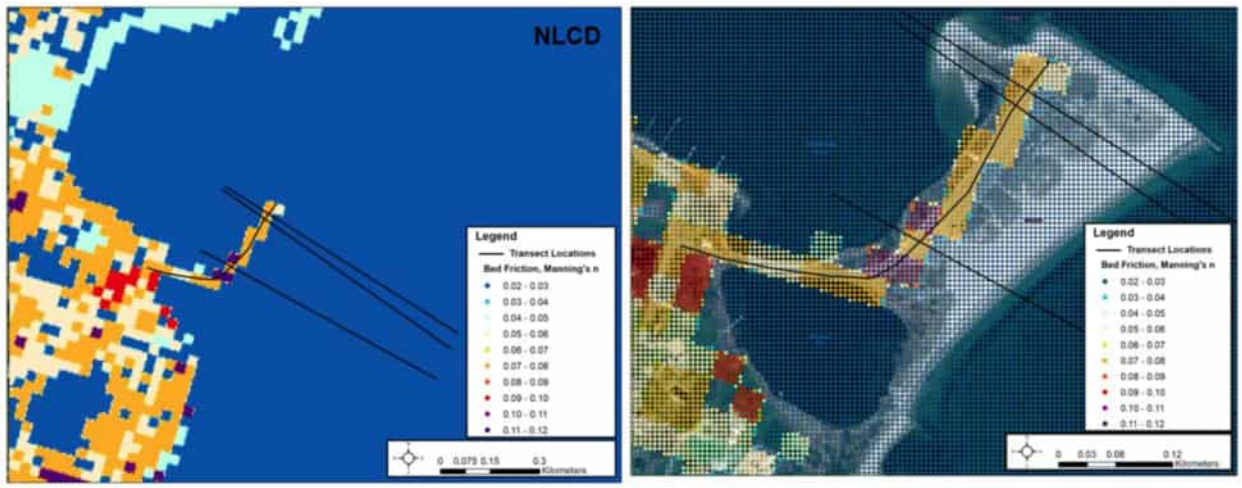


**Figure 3-4: A layout of Manning Coefficients as they apply to each grid cell in the computational domain and relations to provided cable locations.**

### 3.1.2 Grain size distributions

A beach's average grain size is representative of the typical wave climate of the area. Coarser sediment (coarse grain sand, small pebbles, etc.) is a result of a very high energy wave climate whereas finer sediment (fine sand, mud, clay) is the result of having a milder wave climate (Dean, R., & Dalrymple, R. 2001). Simulations require detailed information of the sediment characteristics for accurate modelling of the transport. Grain size, which can be classified by sieve analysis, greatly impacts transport velocity. A study performed by Mott MacDonald for AVANGRID collected sediment samples along the nearshore area of Dowses Beach, MA and analysed through a sieve analysis. For beach sediment sizes coarser than fine sand, the coarser the sediment of a beach is, the lower the anticipated erosion will be. In an effort to be conservative, but realistic, the model was forced with data from sampled locations with finer sediment closer to the minimum range listed in Table 3-2. Sieve analysis recorded the D50 and D15 (MacDonald, 2022) and yielded that sediment in the modelling area is comprised of mostly medium sand to fine sand with a D50 of ~0.3 mm. As this beach's D50 is on the medium to fine side of sand, and, considering the limitation in fetch within Nantucket Sound from the islands of Martha's Vineyard, Nantucket, and the Monomoy complex, it is expected that the area is somewhat protected from swells in the open Atlantic and typical wave action in this area is on the milder side.

**Table 3-2: Grain size distribution averages (mm) of sites located within the study area.**

| Particle Size Distribution | Low Grain Size (mm) | High Grain Size (mm) | Average |
|---|---|---|---|
| D15 | 0.11 | 0.27 | 0.19 |
| D50 | 0.29 | 0.56 | 0.39 |

### 3.1.3 Water levels and sea level rise scenarios

Water level projections for future scenarios were provided by the Woods Hole Group (WHG) from the state-wide accepted MC-FRM model. These projections are consistent with the adopted “high SLR” standard projection of the State of Massachusetts combined with dynamic tidal and storm conditions. The MC-FRM model was calibrated for normal tidal conditions and simulated future combined surge and wave propagation under projected SLR (Bosma et al., 2015). The MC-FRM model approach is based on a Monte Carlo approach where tide and phase are randomized as the extreme event occurs. MC-FRM projections of SLR and the associated Mean Lower Low Water and Mean Higher High Water tidal datums for Dowses Beach, MA in 2030, 2050, and 2070 are shown in Table 3-3.

**Table 3-3: Dowses Beach, MA predicted Sea level Rise (m) and projected tidal datum elevations for 2030, 2050, and 2070 (m with respect to NAVD88).**

| Year | Sea Level Rise [ m ] | MHHW [ m NAVD88 ] | MLLW [ m NAVD88 ] |
|---|---|---|---|
| 2030 | 0.39 | 1.03 | -0.12 |
| 2050 | 0.76 | 1.40 | 0.24 |
| 2070 | 1.31 | 1.95 | 0.79 |

### 3.1.4 Boundary conditions: Wave height, direction and surge

To force the sediment transport model at the boundary, MC-FRM results were acquired from WHG for the wave and water level of extreme events (Bosma et al., 2015). Synthetic extreme events representative of 50-year, 100-year, and 200-year storms in 2030, in 2050, and in 2070 were acquired. They were slightly tailored (time series were either extended or trimmed) to peak at the same time. WHG extracted the results of storm simulations, propagating across the Atlantic for each design time frame, at the offshore limit of the coastal domain and provided 50-year, 100-year, and 200-year events’ wave parameters and total water level (including surge, tide and SLR). WHG generated storm results for different return periods by scaling individual event conditions (i.e. significant wave height (Hs) and water level (SSH) to the relevant return period (Figure 3-5 through Figure 3-13).

These values were used in boundary conditions for the local morphodynamic simulations with the numerical model XBeach. The relevant offshore wave variables were used to create offshore boundary conditions assuming a JONSWAP wave spectrum (Hasselmann et al., 1980). Simulations were designed to capture the wave climate evolving along the duration of each storm event. Note that, though these individual representative storms may differ in their setup and setdown conditions, the peak of all storms (the brown-colored part of the wave roses) is directed near-perpendicular to Dowses Beach with waves coming out of the southeast quadrant.

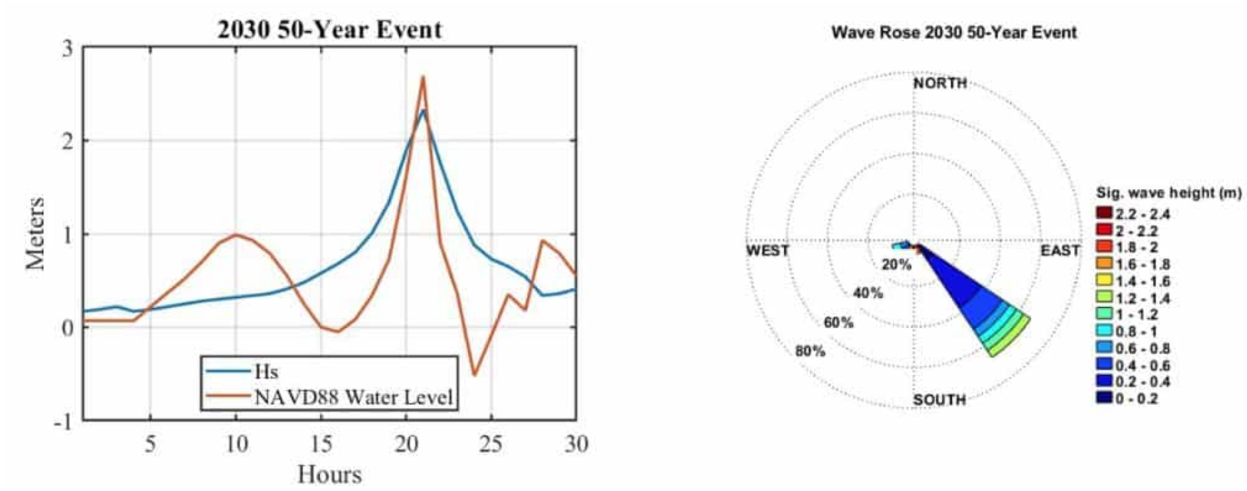


**Figure 3-5: Significant wave height and water level (left), for 2030 SLR 50-Year event scenario, simulated by WHG at the offshore boundary of the coastal grid, and used in boundary conditions for the morphodynamic simulations [XBeach model].**

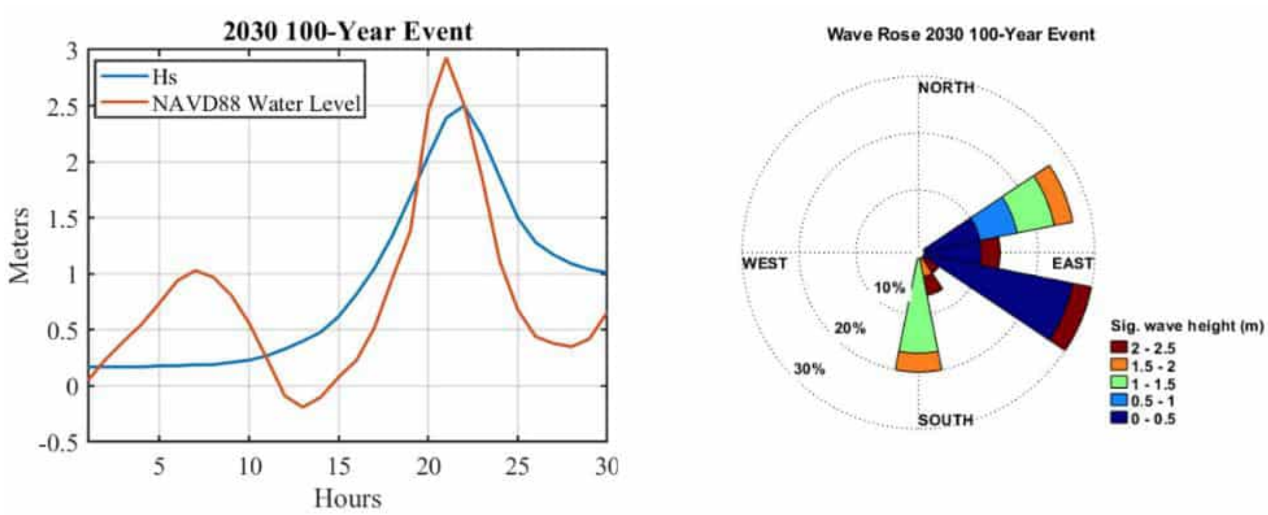


**Figure 3-6: Significant wave height and water level (left), for 2030 SLR 100-Year event scenario, simulated by WHG at the offshore boundary of the coastal grid, and used in boundary conditions for the morphodynamic simulations [XBeach model].**

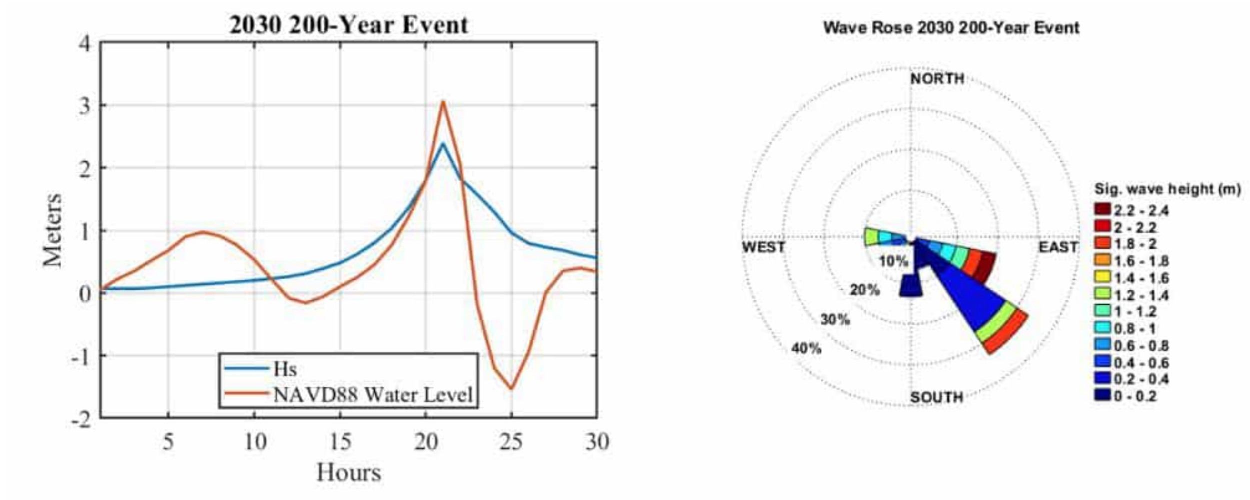


**Figure 3-7: Significant wave height and water level (left), for 2030 SLR 200-Year event scenario, simulated by WHG at the offshore boundary of the coastal grid, and used in boundary conditions for the morphodynamic simulations [XBeach model].**

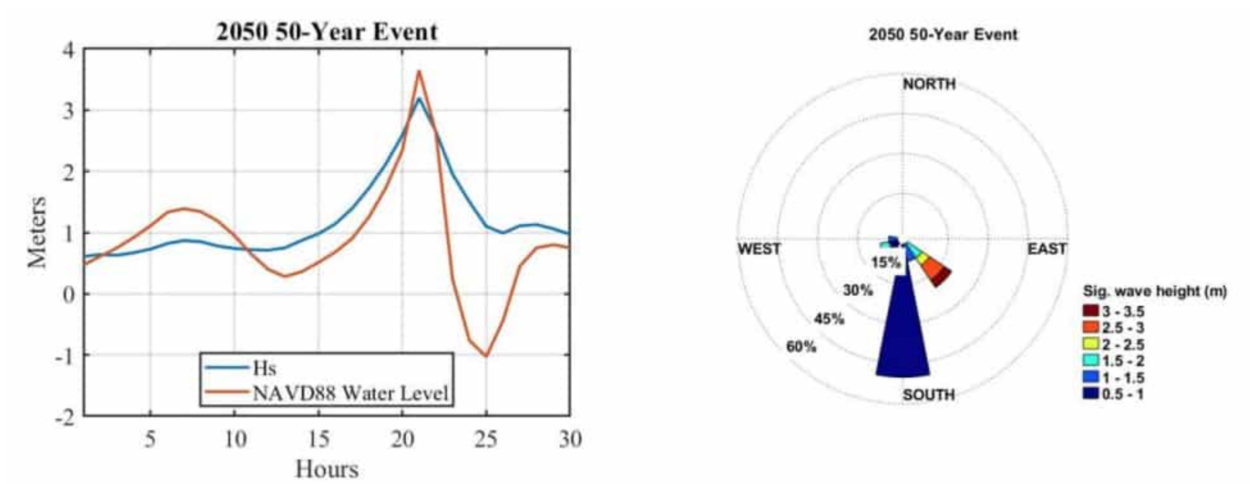


**Figure 3-8: Significant wave height and water level (left), for 2050 SLR 50-Year event scenario, simulated by WHG at the offshore boundary of the coastal grid, and used in boundary conditions for the morphodynamic simulations [XBeach model].**

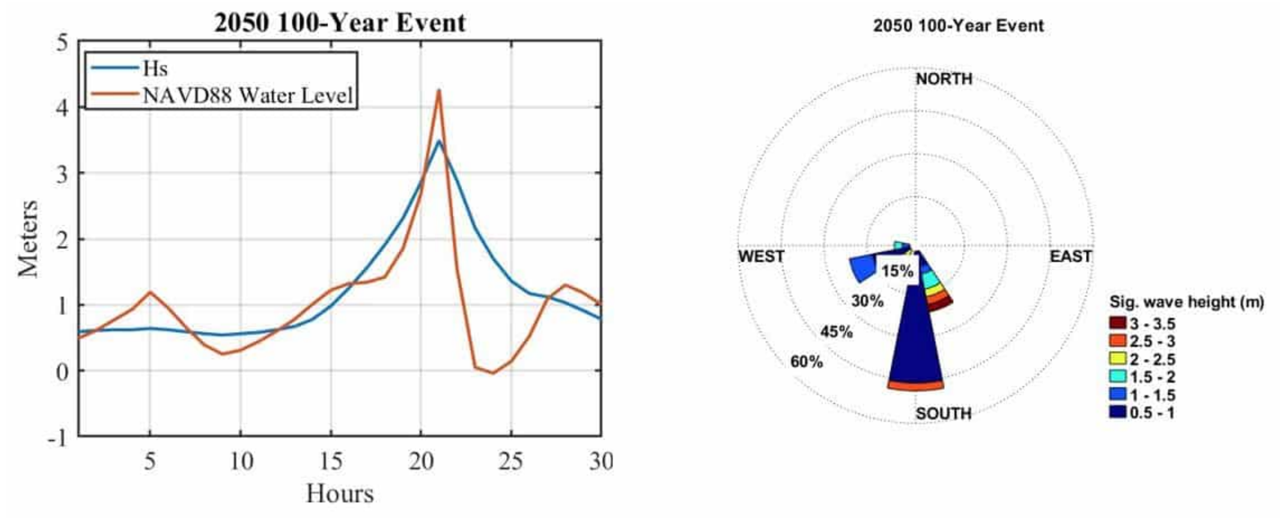


**Figure 3-9: Significant wave height and water level (left), for 2050 SLR 100-Year event scenario, simulated by WHG at the offshore boundary of the coastal grid, and used in boundary conditions for the morphodynamic simulations [XBeach model].**

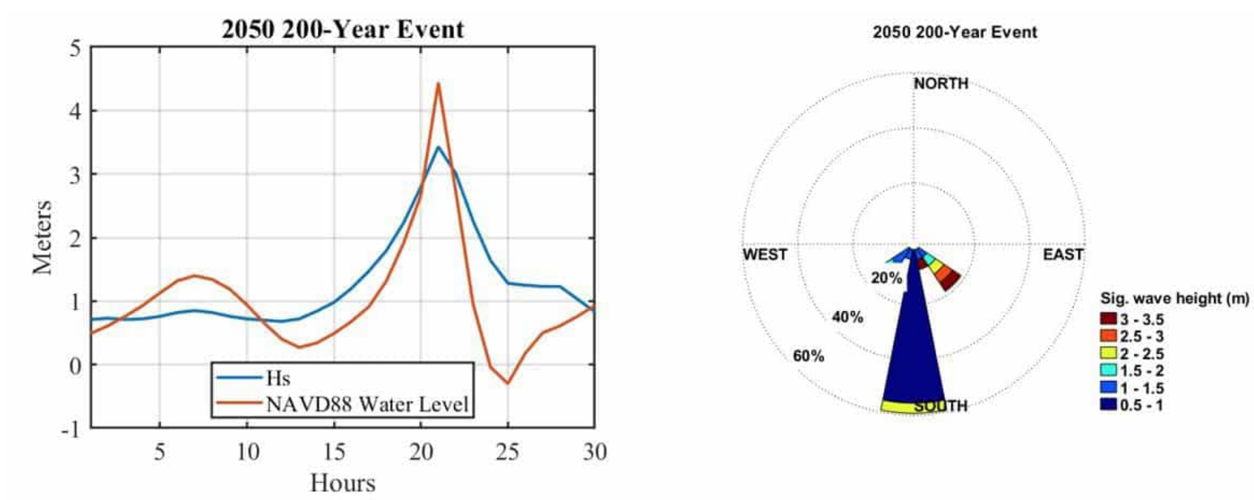


**Figure 3-10: Significant wave height and water level (left), for 2050 SLR 200-Year event scenario, simulated by WHG at the offshore boundary of the coastal grid, and used in boundary conditions for the morphodynamic simulations [XBeach model].**

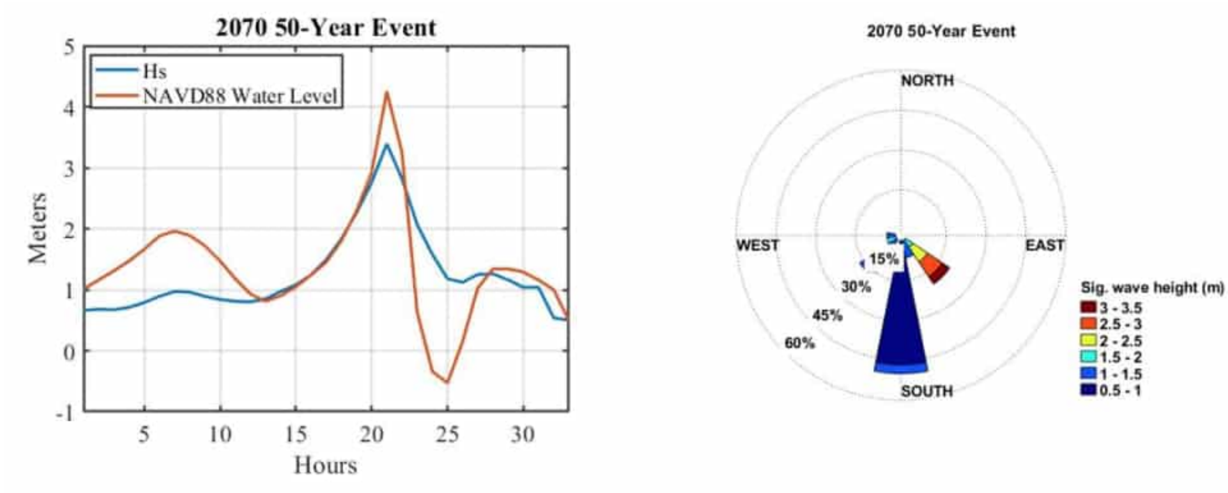


**Figure 3-11: Significant wave height and water level (left), for 2070 SLR 50-Year event scenario, simulated by WHG at the offshore boundary of the coastal grid, and used in boundary conditions for the morphodynamic simulations [XBeach model].**

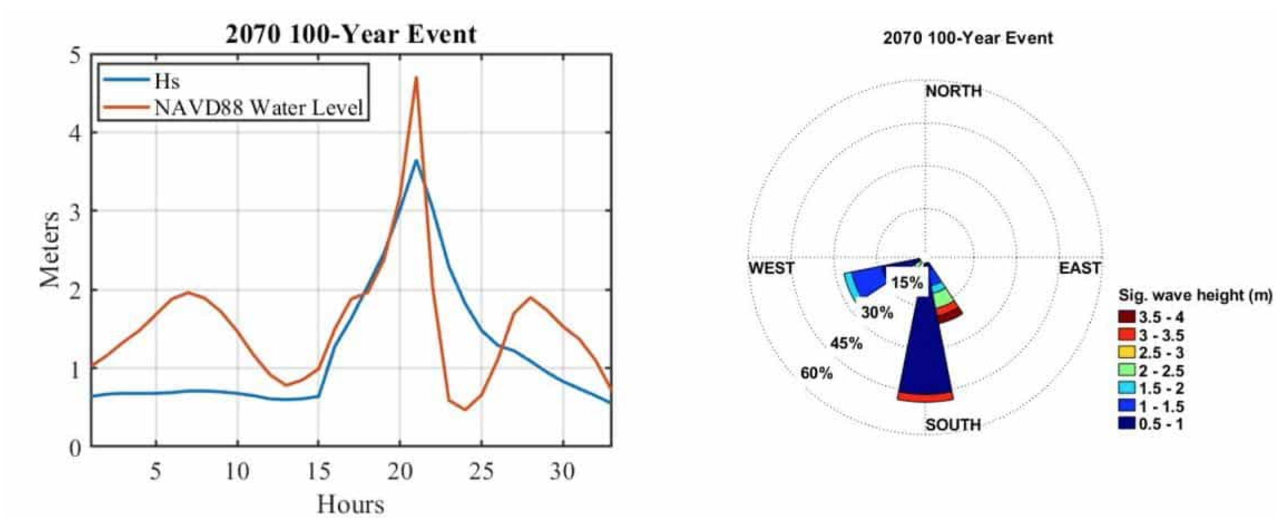


**Figure 3-12: Significant wave height and water level (left), for 2070 SLR 100-Year event scenario, simulated by WHG at the offshore boundary of the coastal grid, and used in boundary conditions for the morphodynamic simulations [XBeach model].**

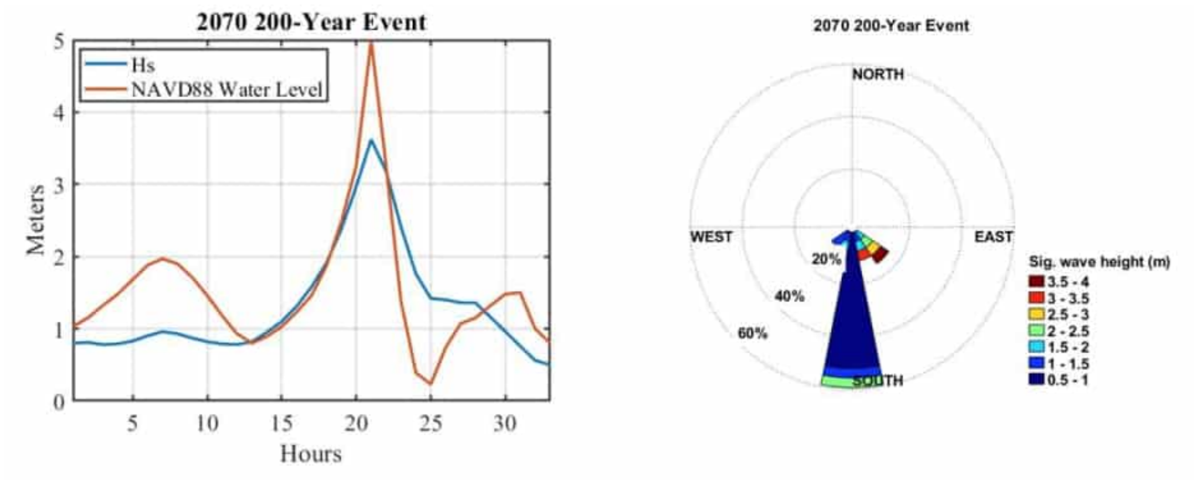


**Figure 3-13: Significant wave height and water level (left), for 2070 SLR 200-Year event scenario, simulated by WHG at the offshore boundary of the coastal grid, and used in boundary conditions for the morphodynamic simulations [XBeach model].**

## 3.2 Model Sensitivity Analysis

As XBeach has been proven to be most accurate when calibrated to the site's specific bathymetry and wave climate, a calibration with an historical storm would be desirable. To achieve this requirement, RPS attempted an assessment of the impact of Superstorm Sandy at the site. However, due to lack of availability of rigorous pre and post event data, the validation approach was reduced to a visual validation based on historical pictures, complimented by a sensitivity analysis.

Hurricane Sandy originated October 22, 2012, off the coast of Nicaragua (Gibbens, 2021). The storm, one of the largest diameter storms ever recorded in the Atlantic, traveled up the east coast of the United States with a landfall in New Jersey on October 29$^{th}$, causing amplified water levels and wave heights over a large region from coastal Maryland to Massachusetts. Hurricane Sandy was labeled a category 1 hurricane at landfall bringing water level conditions reflecting behavior of a near-10-year extreme event at the nearby NOS station at Woods Hole[1] [2], and the 5$^{th}$ largest wave height conditions measured over the 14 years of wave observations at the NDBC 44020 buoy in Nantucket Sound[3].

[1] https://tidesandcurrents.noaa.gov/est/curves.shtml?stnid=8447930

[2] https://tidesandcurrents.noaa.gov/waterlevels.html?id=8447930&units=metric&bdate=20121024&edate=20121030&timezone=LST/LDT&datum=MHHW&interval=6&action=

[3] https://www.ndbc.noaa.gov/station_history.php?station=44020

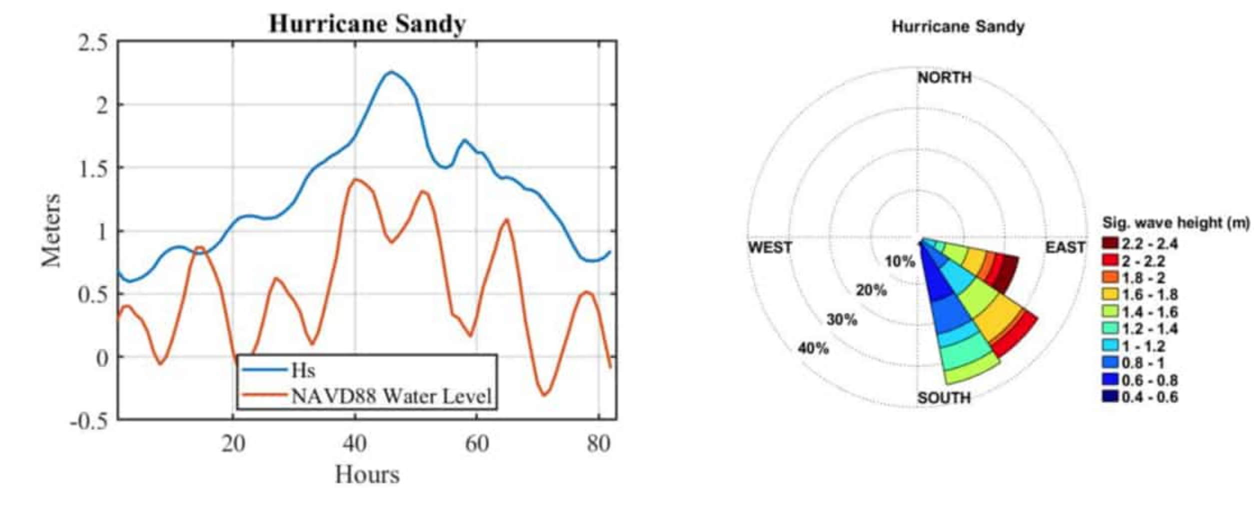


**Figure 3-14: Significant wave height and water level (left), for Hurricane Sandy [XBeach model].**

Hurricane Sandy is remembered for the devastating damages it caused all along the east coast resulting in an estimated minimum of $70 billion dollars in damages, which makes it among one of the costliest storms in U.S history (Gibbens, 2021). The area of Barnstable, MA was one of the more severely affected areas in Massachusetts featuring wind gusts of over 65 mph and maximum tidal elevation of at the NOAA tidal gauges in Woods Hole, Nantucket, and Chatham, MA all exceeding 1 m (NOAA, n.d). The water levels and wave conditions for the storm were also provided by Woods Hole Group. Water levels were provided as storm surge and astronomical tide and were shifted in time, so their superposition (the storm tide) peaked at a level closest to those observed by USGS High Water Marks from Hurricane Sandy (Figure 3-14).

While there is no public photographic evidence or recorded quantitative data revealing the extent of Hurricane Sandy's damages at the Dowses Beach area, LiDAR from 2011 and 2013 / 2014 show little to no net change in the beach system over the 3 year period (Figure 3-15), which included storms with wave heights higher than hurricane Sandy (Figure 3-16). In Figure 3-16, the shown return periods of wave heights at NDBC 44020 were estimated using a Generalized Pareto Distribution fit to the available data. NDBC 44020 typically sees higher waves than the waves that reach Dowses Beach. The lack of bed level change over the years suggests that seasonal and temporal change in wave climate at Dowses Beach work in pattern with the area's persistent dune system to restore the beach over time.

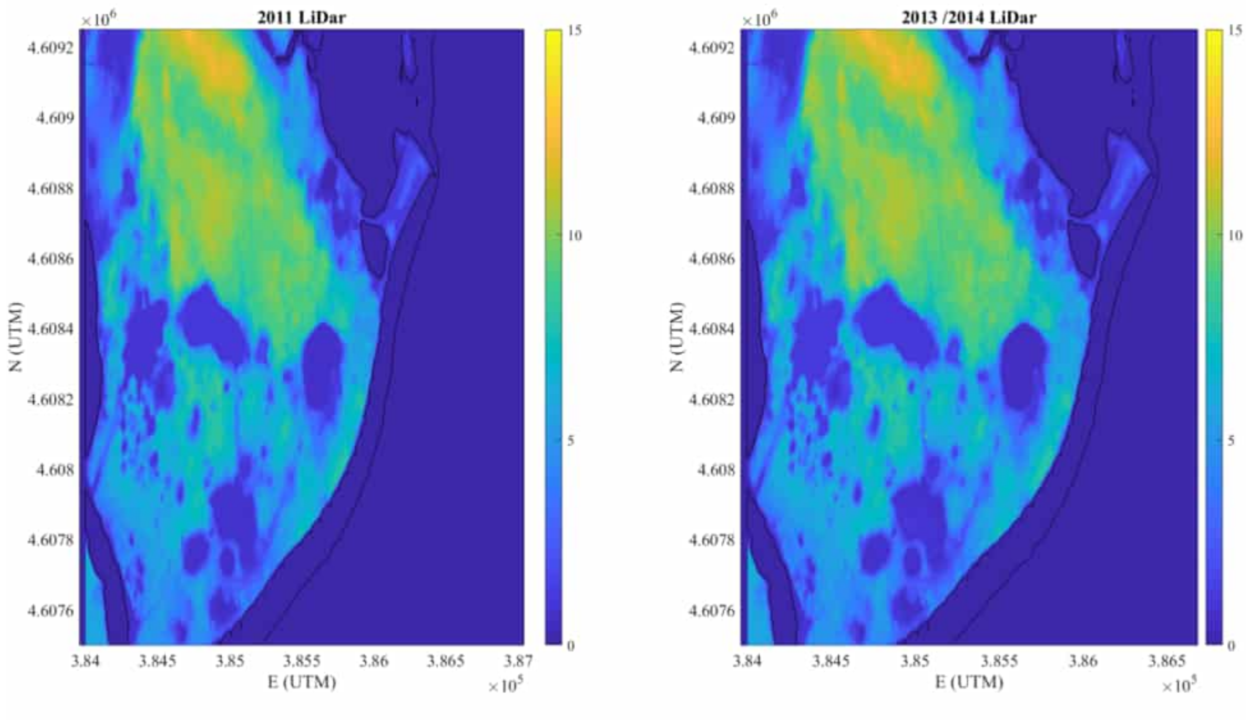


**Figure 3-15: Dowses Beach LiDAR data from 2011 (left) and 2013 / 2014 (right). Bed-Level is measured in meters [m] NAVD88.**

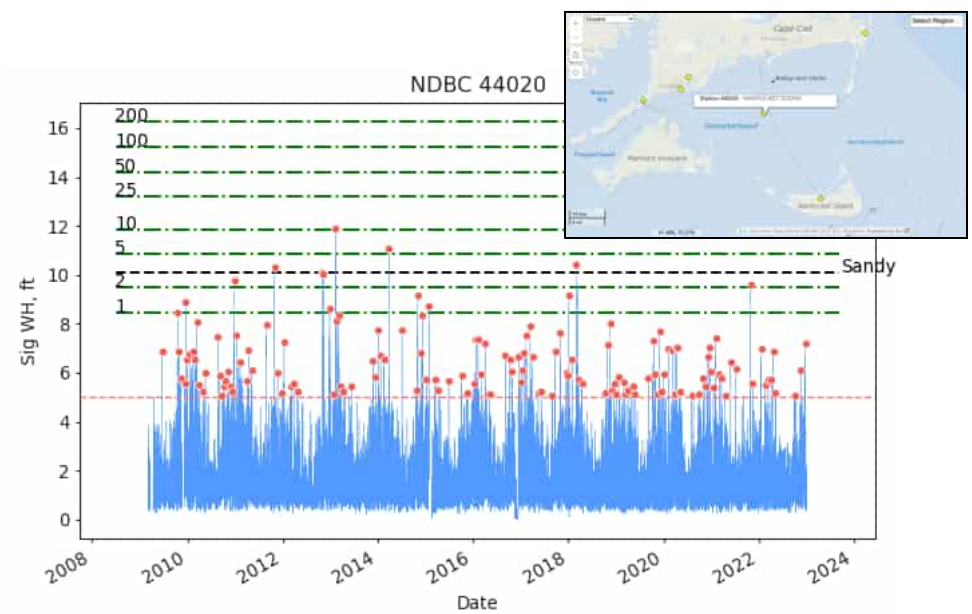


**Figure 3-16: Significant wave height (ft) recorded at NDBC buoy station 44020 (Nantucket Sound) from 2009 to 2023 (NOAA, n.d). Estimated return periods of wave heights are denoted by green dashed lines. Location of the NDBC station in the middle of Nantucket Sound shown on the insert.**

### 3.2.1 FACUA

The main driver of dune erosion is increased wave action generated by an extreme event. Erosion is highly sensitive to wave skewness and wave asymmetry; both are controlled in XBeach by the FACUA parameter. The FACUA parameter has a default value in XBeach of 0.1, but based on previous studies, is usually increased for storm events to a maximum value of 0.3. As there was no field data on topographic changes due to superstorm Sandy at the study area, the adequacy of any selected FACUA parameter's value could not be verified at the site.

Consequently, several parameter values were defined based on existing literature with similar use cases, and a sensitivity study was performed to show the uncertainty in the response due to the lack of strict validation of the FACUA parameter's selected value. The sensitivity study was performed using the wave climate of Hurricane Sandy and tested FACUA values of 0.1 (the XBeach default), 0.2, and 0.3, the currently most accepted value for storm events in the area.

Figure 3-17 to Figure 3-19 illustrate the sensitivity of the bottom profile and coastal erosion at the cable landing sites to different FACUA parameters for hurricane Sandy simulations.

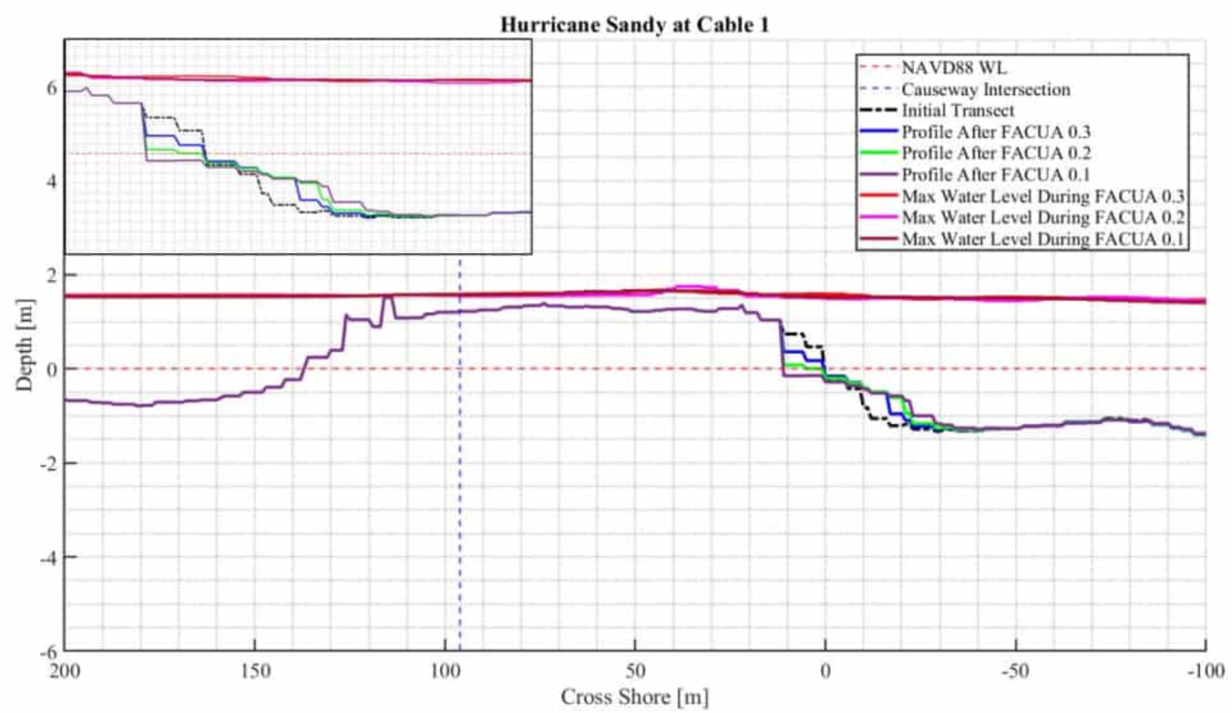


**Figure 3-17: XBeach-simulated post-storm cross-shore transect of Cable 1 with FACUAs of 0.1 (Purple), 0.2 (Green), and 0.3 (Blue). The pre-storm transect is marked with a black dashed line and sea level is marked with a red dashed line.**

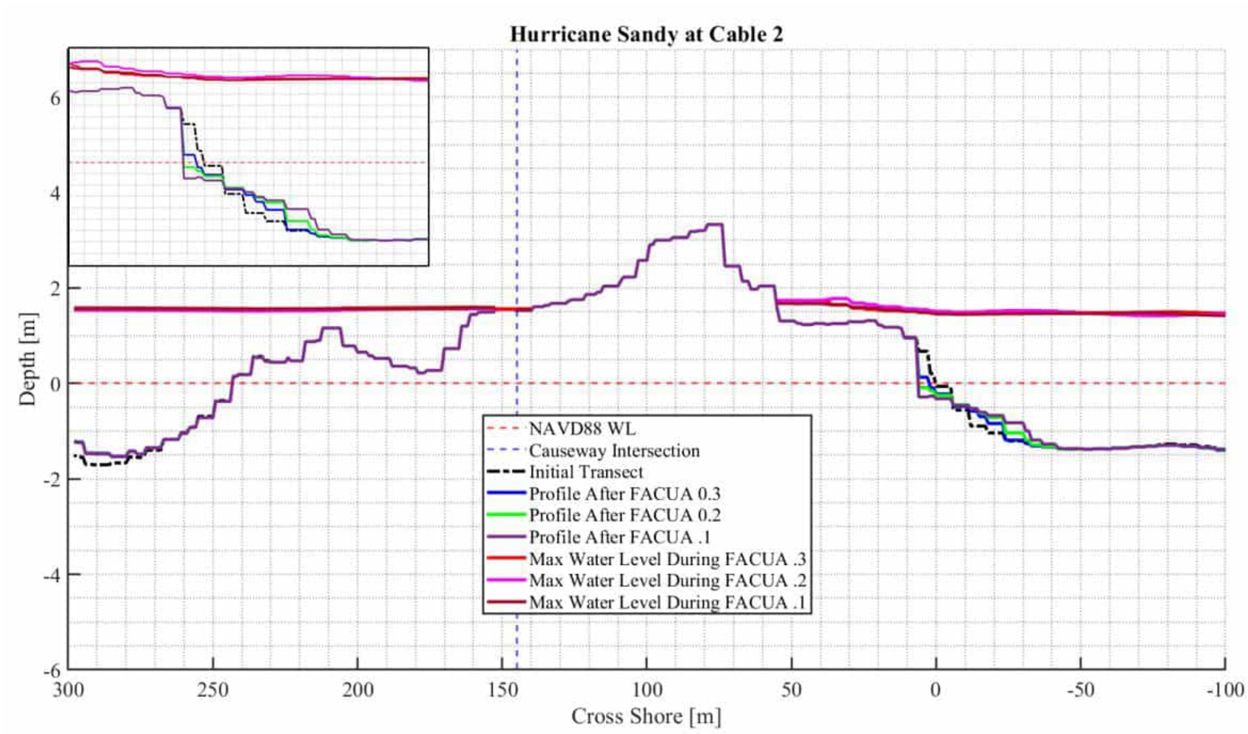


**Figure 3-18: XBeach-simulated post-storm cross-shore transect of Cable 2 with FACUAs of 0.1 (Purple), 0.2 (Green), and 0.3 (Blue). The pre-storm transect is marked with a black dashed line and sea level is marked with a red dashed line.**

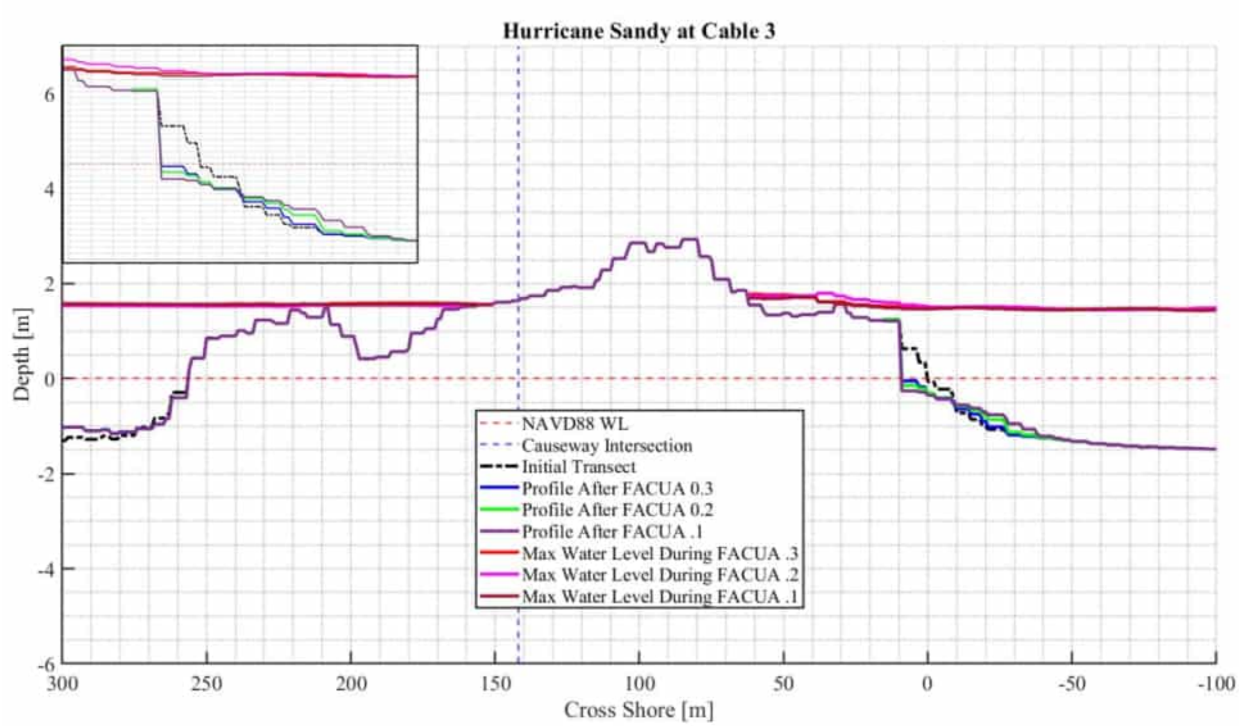


**Figure 3-19: XBeach-simulated post-storm cross-shore transect of Cable 3 with FACUAs of 0.1 (Purple), 0.2 (Green), and 0.3 (Blue). The pre-storm transect is marked with a black dashed line and sea level is marked with a red dashed line.**

The default FACUA value, 0.1 in XBeach has been correlated to overestimation of beach erosion (Schambach et al., 2018 and de Vet et al., 2015) and indeed shows the most dune erosion at the site. Examination of all post-storm transects reflected a similar behaviour to the one suggested by the literature, with the amount of topographic change decreasing with an increase in FACUA values. A 2017 study by Elsayed and Oumeraci, XBeach developers, has provided an empirical equation for FACUA based on the inner beach slope. For Dowses Beach, the resulting FACUA value based on the Elsayed and Oumeraci (2017) method is 0.3. To be consistent with the literature, a FACUA value of 0.3 was chosen for this study.

## 3.3 Modeling Scenarios

RPS modeled extreme events in 2030, 2050, and 2070. For each year, 50- year, 100- year, and 200-year extreme events were simulated. As climate change conditions create an increased likelihood of back-to-back extreme events, a combination of a 50-year and 100-year extreme events hitting the shoreline back-to-back were also modeled (Table 3-4). Historically the area has experienced back-to-back events like Carol (Aug. 1954) and Edna (Sep. 1954) which were among the worst tropical cyclones and hit this shoreline within a few weeks.

**Table 3-4. Summary of scenarios**

| Year | Scenario |
|---|---|
| 2030 | 50-year event |
| | 100-year event |
| | 200-year event |
| 2050 | 50-year event |
| | 100-year event |
| | 200-year event |
| | 50-year and 100-year events back-to-back |
| 2070 | 50-year event |
| | 100-year event |
| | 200-year event |
| | 50-year and 100-year events back-to-back |

Simulations were run using generated bathymetry (Section 3.1.1), local Manning's friction parameters, and FACUA of 0.3 empirically derived for the specific area of study and consistent with other studies in the region (Section 3.2.1).

## 3.4 Study Assumptions and Limitations

This is a planning level study using a 2D numerical model, XBeach, to simulate bed level changes and wave forces along the proposed cable route at Dowses Beach, MA. The study is used to inform a Draft Environmental Impact Report (DEIR) analysis on:

a. likely nearshore, beach, and dune erosion at the preferred landing site to support assessment of whether cables and associated infrastructure maintain adequate burial depth over the design life of the project;

b. potential impacts as a result of erosion and storm surge; and

c. potential effects of back-to-back storms, such as Hurricanes Carol and Edna in 1954

The results of the present study are based on predictions of an advanced numerical model, XBeach, which, like every numerical model, has limitations and simplifications both ingrained and as applied.

Sensitivity studies for FACUA have shown, as also shown here, that the XBeach model results are sensitive to the wave skewness and asymmetry parameter known as FACUA. No pre- and post-event profiles were made available to calibrate the numerical model with. Literature and empirical guidance were used to set the main FACUA calibration parameter to 0.3 for Dowses Beach, for all storms modeled in this study.

The most conservative, in terms of erosion potential, grain size near the study area was used based on the minimum of D50 and D15 samples.

Manning's n values came from a 30m national land cover coverage, considered fixed in time and space. That input resolution is lower than the native XBeach model resolution used here which was 5m. Further, conservatively, all surfaces (including sand, pavement, dune vegetation, etc.) were modeled as erodible and erosion control measures (such as riprap) were not included given the model's resolution.

Single return level representative storms modeled (one per return level and projection year) were based on Massachusetts standard MC-FRM (a MA-CZM model) and the “high” SLR rates assumed by it, provided to RPS by that model’s creator, the Woods Hole Group (WHG).

The representative return period storm selection from WHG was based on water level return periods. Peak wave energy for the 100-year storm was found to be slightly larger than for the 200yr storm, even though the peak water level for the 200year storm was higher.

For the back-to-back storm scenario RPS, in agreement with the client, chose to assume a 50-year storm would be immediately followed by a 100-year storm.

Nearest model cell neighbor was used for extracting information for bed level and wave force along cable transects.

Although water levels for each future storm include SLR in the CZM model forcing, initial bathy-topography of the beach is assumed unchanged. By 2050 (2070), without nourishment or natural accretion, the beach is projected to be submerged at normal high (mean) tide, consistent with simulations.

The model performed here does not consider any cable or other structure. Design of such infrastructure should give appropriate consideration of all wave-induced forces impounding a proposed structure, including sediment, current/wave/tide loads, as well as potential bed scouring due to the structures themselves.

# 4. RESULTS AND DISCUSSION

Results of XBeach simulations were used to map the change in bathymetry and topography due to sediment transport, and the resulting erosion and accretion along the suggested cable locations and causeway. These simulated erosional patterns were examined for all scenarios (Table 3-4).

The cross-sections presented in these figures (described in detail below) display the maximum water level during the extreme events along the pre- and post-storm topo-bathymetry profiles, with respect to NAVD88. Figures additionally mark key spatial and conceptual reference features, including the denotation of cable / causeway intersection points as well as projected Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW) tidal datums, an indication of the daily great diurnal range expected in the future consistent with “high” SLR rates. To orient the reader with regard to spatial locations along each transect, a map with “milepoints” consistent with the transect figures is provided in the Appendix.

The resulting wave storm forces were tracked across the domain and along each cable causeway location. The maximum wave force magnitude and corresponding normalized wave direction is displayed and tabulated for each storm scenario.

## 4.1 Sediment Transport for 2030 Scenarios

As summarized in Table 3-4, three scenarios were modeled for the projected 2030 sea level rise (SLR) conditions, a 50-year storm, a 100-year storm, and a 200-year storm (Figure 3-5, Figure 3-6, Figure 3-7 ).

Erosional patterns and wave forces were examined across the entire domain as well as at the cable landings and causeway locations. SLR projections for 2030 were the lowest of all three decades modeled. This resulted in the lowest simulated amount of net erosion and bed level change (Figure 4-1 through Figure 4-4).

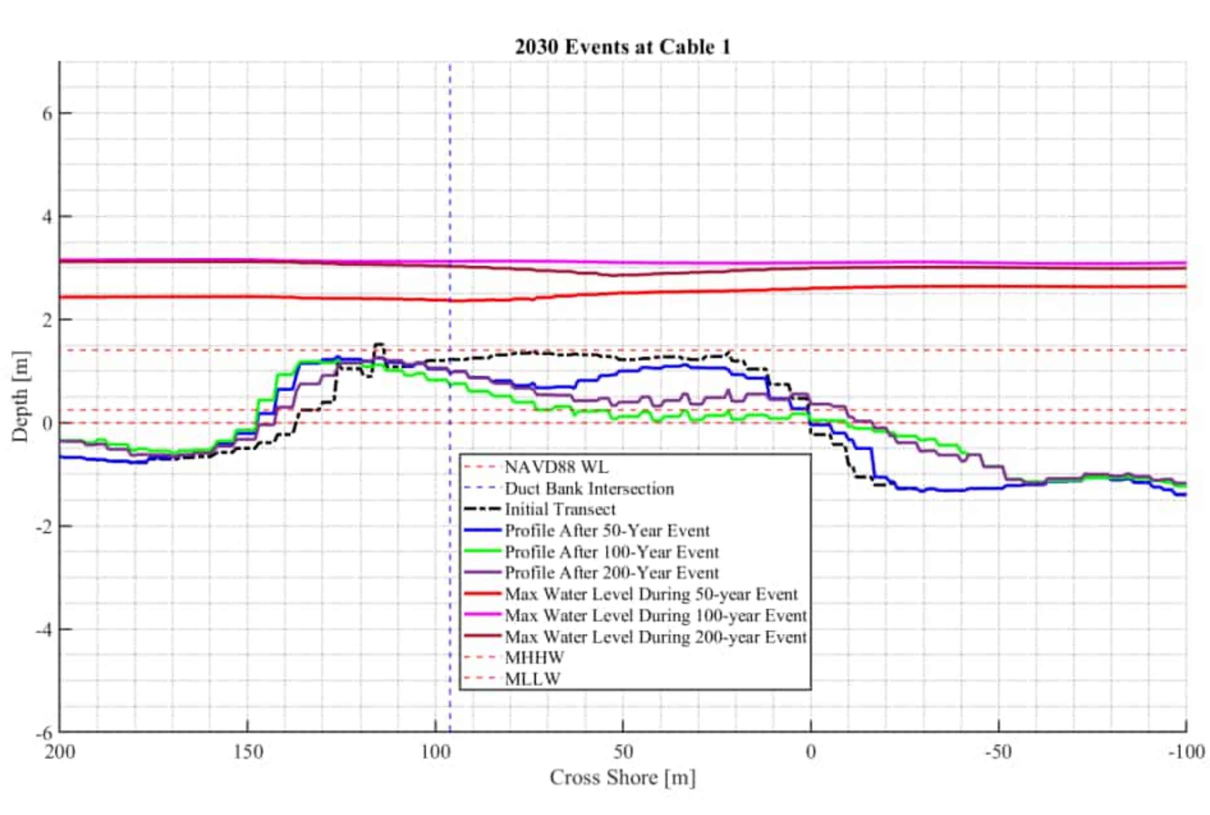


**Figure 4-1: XBeach-simulated post-storm cross-shore transect at Cable 1 landing location for 50-year (blue), 100-year (green), and 200-year (purple) future [2030] events, with corresponding maximum water level (50-year: red; 100-year: pink; 200-year: maroon); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

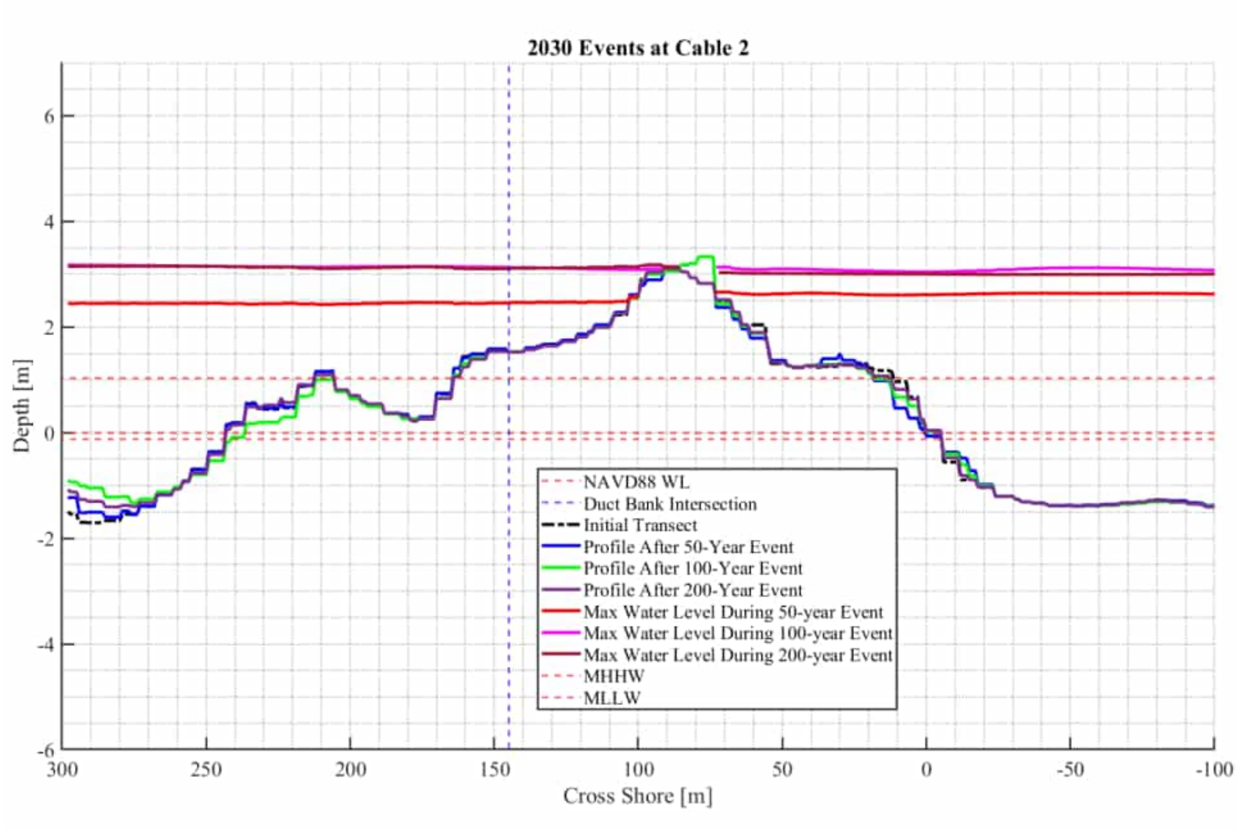


**Figure 4-2: XBeach-simulated post-storm cross-shore transect at Cable 2 landing location for 50-year (blue), 100-year (green), and 200-year (purple) future [2030] events, with corresponding maximum water level (50-year: red; 100-year: pink; 200-year: maroon); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

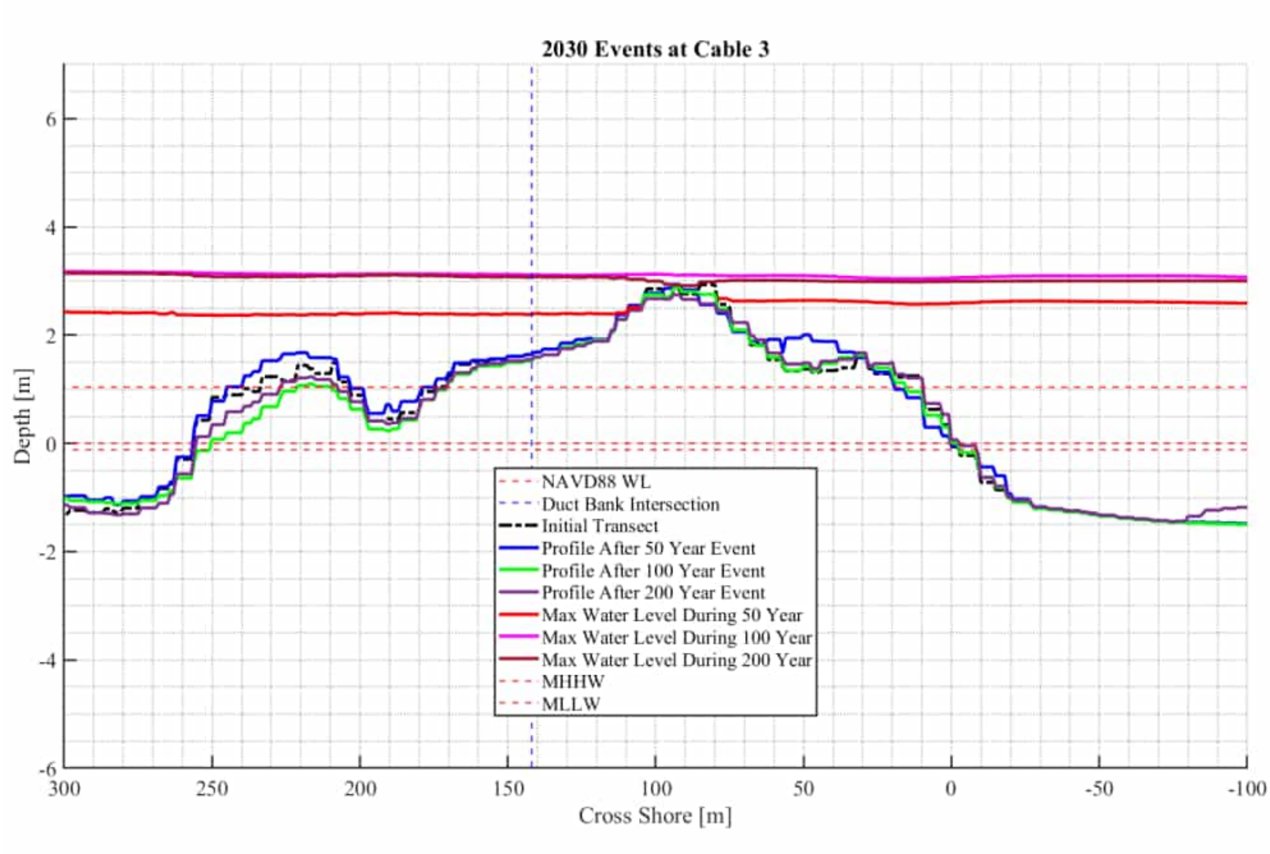


**Figure 4-3: XBeach-simulated post-storm cross-shore transect at Cable 3 landing location for 50-year (blue), 100-year (green), and 200-year (purple) future [2030] events, with corresponding maximum water level (50-year: red; 100-year: pink; 200-year: maroon); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

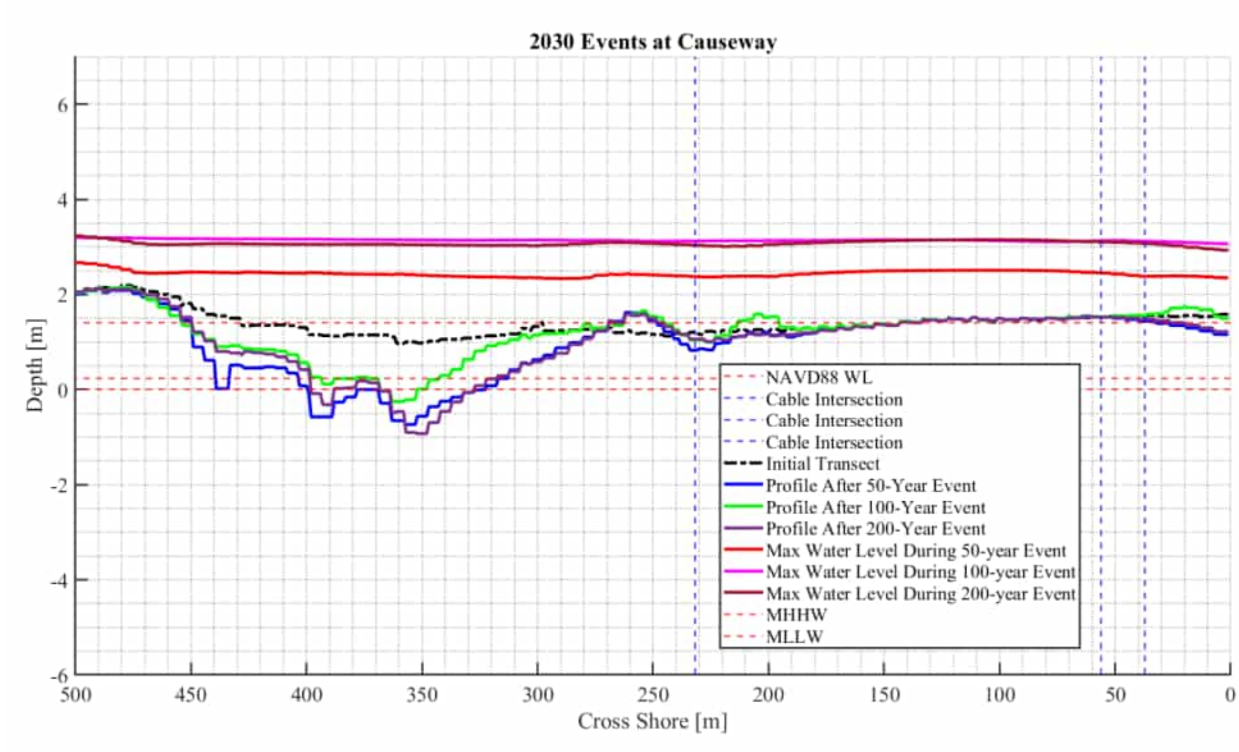


**Figure 4-4: XBeach-simulated post-storm cross-shore transect along Causeway location for 50-year (blue), 100-year (green), and 200-year (purple) future [2030] events, with corresponding maximum water level (50-year: red; 100-year: pink; 200-year: maroon); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

Across all three landing cable locations, the model simulations for the three extreme events predicted areas of erosion and accretion. Note that compared to the other cable landing transects (Cable 2 and Cable 3), the Dowses Beach transect along Cable 1 is not really protected by a dune, or the dune crest is at least at much lower elevation. Instead, the beach is a wide berm. Along Cable 1, inundation and lowering of the pre-storm or initial "dune crest" during all storm events was evident in the model (Table 3-1). The initial dune crest was eroded and sediment was transported from the initial dune crest on both opposite edges of the spit where the beach is located - both seaward and toward East Bay (Figure 4-1). Transects of higher dune elevation (Cables 2 & 3, Figure 4-2 and Figure 4-3, resp.) showed little to no change in dune crest elevation and maintained a beach profile nearly identical to that before the event (Table 4-1).

The sections of the causeway that were sheltered by the Dowses Beach dune kept the same profile pre and post storm for the year 2030 model simulations (Figure 4-4). Sections of the causeway that were directly exposed to increasing water levels (such as at Cable 1) displayed significant decrease in elevation (Figure 4-1 & Figure 4-4). The Causeway section located in-between East Bay and Phinneys Bay in particular (around 300 to 500m in Figure 4-4) were predicted to be susceptible to flooding in the model due to their low elevation and exposure to Nantucket Sound through overwash of the narrow stretch of land connecting Dowses Beach to the mainland south of Phinneys Bay. Exposure to lower-fetch waves propagating within East Bay may also play a role.

**Table 4-1: Dune crest height [m] at cable locations before (initial, pre-storm) and after 50-year, 100-year, and 200-year storm events simulated by XBeach for 2030 conditions.**

| Site Location | Pre-Storm | Post 50 Year | Post 100 Year | Post 200 Year |
|---|---|---|---|---|
| Cable 1 (Cross Shore= 22 m) | 1.35 | 1.02 | 0.23 | 0.64 |
| Cable 2 (Cross Shore= 74 m) | 3.33 | 3.33 | 3.33 | 2.82 |
| Cable 3 (Cross Shore= 80 m) | 2.90 | 2.75 | 2.56 | 2.58 |

Post-storm bed level change maps illustrate the sediment transport that was simulated to occur during the modelled events (Figure 4-5). All cases show instances of erosion and accretion with the 50-Year storm showing the least amount of erosion overall. Accretion is mostly also noted along the southwest shoreline of Dowses Beach, as dune recession causes sediment to be overwashed into Phinney's Bay. For the rarest events, depictions of sediment motion show initial erosion of the narrow strip of land southwest of Dowses Beach and deposition of the eroded material in Phinneys Bay. This is followed, at the peak of the storm, by erosion of the dune at Dowses Beach and especially around cable 1 and the causeway strip between Phinneys and East Bay with deposition of the eroded material at the East Bay and Dowses Beach nearshore region, accompanied with redistribution of the deposited material within Phinneys Bay.

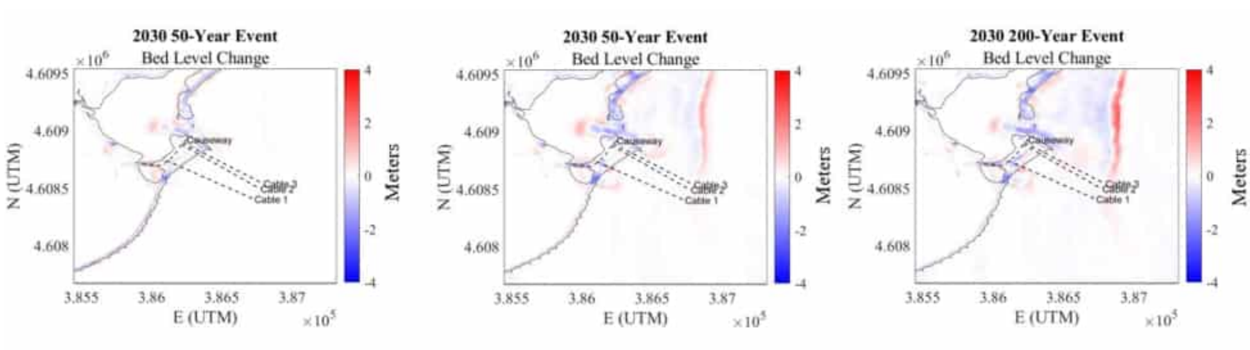


**Figure 4-5: Simulated bed level changes (m), accretion (red) and erosion (blue) at the study area for 50-year (left), 100-year (middle), and 200-year (right) storms, projected for the year 2030.**

Changes in water levels across the domain were recorded and the maximum water level across the domain was mapped (Figure 4-6). Water level mapping revealed that the more severe 2030 SLR scenarios (100 & 200 Year) were predicted by the model to result in overwash and breaching along dune crest especially along the more exposed cable 1 and southwest region, which is reflected in the mapping of bed level change (Figure 4-5). The cable 1 transect across Dowses Beach and the causeway, located in between East Bay and Phinneys Bay, are shown to be flooded during all 2030 SLR scenarios.

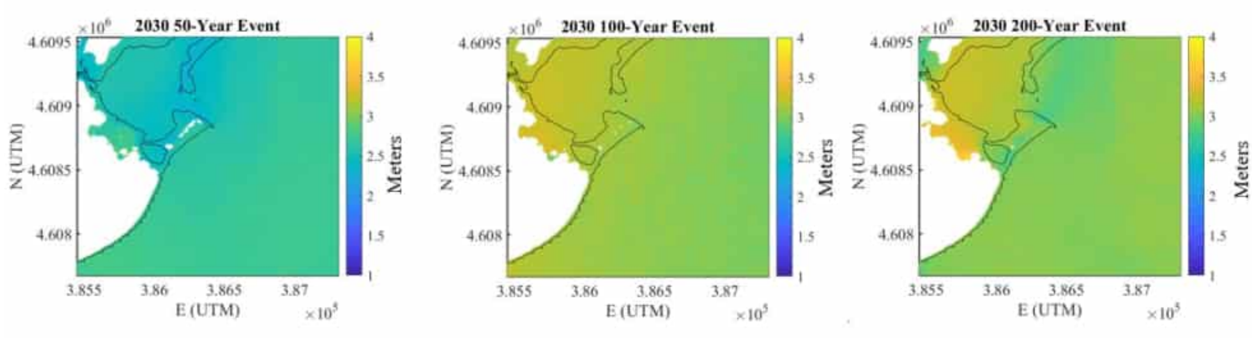


**Figure 4-6: Maximum simulated water level (m) over each grid cell of the modelling domain throughout the duration of 50-year (left), 100-year (middle), and 200-year (right) storms, projected for the year 2030.**

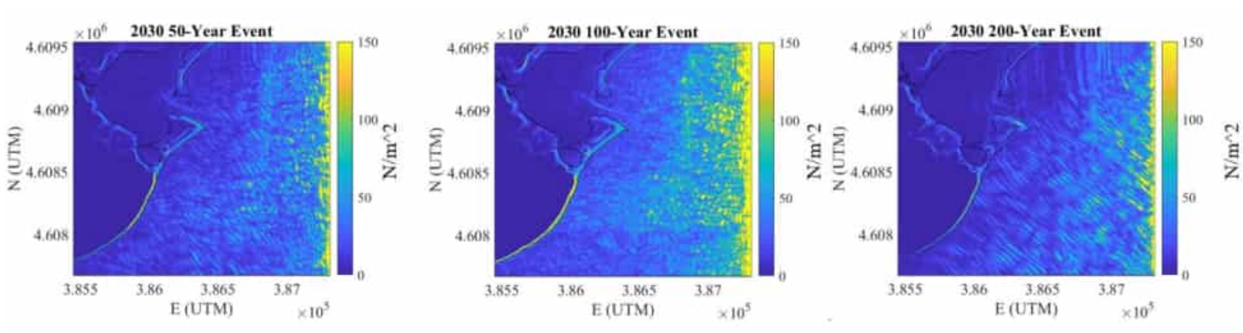


**Figure 4-7: Maximum simulated wave force magnitude (N/m$^2$) over each grid cell throughout the duration of 50-year (left), 100-year (middle), and 200-year (right) storms, projected for the year 2030.**

The mapped event-wide-maximum simulated wave force (Figure 4-7) shows the effects of bathymetry on wave character and in turn erosional patterns. The 2030 conditions display the greatest amount of wave radiation energy at the seaward boundary. As the waves propagate through the changing shoaling oceanic bathymetry wave force significantly decreases in amplitude. Transects of wave forces along the cables show the decline in wave force with significant spike as the waves hit the shoreline and induce breaking (Figure 4-8, through Figure 4-11).

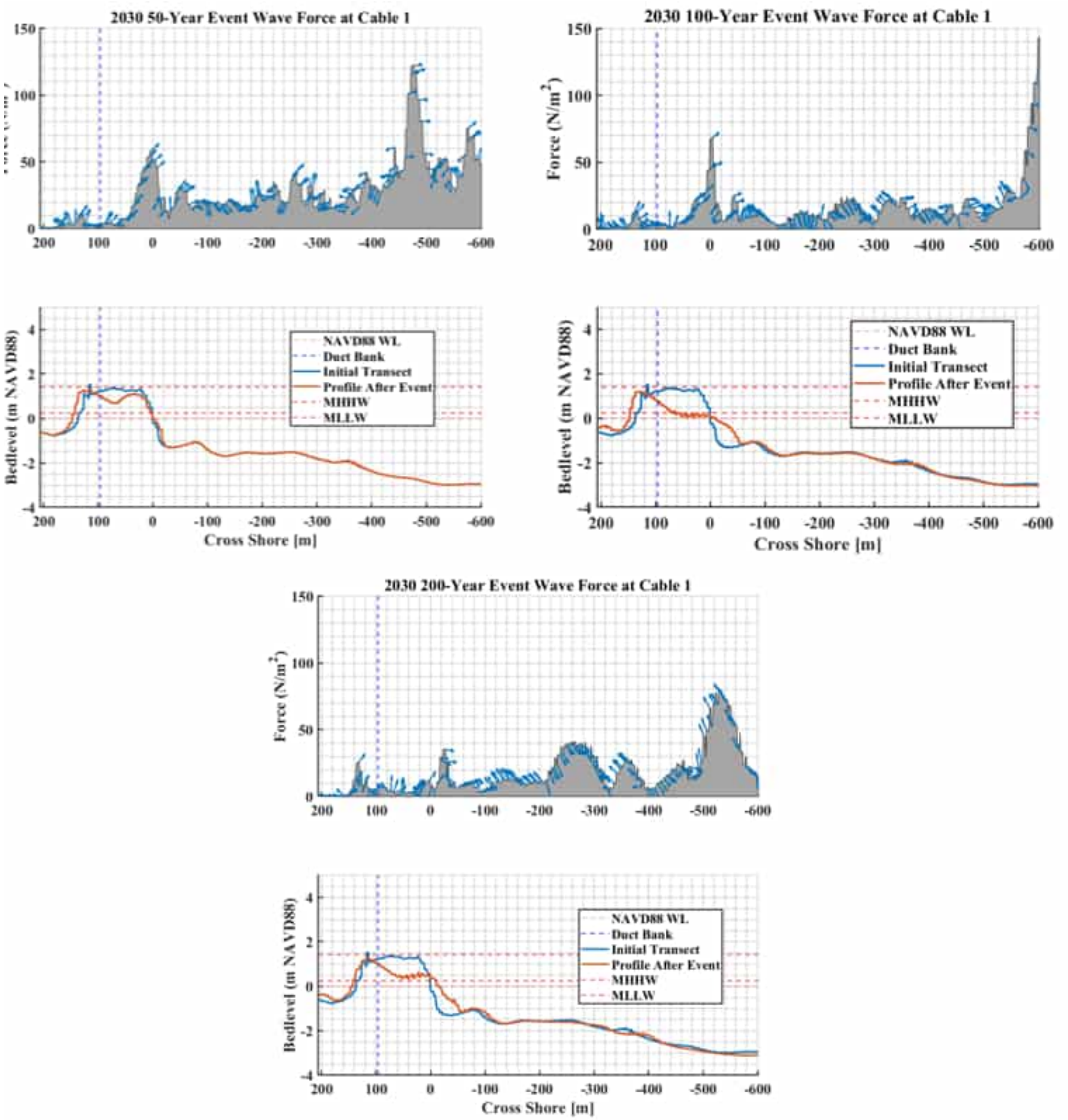


**Figure 4-8: Simulated initial and post-storm cross-shore transect at Cable 1 (bottom) with corresponding maximum wave force magnitude and direction (normalized arrows) along transect (top) for projected 2030 conditions during 50- year (top-left), 100-year (top-right), and 200-year (bottom) storms.**

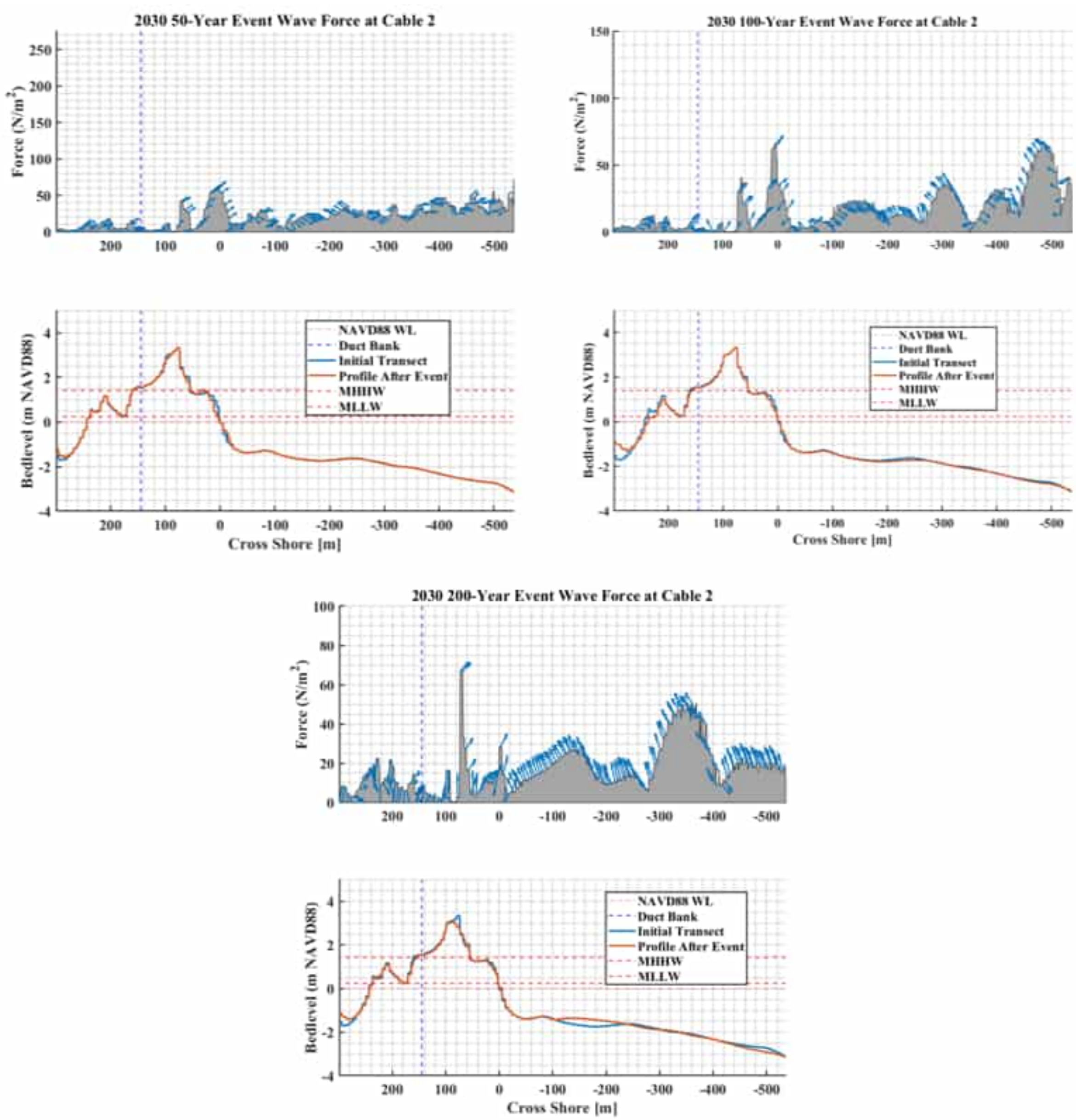


**Figure 4-9: Simulated initial and post-storm cross-shore transect at Cable 2 (bottom) with corresponding maximum wave force magnitude and direction (normalized arrows) along transect (top) for projected 2030 conditions during 50- year (top-left), 100-year (top-right), and 200-year (bottom) storms.**

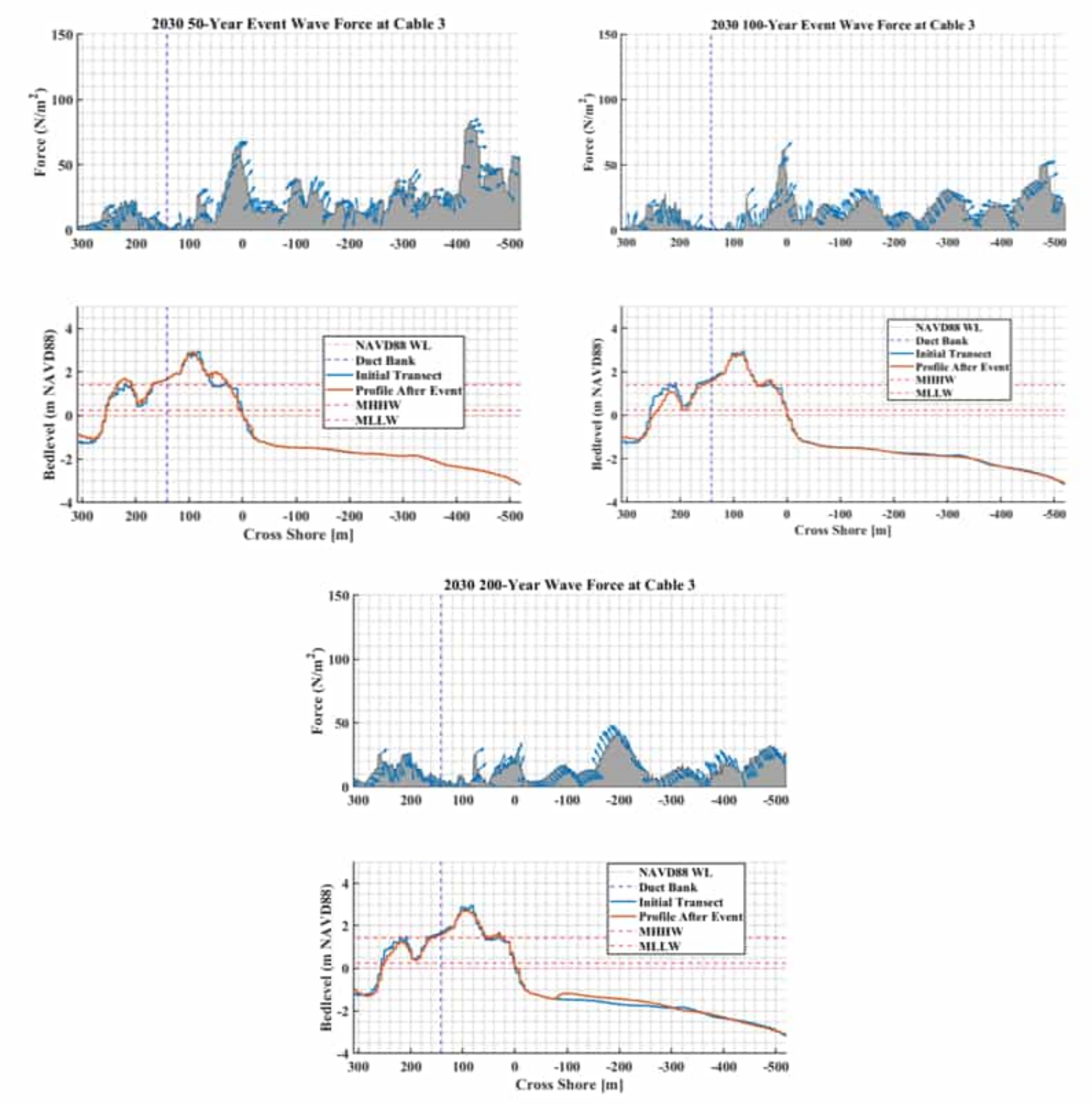


**Figure 4-10: Simulated initial and post-storm cross-shore transect at Cable 3 (bottom) with corresponding maximum wave force magnitude and direction (normalized arrows) along transect (top) for projected 2030 conditions during 50- year (top-left), 100-year (top-right), and 200-year (bottom) storms.**

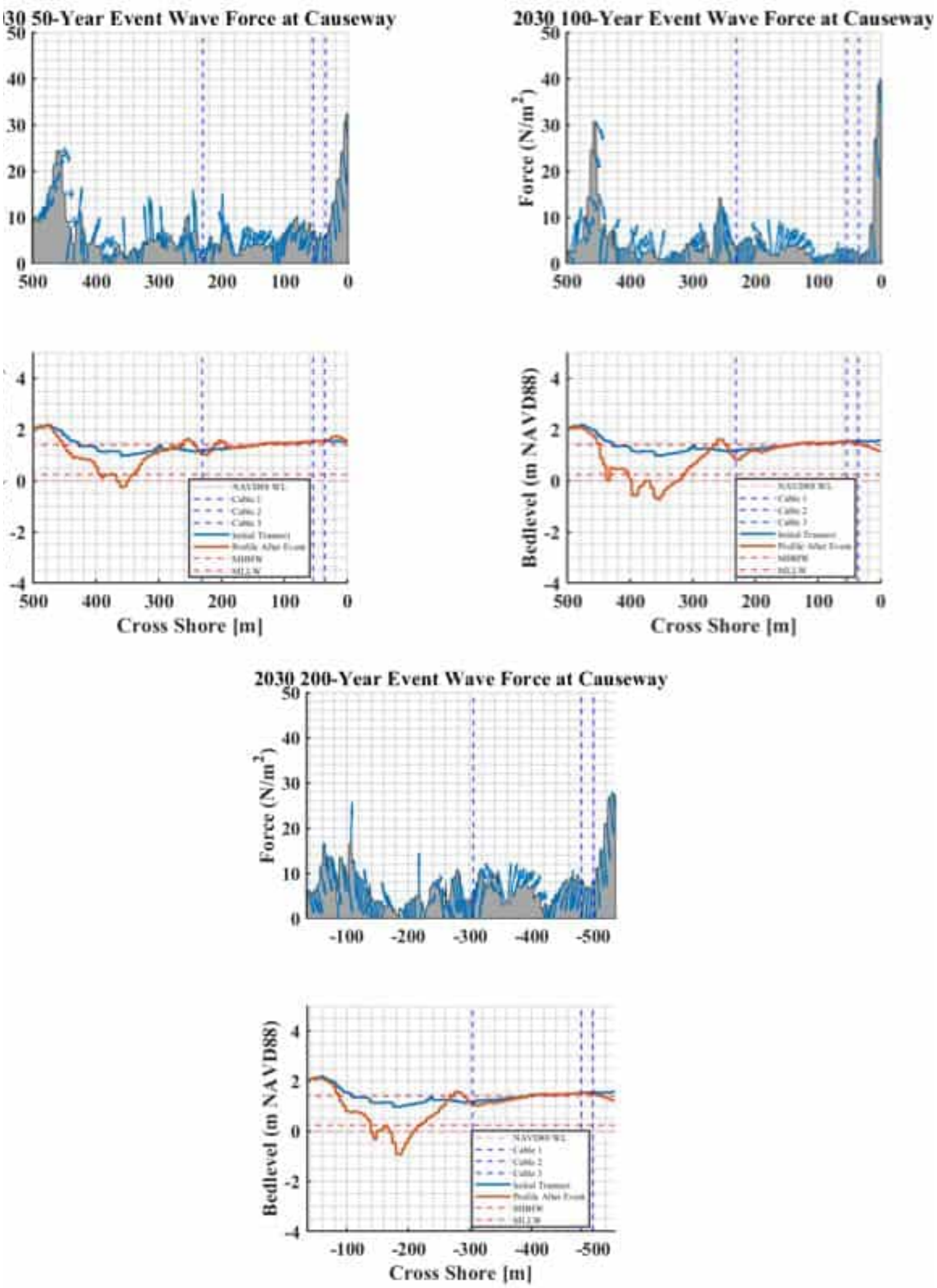


**Figure 4-11: Simulated initial and post-storm cross-shore transect at Causeway (bottom) with corresponding maximum wave force magnitude and direction (normalized arrows) along transect (top) for projected 2030 conditions during 50- year (top-left), 100-year (top-right), and 200-year (bottom) storms.**

## 4.2 Sediment Transport for 2050 Scenarios

As summarized in Table 3-4, three similar scenarios to the ones described in the previous section were modeled for the projected 2050 conditions, a 50-year storm, a 100-year storm, a 200-year storm. For 2050 conditions, and additional back-to-back 50-100-year storm was simulated.

Erosional patterns and wave forces were simulated across the domain as well as at the cable landings and causeway locations. As for the 2030 SLR scenarios, bed level change was mapped across all transects (Figure 4-12 to Figure 4-15). Note that, by 2050, and since no change in initial beach profile compared to today has been assumed in this study, the berm of Dowses Beach is predicted to be underwater for a few minutes every day as its elevation will be just lower of the 2050 MHHW line. Dynamic simulations of simulated sediment accretion and deposition do indeed show a bit of intermittent erosion of the Dowses Beach berm and the low-lying strip of land southwest of Dowses Beach predicted around the first high tide, before the storm hits near the next high tide. The model predicts that the dune at Dowses Beach will be overtopped by all storms evaluated here.

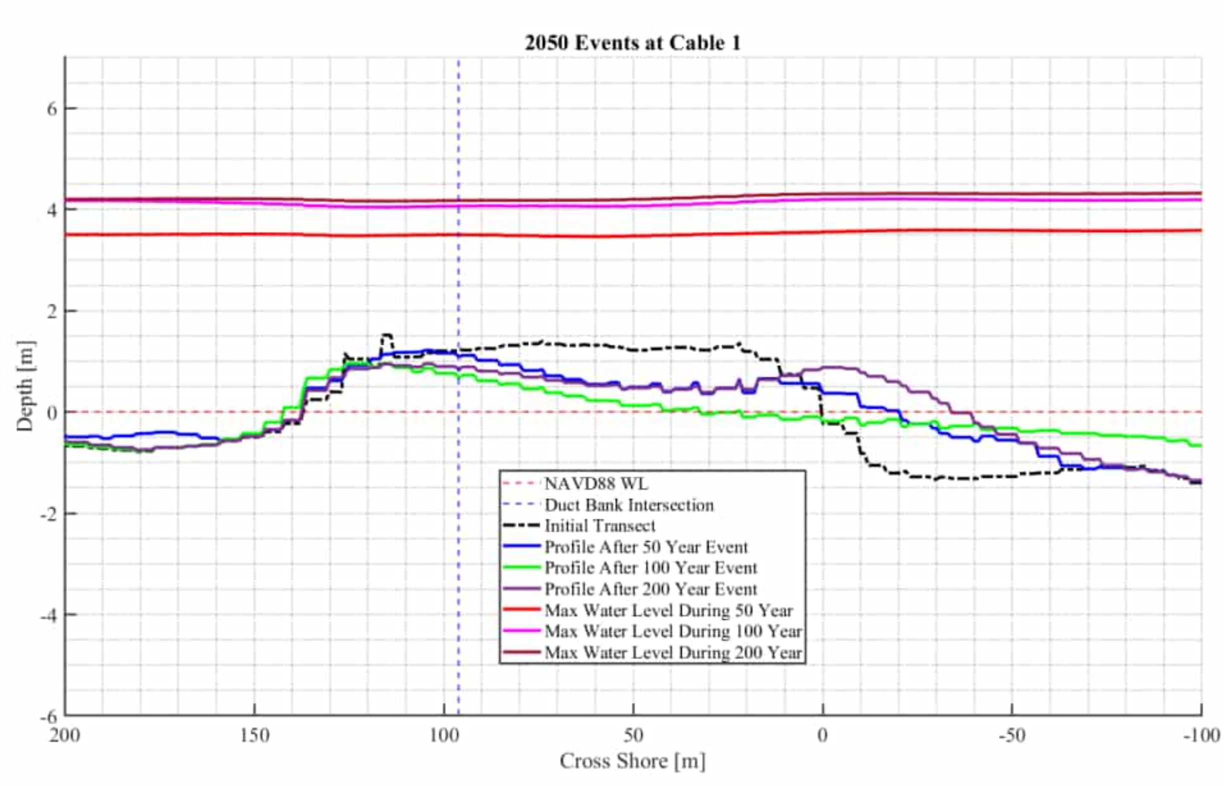


**Figure 4-12: XBeach-simulated post-storm cross-shore transect at Cable 1 landing location for 50-year (blue), 100-year (green), and 200-year (purple) future [2050] events, with corresponding maximum water level (50-year: red; 100-year: pink; 200-year: maroon); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

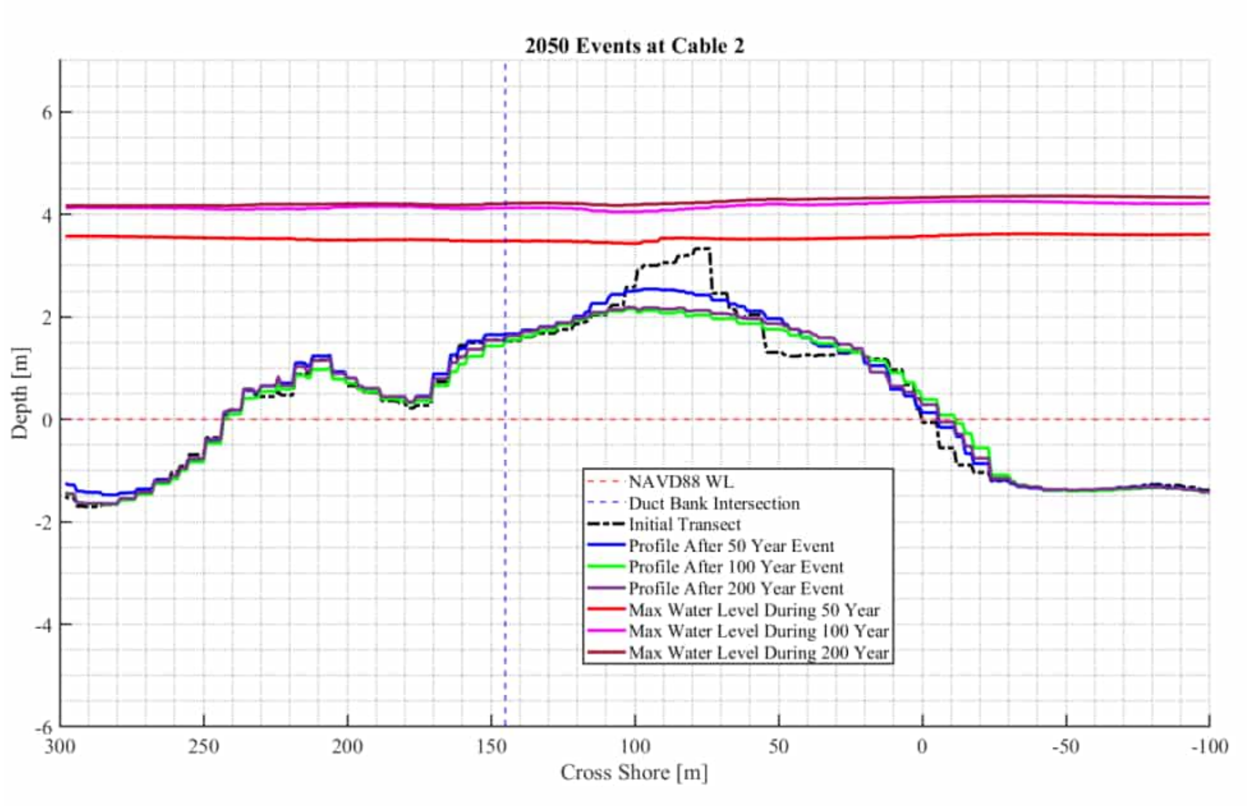


**Figure 4-13: XBeach-simulated post-storm cross-shore transect at Cable 2 landing location for 50-year (blue), 100-year (green), and 200-year (purple) future [2050] events, with corresponding maximum water level (50-year: red; 100-year: pink; 200-year: maroon); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

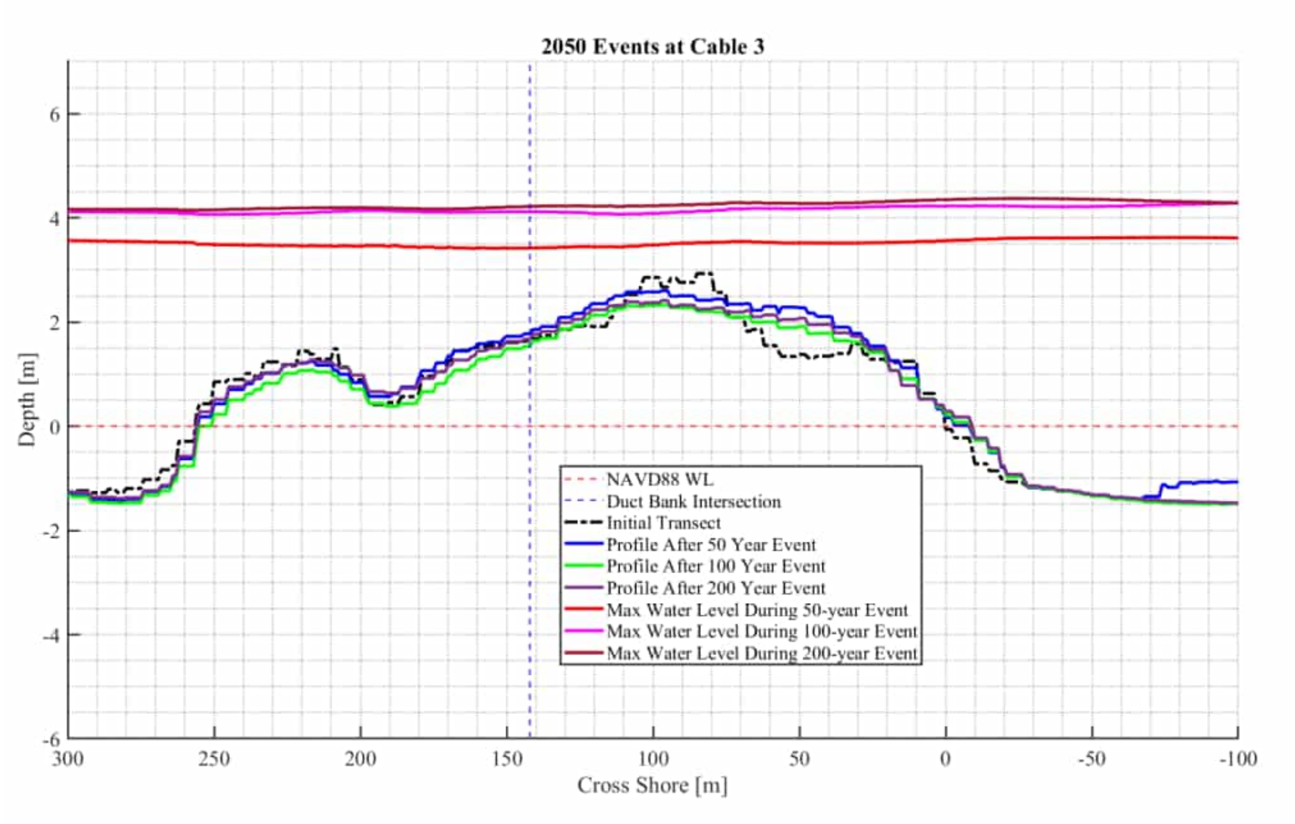


**Figure 4-14: XBeach-simulated post-storm cross-shore transect at Cable 3 landing location for 50-year (blue), 100-year (green), and 200-year (purple) future [2050] events, with corresponding maximum water level (50-year: red; 100-year: pink; 200-year: maroon); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

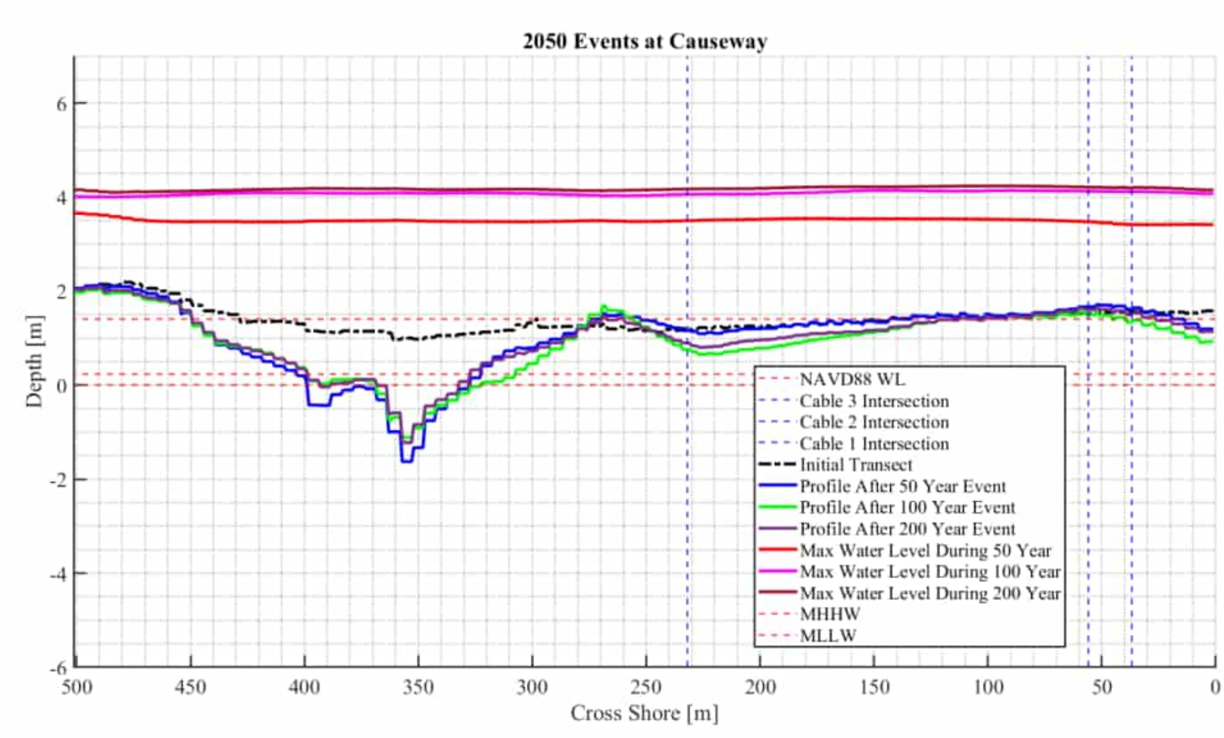


**Figure 4-15: XBeach-simulated post-storm cross-shore transect at Causeway landing location for 50-year (blue), 100-year (green), and 200-year (purple) future [2050] events, with corresponding maximum water level (50-year: red; 100-year: pink; 200-year: maroon); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

Across all three landing cable transects, the model simulated notable erosion and accretion caused by the three extreme events. All transects experience inundation of dune crest at the peak of these storm events. This caused the initial dune crest to be eroded in the model and sediment to be transported from the initial dune crest seaward. While all extreme events are similar in magnitude and consequences, the 100-year event model simulation displays slightly higher boundary condition wave heights (Figure 3-9), inducing slightly more sediment transport landward than the 50-year and 200-year simulated events at cable locations.

The sections of the causeway within Dowses Beach proper that were sheltered by the highest dune crest elevations (near Cable 2) showed to have little to no changes in bed-level, whereas the lower sections of the causeway that were directly exposed to increasing water levels (such as near Cable 1, and to a lesser extent Cable 3) displayed decrease in elevation in the model. The Causeway section located in between East Bay and Phinneys Bay was again simulated to be the most vulnerable as it is susceptible to flooding in the model due to its low elevation and lack of natural dune protection.

A back-to-back event was also modelled for year 2050 conditions, by concatenating the two event, 50- and 100 year, time series assuming they would impact the shoreline with no time between them for the dune system to recover (Figure 4-16). This process doubled the period of exposure and increased the wave action and surge impact on the shoreline. The resulting change in the dune topography due to this back-to-back event is presented in Figure 4-17 through Figure 4-19.

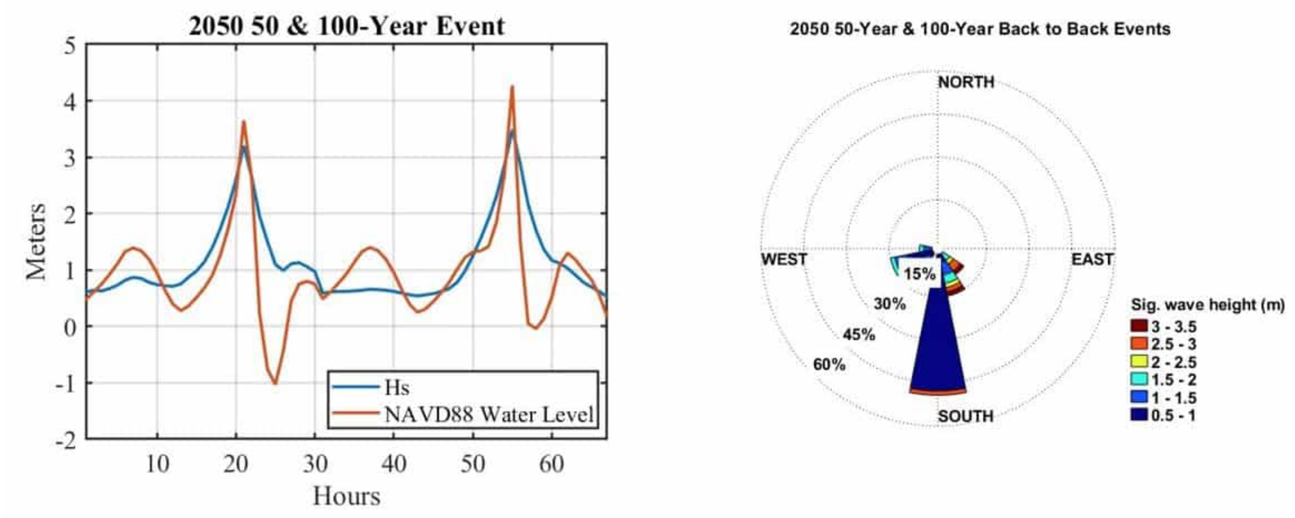


**Figure 4-16: Combined 50-year and 100-year sea-state conditions for a back-to-back event in 2050.**

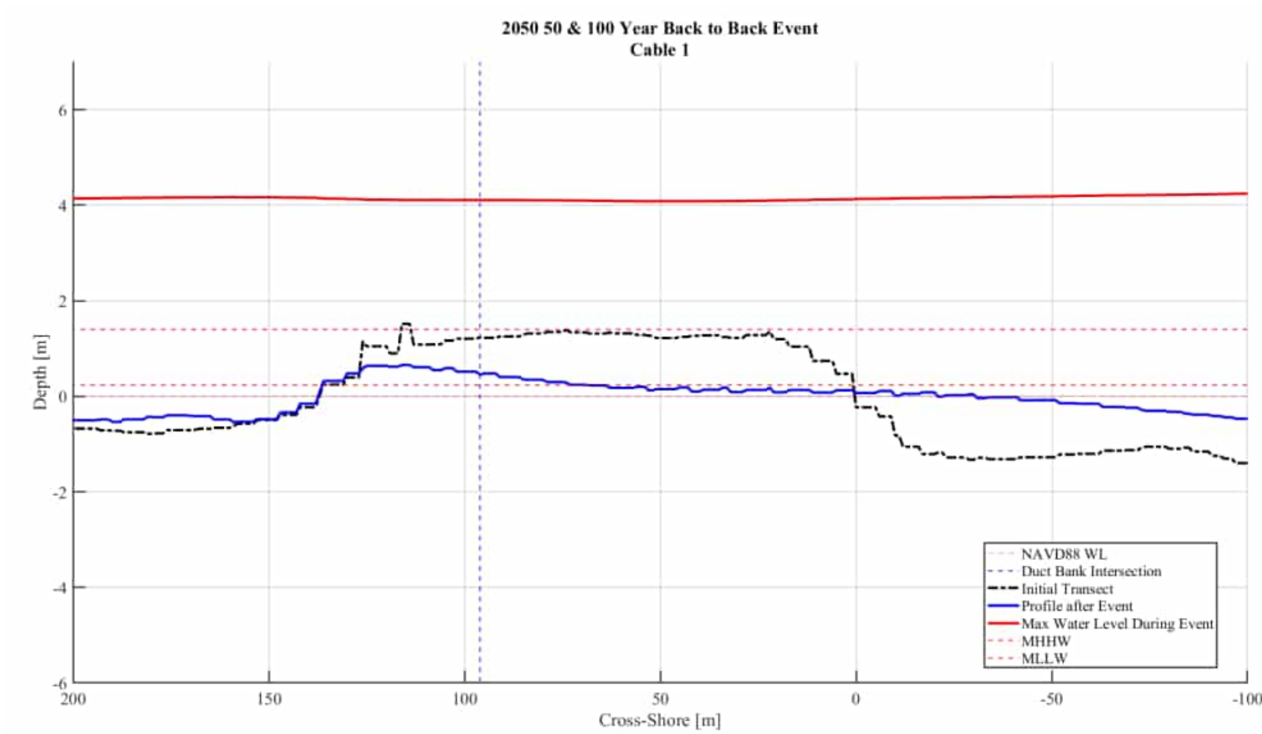


**Figure 4-17: XBeach-simulated post-storm cross-shore transect at Cable 1 landing location for a 50 & 100 – year back to back storm [2050] event (blue), with the associated maximum water level (red);**

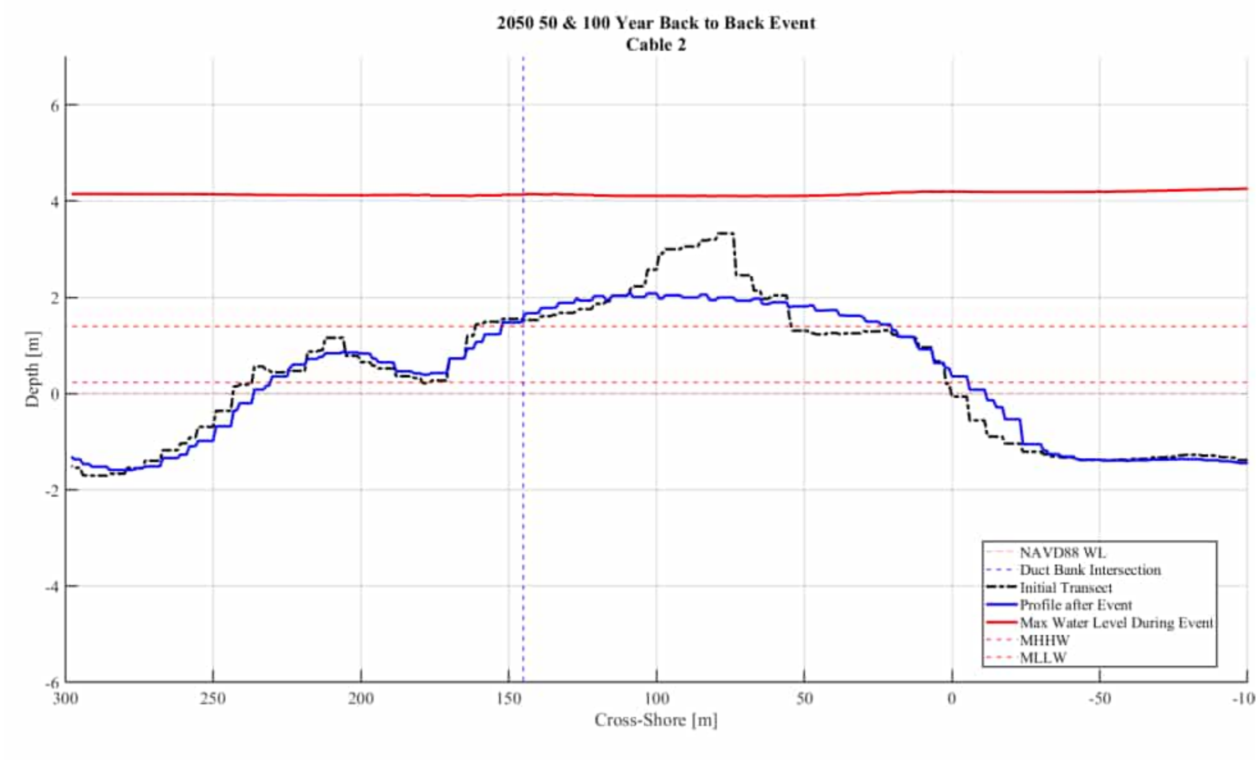


**Figure 4-18: XBeach-simulated post-storm cross-shore transect at Cable 2 landing location for a 50 & 100 – year back to back storm [2050] event (blue), with the associated maximum water level (red); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

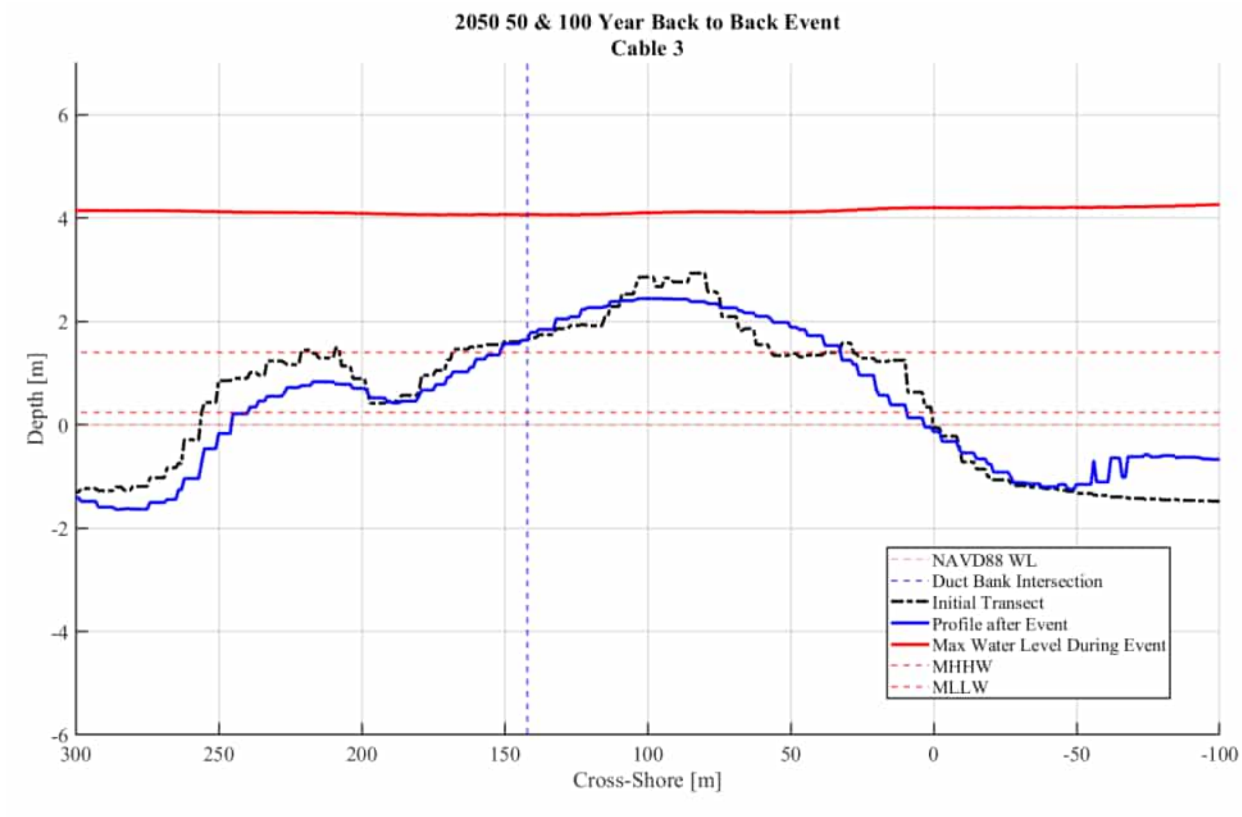


**Figure 4-19: XBeach-simulated post-storm cross-shore transect at Cable 3 landing location for a 50 & 100 – year back to back storm [2050] event (blue), with the associated maximum water level (red); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

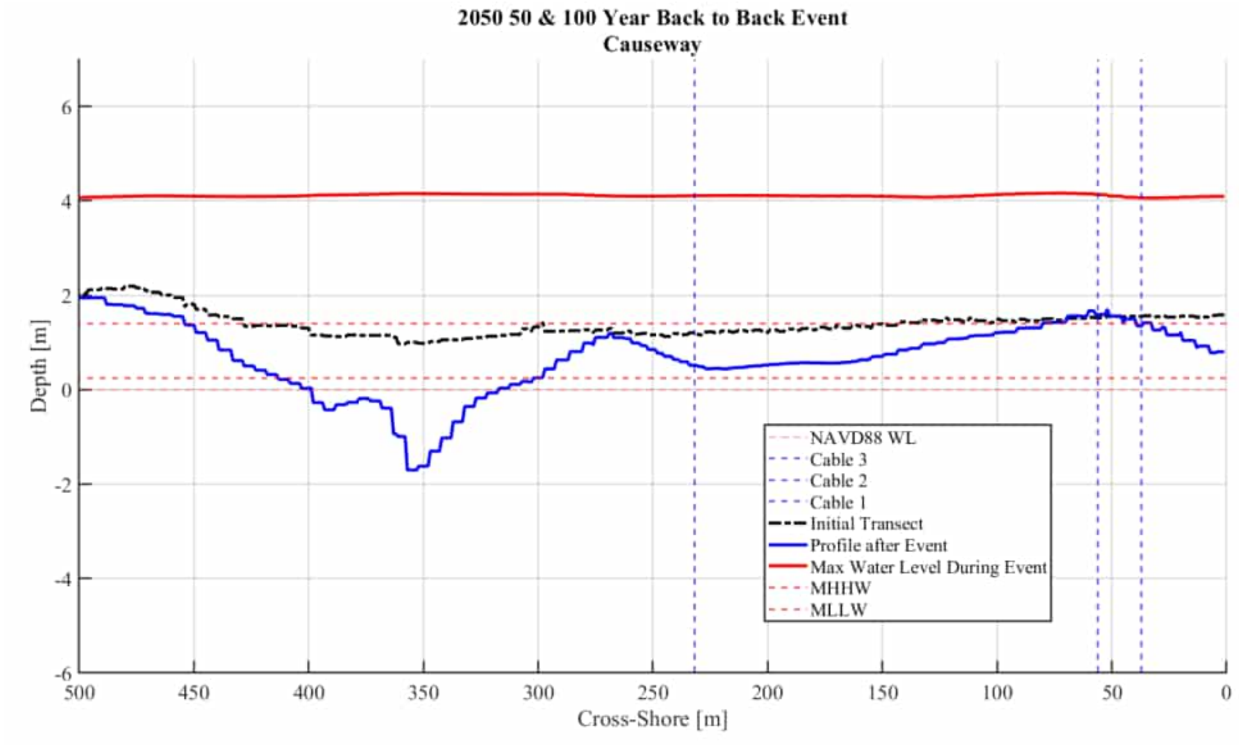


**Figure 4-20: XBeach-simulated post-storm cross-shore transect at Causeway landing location for a 50 & 100 – year back to back storm [2050] event (blue), with the associated maximum water level (red); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

Examination of individual transects for the back-to-back storm conditions showed that there was a significant increase of model-predicted sediment transport during this prolonged event. Table 4-2 displays the initial dune maximum elevation at each transect site as well as the post-storm height at that dune crest initial location for each storm event. After the back-to-back event, the initial dune crest height was simulated to drop by at most 1.34 m at the cable 2 site. The 50-year extreme event caused the least amount of sediment transport of the three events but still caused a maximum of 0.86 m of dune erosion at the cable 1 location. The cable 1 site location shows the lowest projected post storm dune crest amongst the three cable locations. For the back-to-back simulation, Dowses Beach at cable 1 settled barely above the current NAVD88 sea level datum and around projected 2050 MLLW, and thus would be mostly inundated in subsequent tidal cycles. Results were similar for the causeway pass between Phinney's and East Bays. As displayed pre and post storm transects the back-to-back storm event scarps out much of the berm and nearshore area causing sediment to be deposited as waves propagate across the dune and foreshore area. This leads to dune crest erosion being slightly higher in lower grade storms than in the back-to-back case.

**Table 4-2: Dune crest height [m] at cable locations before (initial, pre-storm) and after 50-year, 100-year, 200-year and back-to-back storm events in 2050.**

| Site Location | Pre-Storm | Post 50 Year | Post 100 Year | Post 200 Year | Post back-to-back |
|---|---|---|---|---|---|
| Cable 1 (Cross shore = 22m) | 1.35 | 0.64 | 0.03 | 0.60 | 0.18 |
| Cable 2 (Cross shore = 74m) | 3.33 | 2.42 | 2.04 | 2.12 | 1.99 |
| Cable 3 (Cross shore = 80m) | 2.90 | 2.42 | 2.20 | 2.24 | 2.38 |

Post-storm bed level maps illustrate the sediment transport that was predicted to occur during the modelled events (Figure 4-21). Total erosion of the three individual return period storms is modelled to be more severe than the erosion predicted in the 2030 cases. All cases show instances of 2 m of projected cross shore erosion with the back-to-back storm scenario having the most erosion. Of the three single event scenarios the 100-year extreme event simulated slightly more erosion along the Dowses Beach area. Accretion is also simulated at the shoreline, as dune recession causes sediment to be deposited seawards.

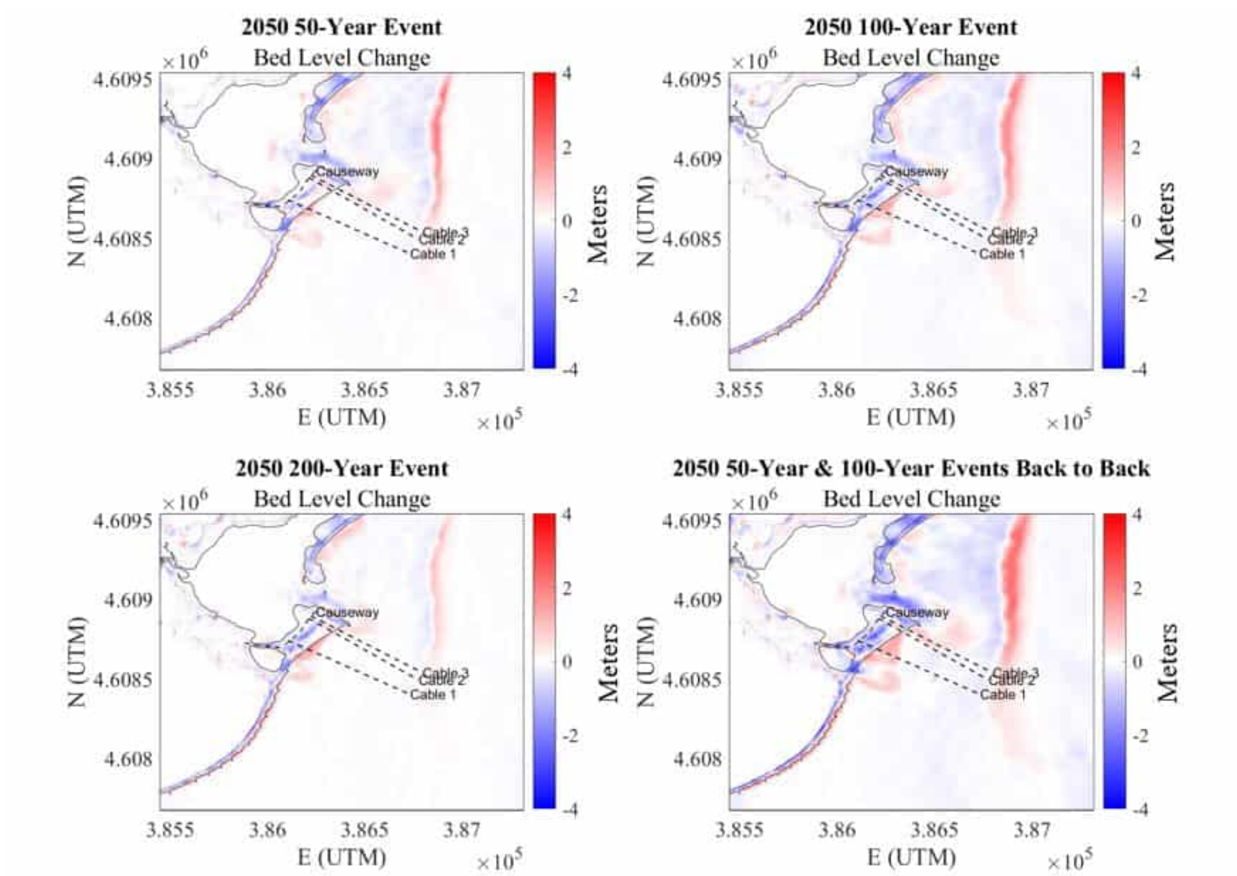


**Figure 4-21: Simulated bed level changes (m), accretion (red) and erosion (blue) at the study area for 50-year (top-left), 100-year (top-right), 200-year (bottom-left), and 50 & 100 – year back to back storm (bottom right) scenarios projected for 2050.**

Changes in water levels across the domain were modelled and recorded. Maximum water levels across the domain were mapped (Figure 4-22). Water level simulations revealed that all 2050 SLR scenarios are projected to result in overwash and breaching along dune crest which is reflected in mapping of bed level change (Figure 4-21). The causeway is projected to be flooded during all year 2050 scenarios as well as the area surrounding Dowses Beach.

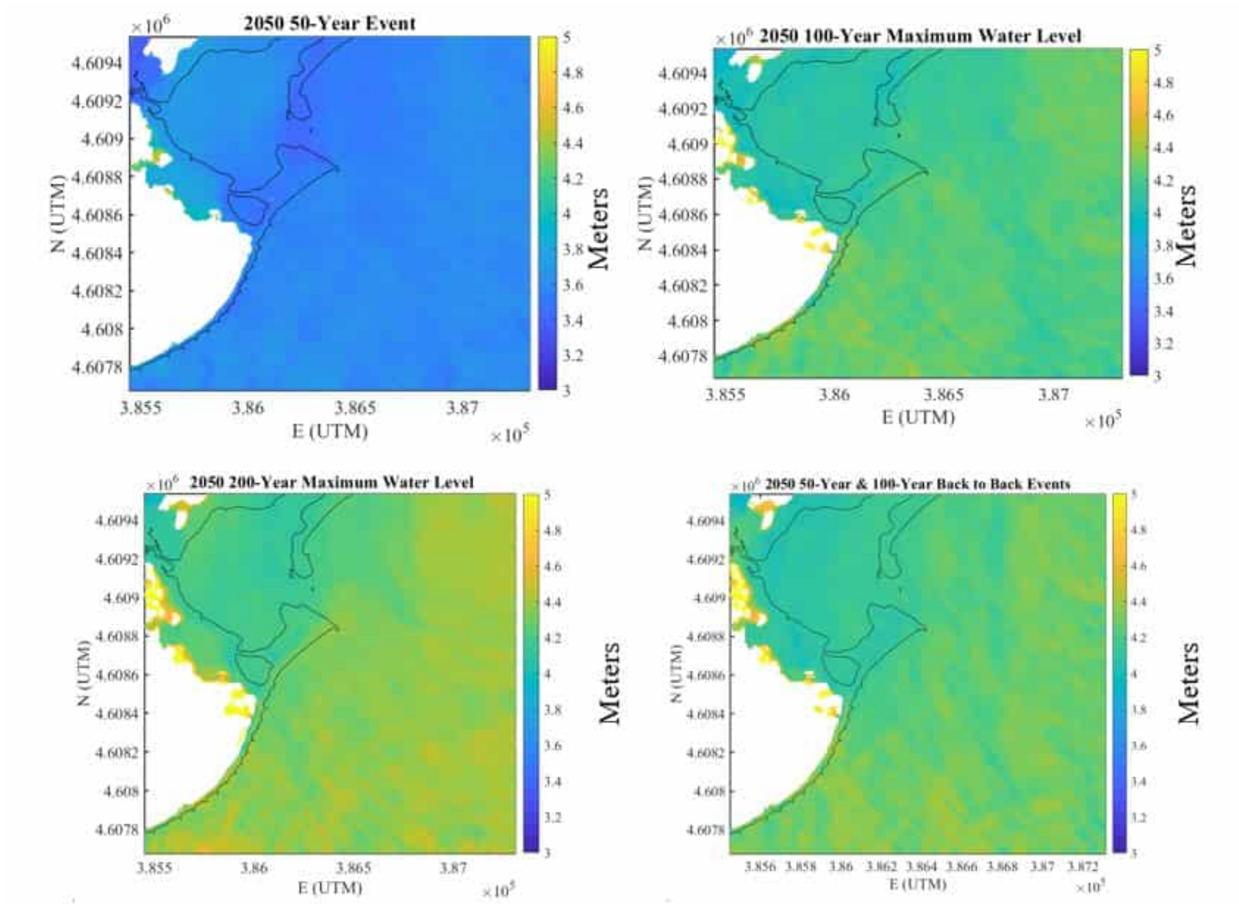


**Figure 4-22: Maximum simulated water level (m) that occurred over each grid cell over the domain throughout the modelled 50-year (top-left), 100-year (top-right), 200-year (bottom-left), and 50 & 100 – year back to back storm (bottom right) scenarios for 2050 projections.**

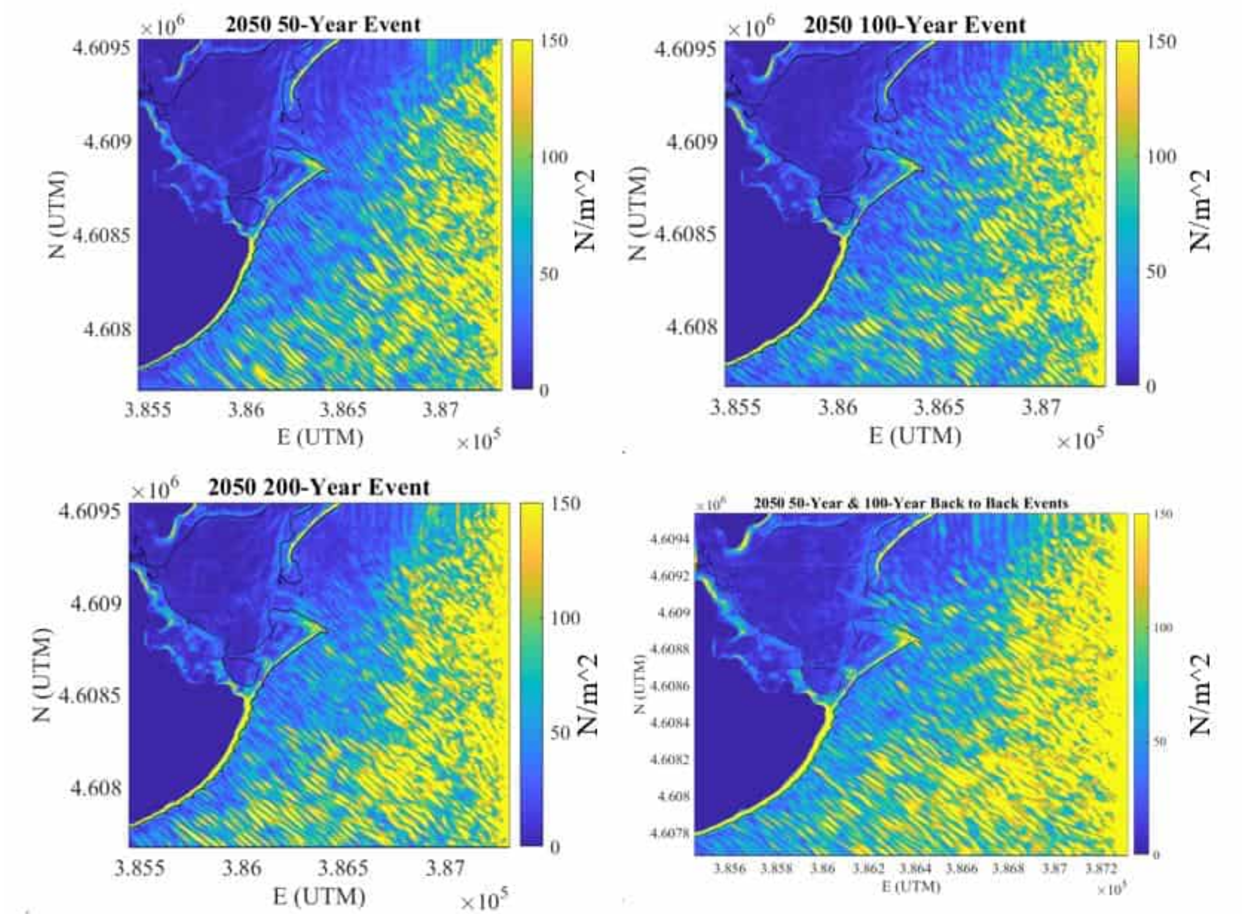


**Figure 4-23: Maximum simulated wave force magnitude (N/m²) that occurred over each grid cell over the domain throughout the modelled 50-year (top-left), 100-year (top-right), 200-year (bottom-left), and 50 & 100 – year back to back storm (bottom right) scenarios for 2050 projections.**

The mapped maximum simulated wave force throughout each event (Figure 4-23) show the effects of bathymetry on wave character and in turn wave breaking patterns. Similar to the 2030 projected storm scenarios, the 2050 scenarios modelled the greatest amount of wave energy at the seaward boundary as well as along the shoreline. This can be attributed to abrupt shoaling in bathymetry that occur at these two locations (Figure 3-2) that induce wave instability and breaking as waves propagate over these areas. The maximum simulated forces along the cable transects and causeway were mapped and revealed that a majority of wave radiation forces is modelled to dissipate before the intersection of the causeway and cable landing (Figure 4-24 through Figure 4-27).

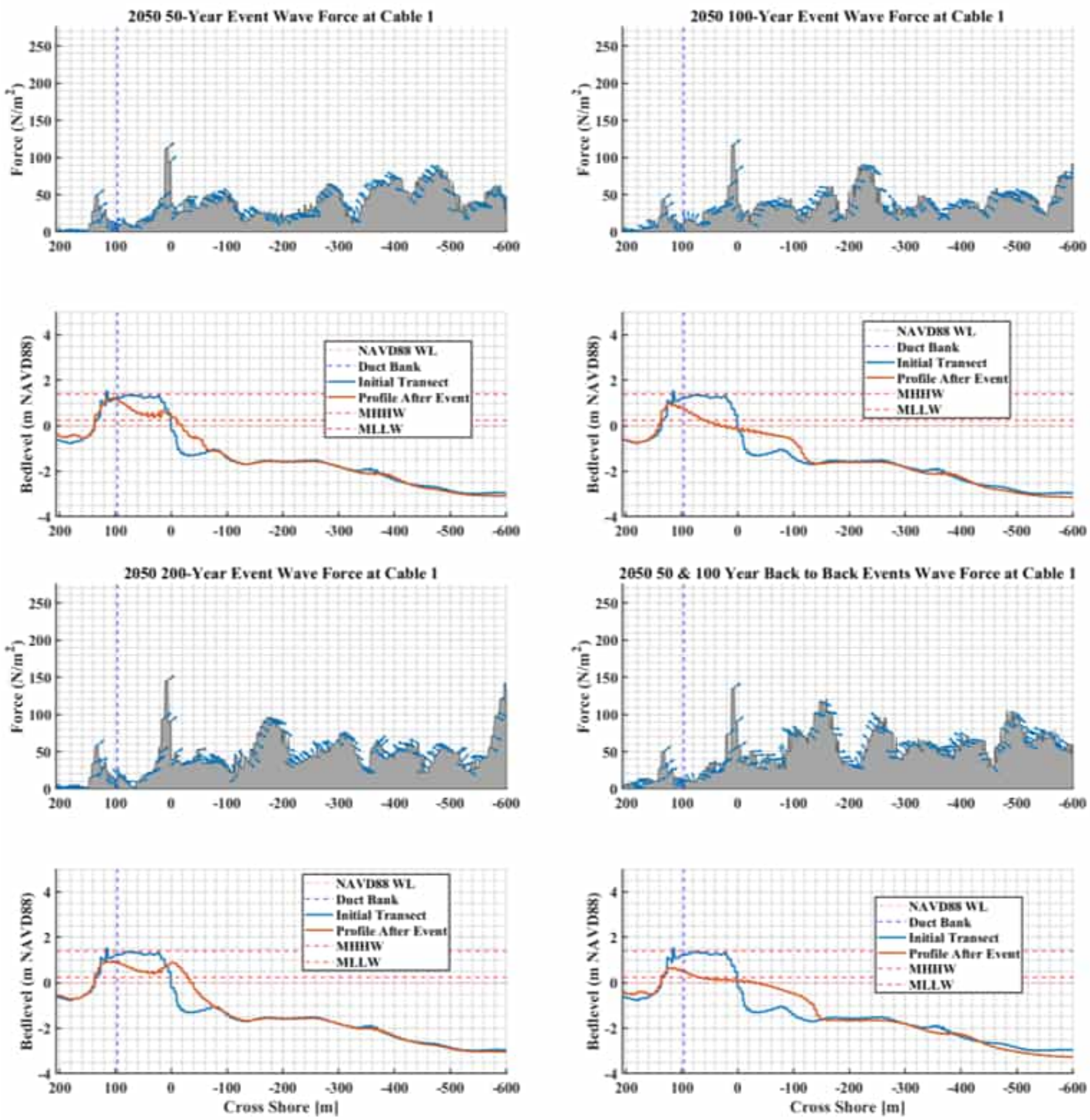


**Figure 4-24: Simulated initial and post-storm cross-shore transect at Cable 1 (bottom) with corresponding maximum wave force magnitude and direction (normalized arrows) along transect (top) for projected 2050 conditions during 50- year (top-left), 100-year (top-right), 200-year (bottom-left), and 50 & 100 – year back to back storm (bottom right) scenarios.**

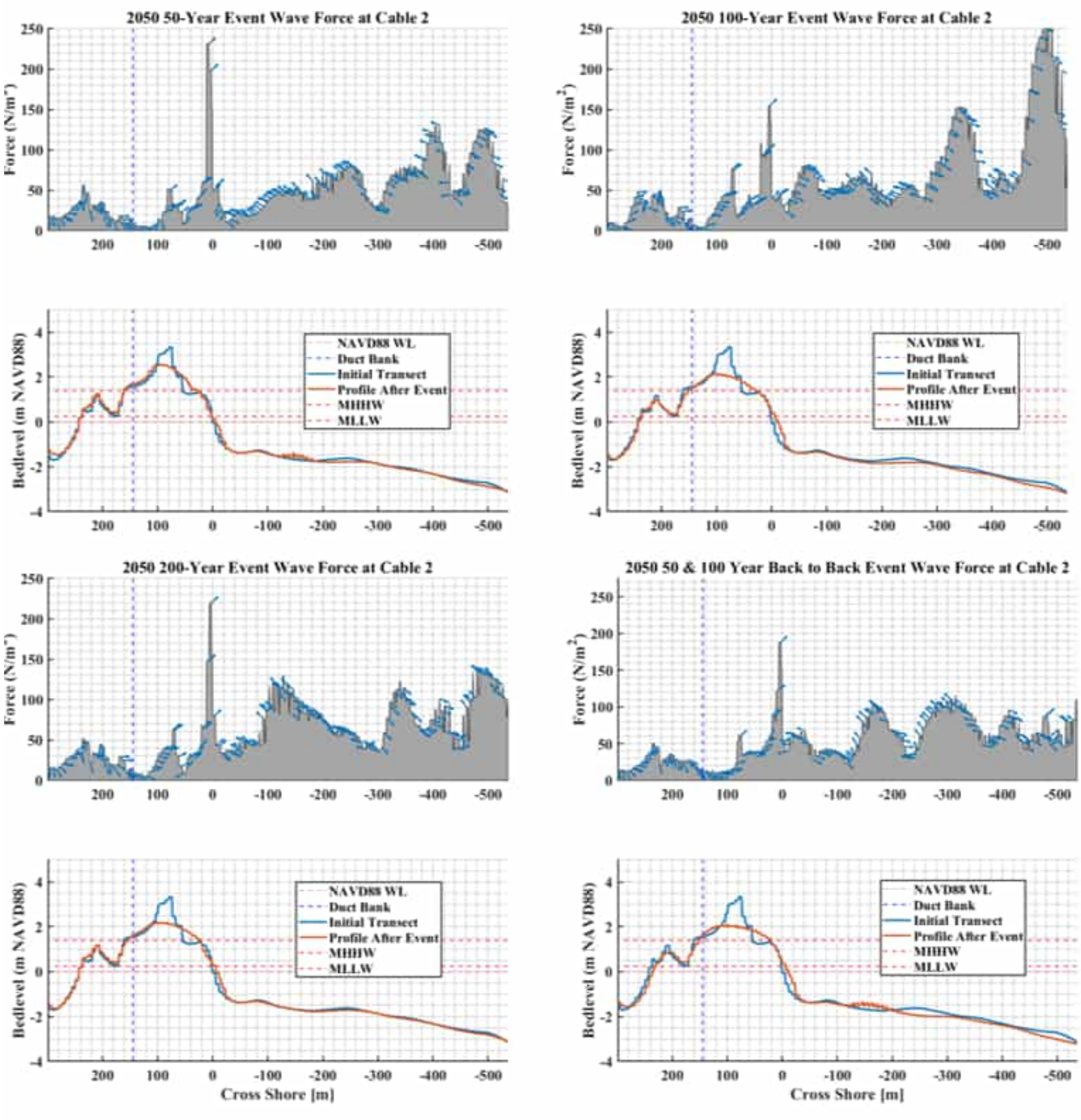


**Figure 4-25: Simulated initial and post-storm cross-shore transect at Cable 2 (bottom) with corresponding maximum wave force magnitude and direction (normalized arrows) along transect (top) for projected 2050 conditions during 50- year (top-left), 100-year (top-right), 200-year (bottom-left), and 50 & 100 – year back to back storm (bottom right) scenarios.**

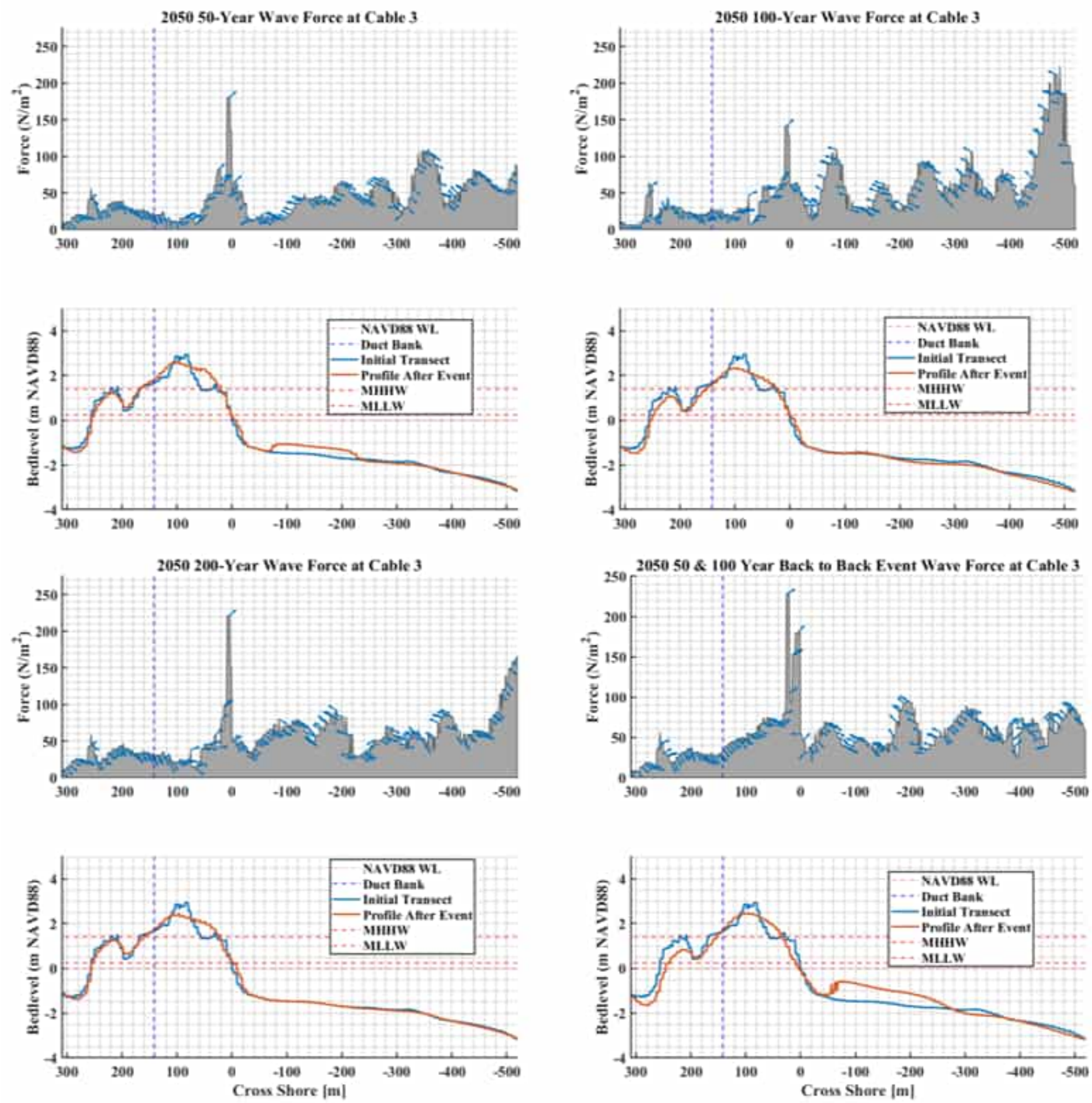


**Figure 4-26: Simulated initial and post-storm cross-shore transect at Cable 3 (bottom) with corresponding maximum wave force magnitude and direction (normalized arrows) along transect (top) for projected 2050 conditions during 50- year (top-left), 100-year (top-right), 200-year (bottom-left), and 50 & 100 – year back to back storm (bottom right) scenarios.**

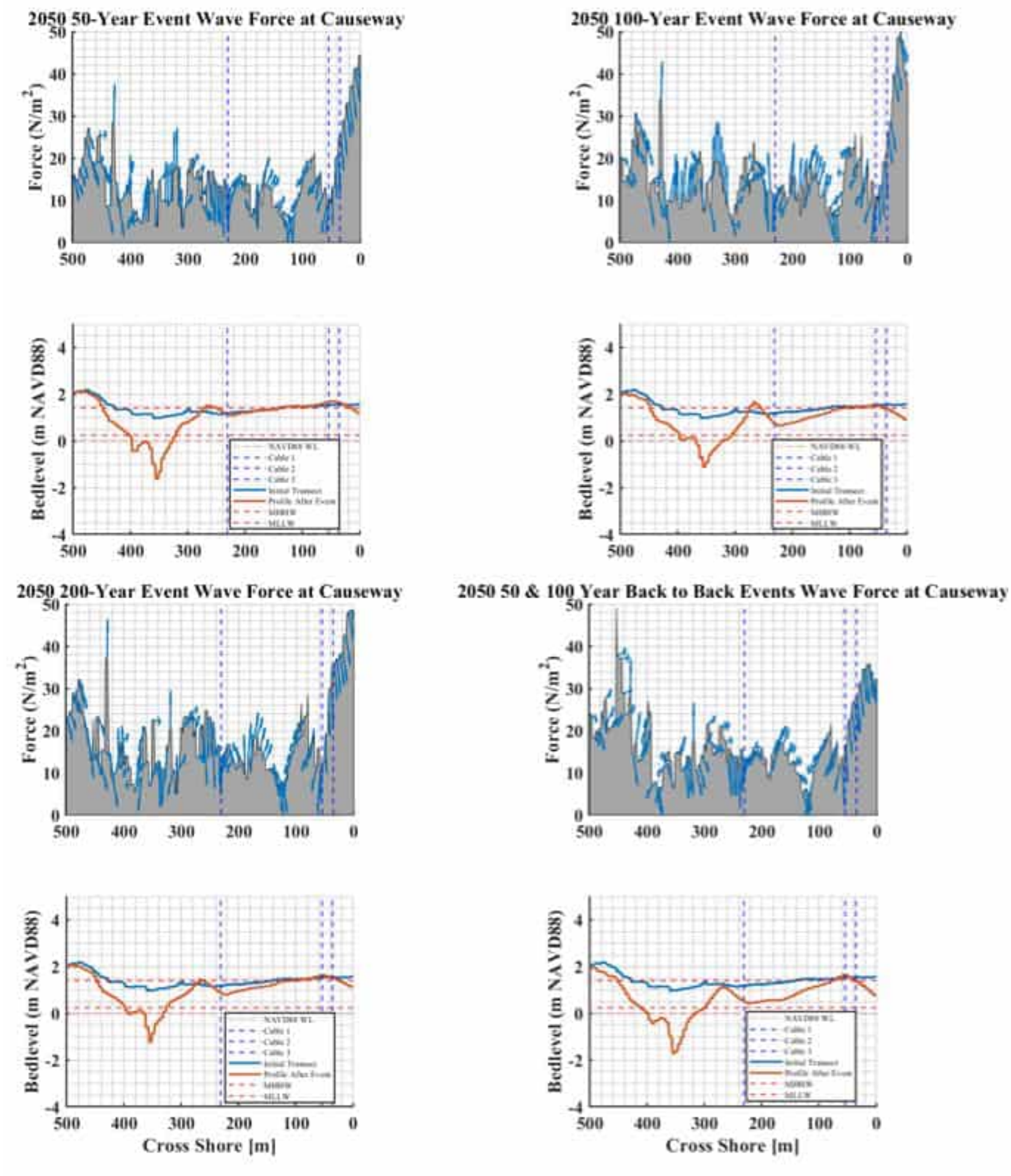


**Figure 4-27: Simulated initial and post-storm cross-shore transect at Causeway (bottom) with corresponding maximum wave force magnitude and direction (normalized arrows) along transect (top) for projected 2050 conditions during 50- year (top-left), 100-year (top-right), 200-year (bottom-left), and 50 & 100 – year back to back storm (bottom right) scenarios.**

## 4.3 Sediment Transport for 2070 Scenarios

As summarized in Table 3-4, and similar to the 2050 scenarios, a 50-year storm, a 100-year storm, a 200-year storm, as well as a back-to-back 50-100-year storm were modeled for the projected 2070 conditions.

Erosional patterns and wave forces were examined across the domain as well as at the cable landings and causeway locations. Similar to projected 2050 scenarios, the modeled 100-year and 200-year extreme events for 2070 showed the most notable changes in bed-level along all three landing cables modeled as they were the most energetic events (Figure 3-12 and Figure 3-13). Maximum water level and post storm bathymetry were simulated and mapped for all four modeled 2070 events (Figure 4-28 through Figure 4-31). As water levels are projected to rise higher by 2070, inundation of the beach berm is predicted to occur more than 12 hours a day under normal tidal conditions, assuming, as noted earlier, that today's initial bed profile remains the same. Moreover, inundation of the causeway itself, as well as the parking lot around it, is simulated to occur each high tide as East Bay waters are expected to rise in tandem to Nantucket Sound waters.

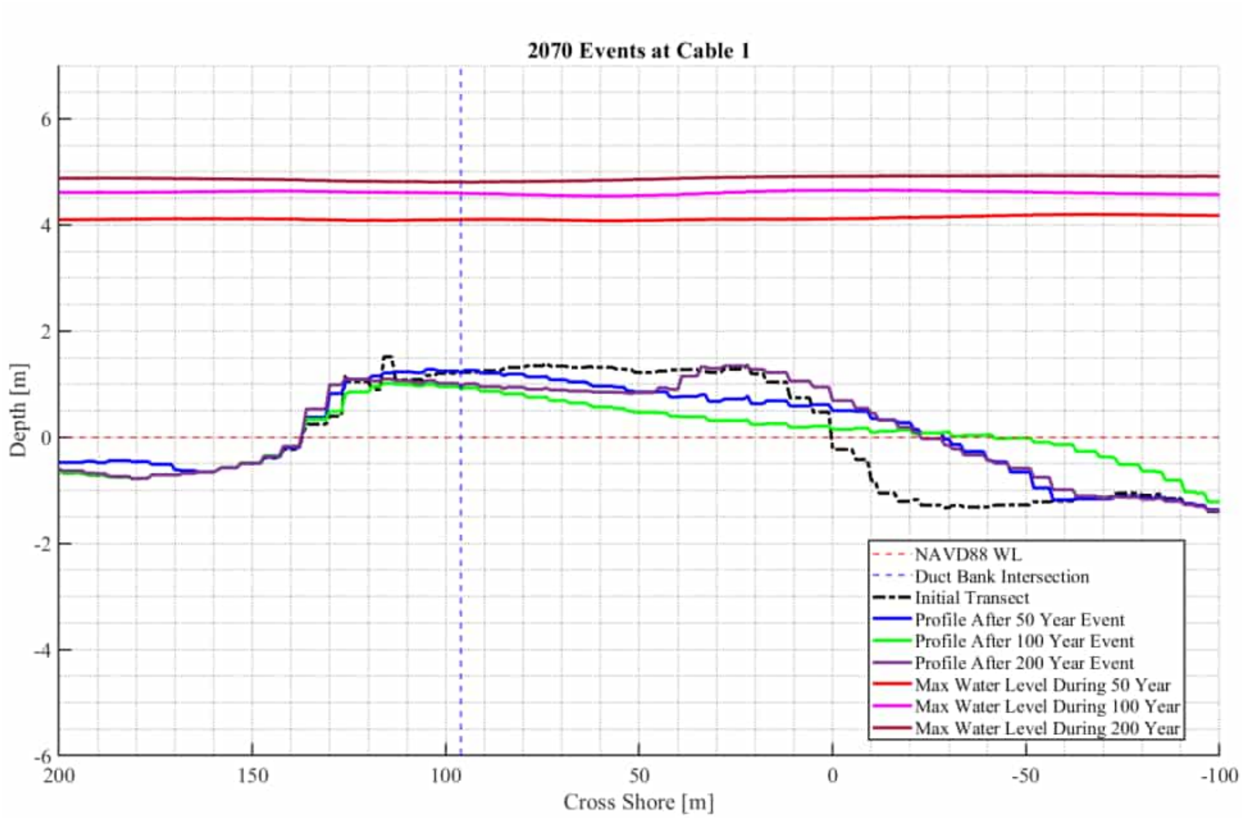


**Figure 4-28: XBeach-simulated post-storm cross-shore transect at Cable 1 landing location for 50-year (blue), 100-year (green), and 200-year (purple) future [2070] events, with corresponding maximum water level (50-year: red; 100-year: pink; 200-year: maroon); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

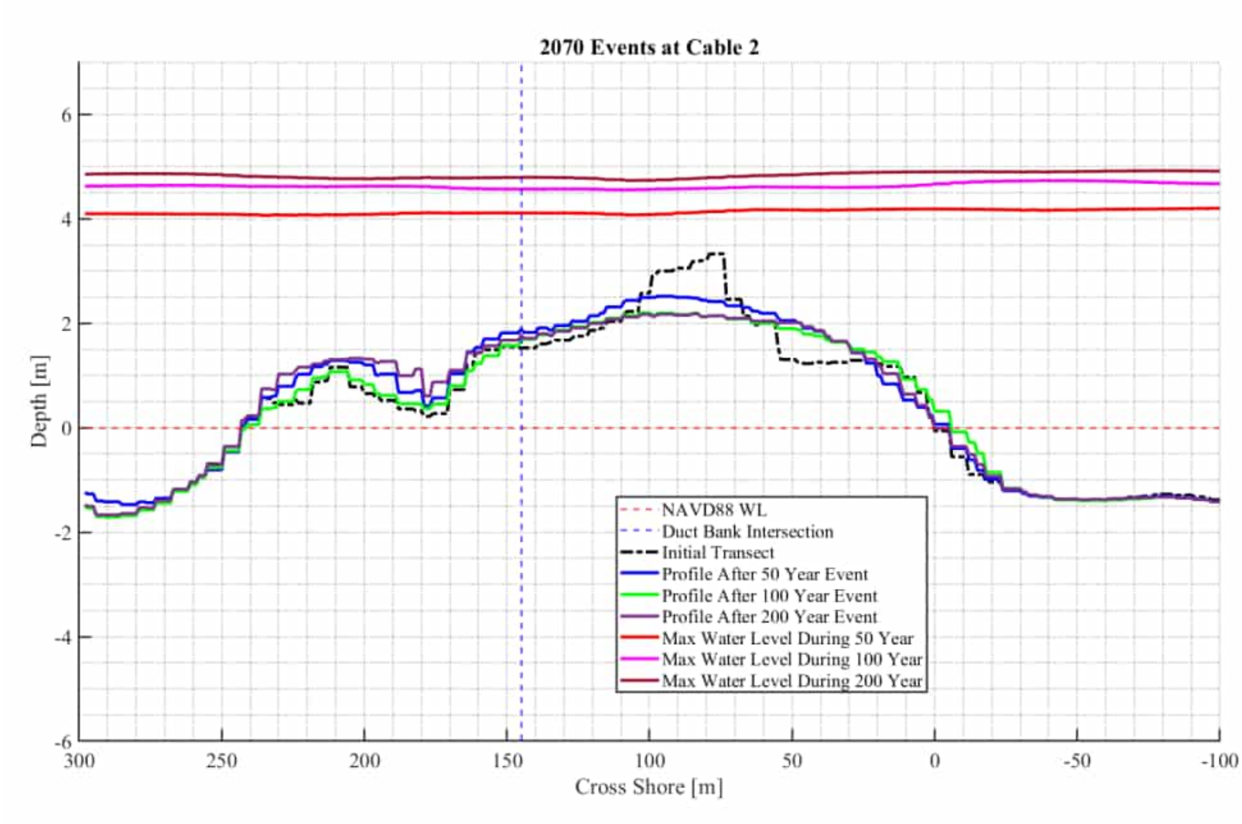


**Figure 4-29: XBeach-simulated post-storm cross-shore transect at Cable 2 landing location for 50-year (blue), 100-year (green), and 200-year (purple) future [2070] events, with corresponding maximum water level (50-year: red; 100-year: pink; 200-year: maroon); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

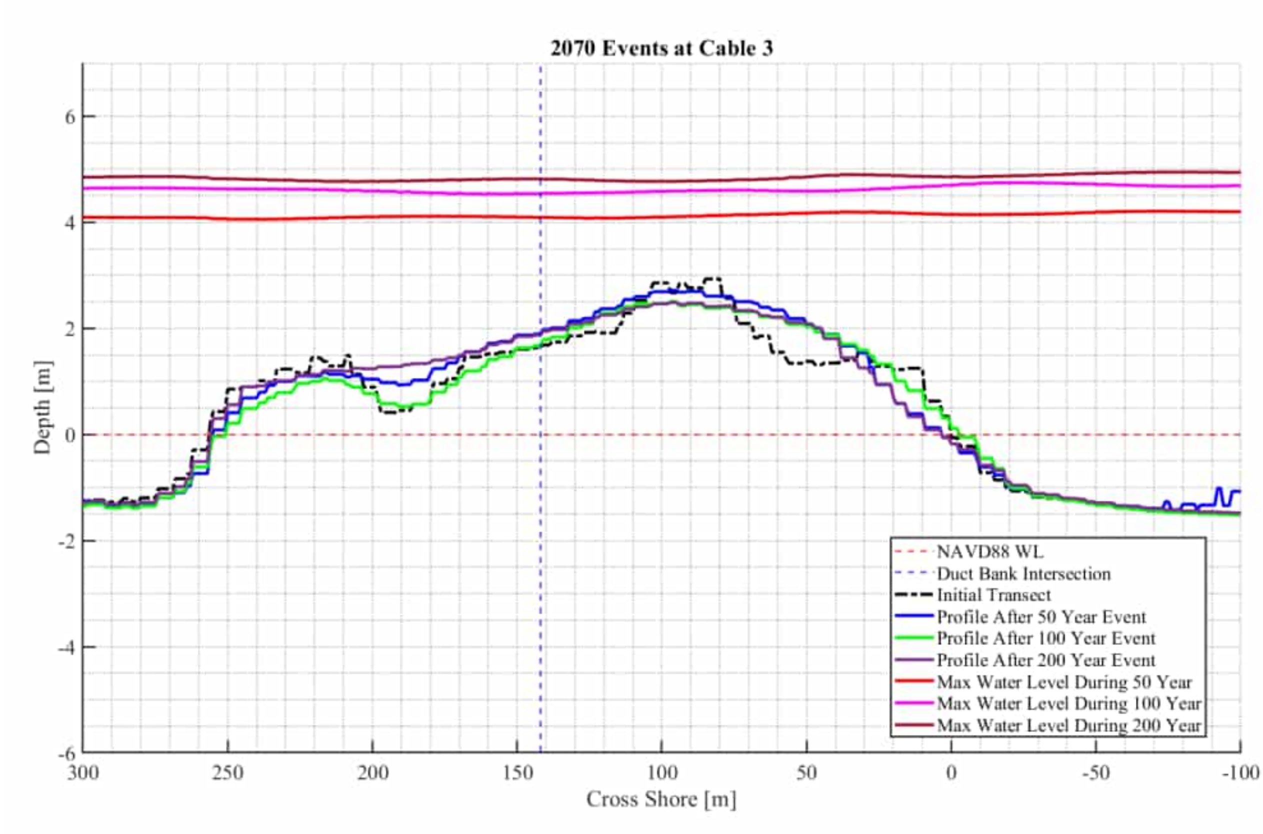


**Figure 4-30: XBeach-simulated post-storm cross-shore transect at Cable 3 landing location for 50-year (blue), 100-year (green), and 200-year (purple) future [2070] events, with corresponding maximum water level (50-year: red; 100-year: pink; 200-year: maroon); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

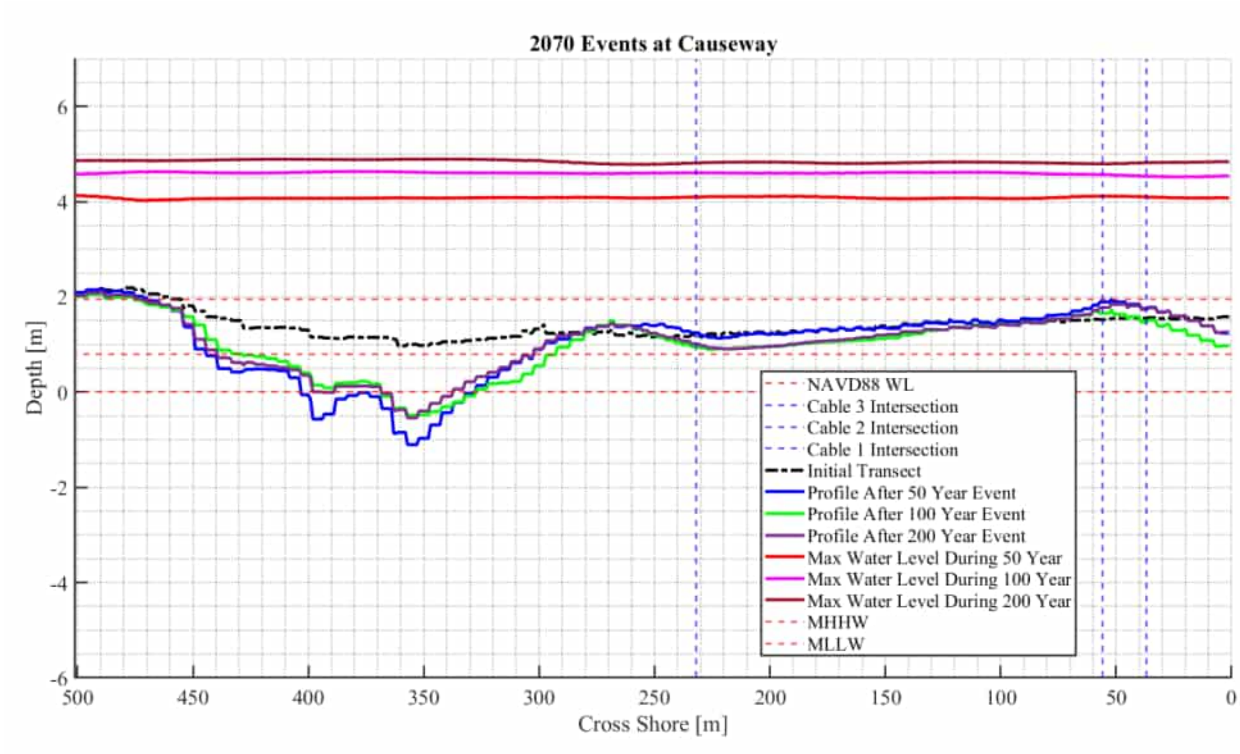


**Figure 4-31: XBeach-simulated post-storm cross-shore transect at Causeway landing location for 50-year (blue), 100-year (green), and 200-year (purple) future [2070] events, with corresponding maximum water level (50-year: red; 100-year: pink; 200-year: maroon); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

Model results are qualitatively similar to the 2050 scenarios. Across all three landing cable transects, the model simulated notable erosion and accretion caused by the three individual extreme events. All transects experience inundation of dune crest during storm events. This caused the initial dune crest to be eroded and sediment to be transported from the initial dune crest seaward. While all extreme events modelled similar magnitude and consequences, the 100-year event displays slightly higher boundary condition wave heights (Figure 3-12), inducing slightly more sediment transport landward than the 50-year and 200-year event at cable locations.

The sections of the causeway that were sheltered by dune crests showed to have little to no changes in bed-level whereas the lower sections of the causeway that were directly exposed to increasing water levels displayed significant decrease in elevation. Causeway sections located in between East Bay and Phinneys Bay in particular are susceptible to flooding due to their low elevation and lack of natural dune protection.

A 50-year and 100-year back-to-back event was modelled for the projected 2070 conditions, by concatenating the two events, 50- and 100 year timeseries, assuming they would impact the shoreline with no time between them for the dune system to recover (Figure 4-32). This process doubled the period of exposure and increased the wave action and surge impact on shoreline. The resulting change in the dune topography due to this back- to-back event is presented in Figure 4-33 through Figure 4-36.

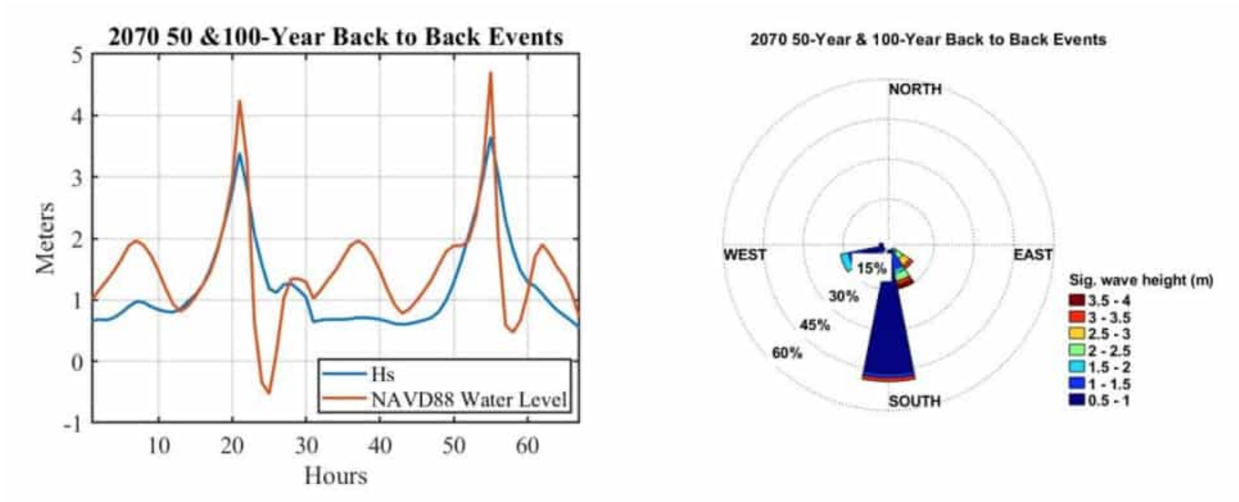


**Figure 4-32: Combined 50-year and 100-year sea-state conditions for a back-to-back event in 2070.**

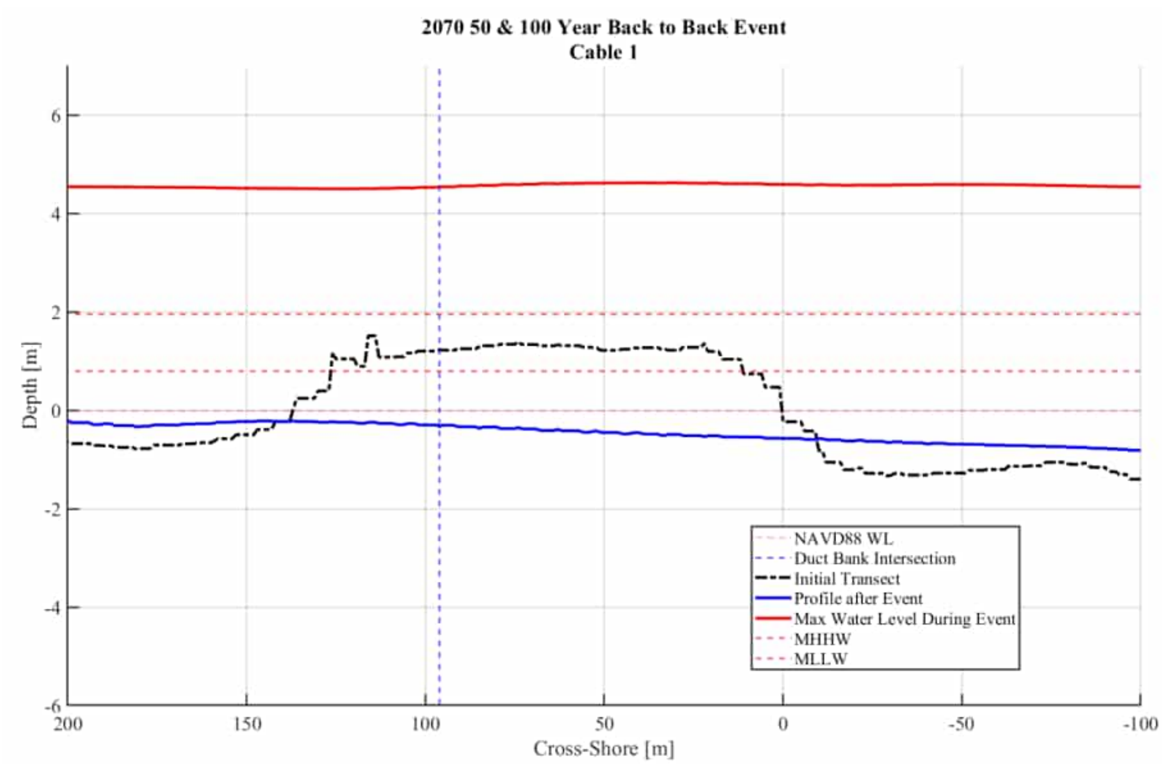


**Figure 4-33: XBeach-simulated post-storm cross-shore transect at Cable 1 landing location for a 50 & 100 – year back to back storm [2070] event (blue), with the associated maximum water level (red); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

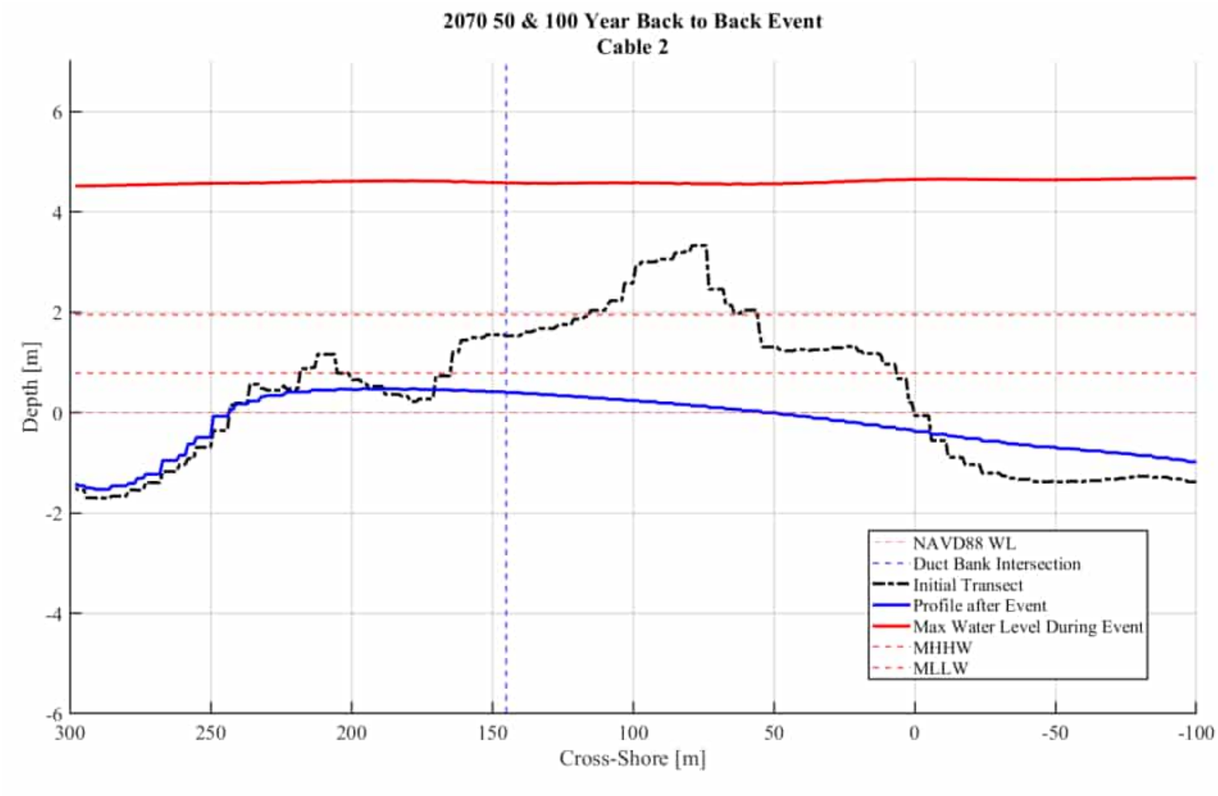


**Figure 4-34: XBeach-simulated post-storm cross-shore transect at Cable 2 landing location for a 50 & 100 – year back to back storm [2070] event (blue), with the associated maximum water level (red); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

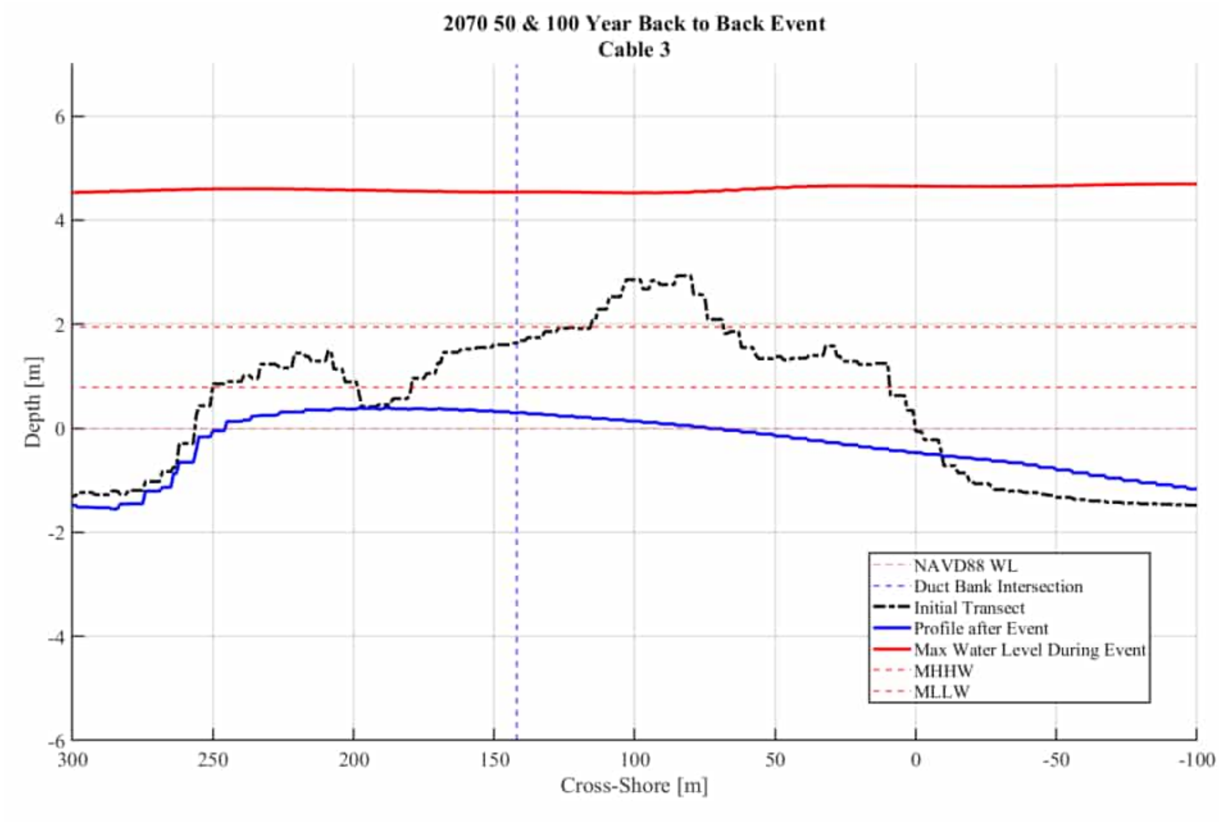


**Figure 4-35: XBeach-simulated post-storm cross-shore transect at Cable 3 landing location for a 50 & 100 – year back to back storm [2070] event (blue), with the associated maximum water level (red); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

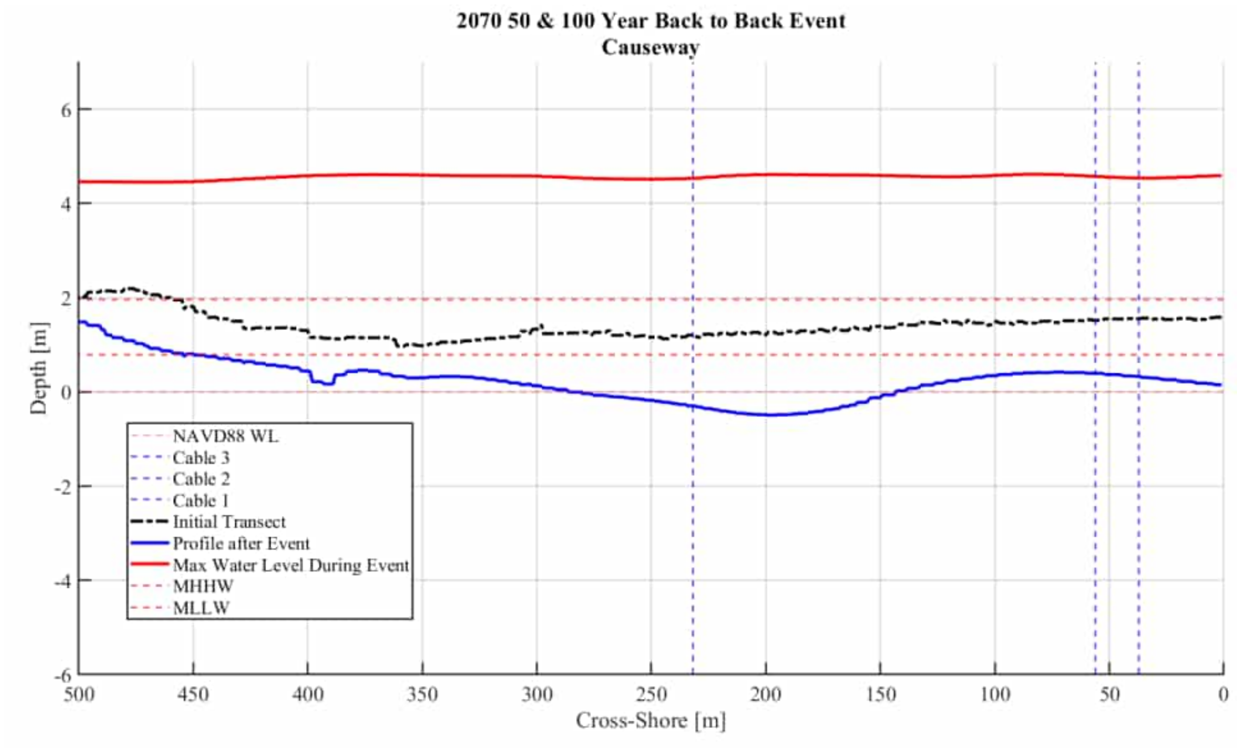


**Figure 4-36: XBeach-simulated post-storm cross-shore transect at Causeway landing location for a 50 & 100 – year back to back storm [2070] event (blue), with the associated maximum water level (red); initial pre-event topo-bathymetry is shown in black (dash) with vertical datum references in red (dash).**

Examination of cable and causeway transects for the simulated back-to-back storm conditions showed a significant amount of sediment transport during this prolonged event. Table 4-3 displays the initial dune maximum elevation at each transect site as well as the post-storm height at that dune crest initial location for each storm event. After the back-to-back event, the dune crest height was simulated to drop over 2 m at the cable 1 site. The 50-year extreme event had the least amount of simulated sediment transport of the three events but, still, a maximum of 0.91 m of dune crest erosion at the cable 2 location was predicted. Under such catastrophic conditions, the Dowses Beach dunes are simulated to completely erode resulting in a flat land profile. At the most vulnerable cable 1 transect a complete levelling of the profile is seen; That beach profile is predicted to fall below the current NAVD88 mean sea level datum following the simulated back to back storm event given the assumptions of this study.

**Table 4-3: Dune crest height [m] at cable locations before (initial, pre-storm) and after 50-year, 100-year, 200-year and back-to-back storm events in 2070.**

| Site Location | Pre-storm | Post 50 Year | Post 100 Year | Post 200 Year | Post Back-to-back |
|---|---|---|---|---|---|
| Cable 1 (Cross shore = 22 m) | 1.35 | 0.77 | 0.32 | 1.32 | -0.69 |
| Cable 2 (Cross shore = 74 m) | 3.33 | 2.42 | 2.14 | 2.14 | 0.13 |
| Cable 3 (Cross shore = 80 m) | 2.90 | 2.60 | 2.41 | 2.37 | 0.05 |

Post-storm bed level maps illustrate the sediment transport that occurred during the modelled events (Figure 4-37). Of the three single event scenarios the 100-year extreme event showed slightly more erosion along the Dowses Beach area similar to in the 2050 sea level rise scenarios. Total erosion in all cases is more severe than the erosion seen in the 2050 cases, but it is dramatically more show in the back-to-back case. All cases show instances of 2 m of cross shore erosion with the back-to-back storm scenario having the most erosion of the dune system. Under such devastating back to back storm tides and waves the model simulated redistribution of sediment throughout the model area, with some of the sediment predicted to be transported further offshore and deposited in the deeper areas of the modelling domain where it may be harder to remobilize under normal conditions.

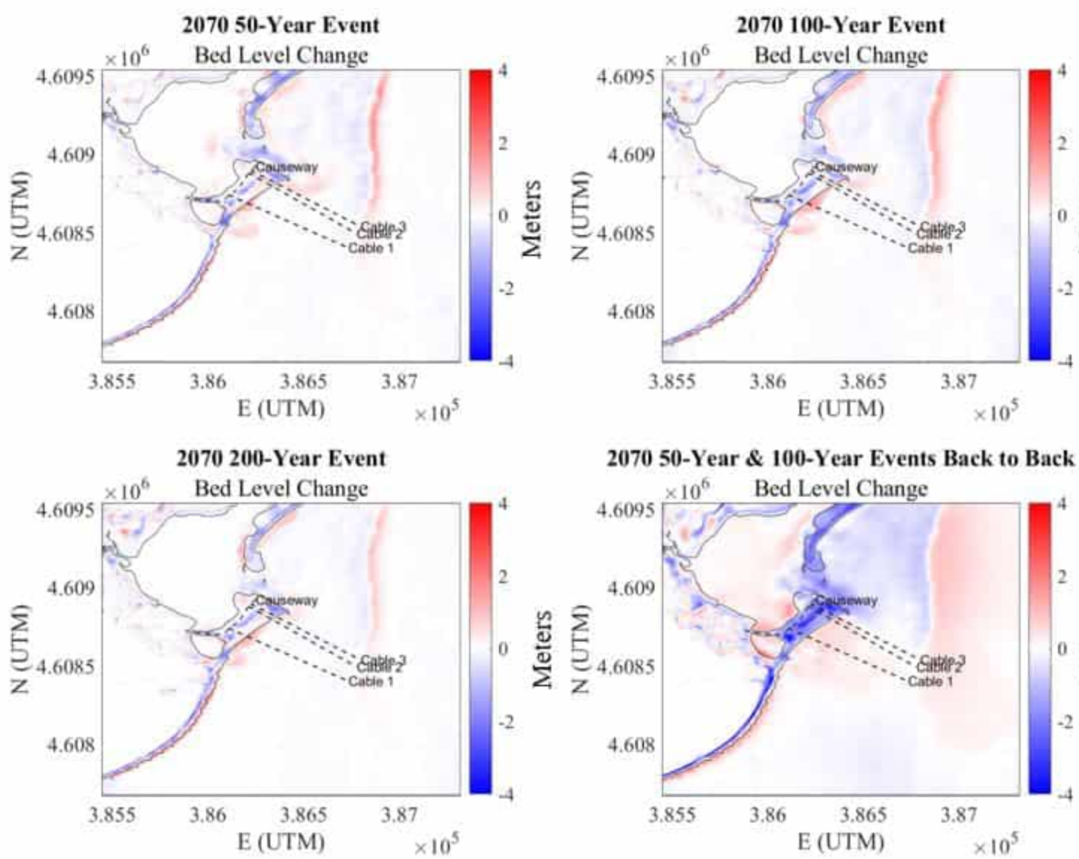


**Figure 4-37: Simulated bed level changes (m), accretion (red) and erosion (blue) at the study area for future 2070 SLR projection, 50-year (top-left), 100-year (top-right), 200-year (bottom-left), and 50 & 100 – year back to back storm (bottom right) scenarios.**

Changes in water levels across the domain were modelled and the maximum water levels across the domain were mapped (Figure 4-38). Water level mapping revealed that all 2070 scenarios predicted overwash and breaching along dune crest which is reflected in mapping of bed level change (Figure 4-37). The causeway located in between East Bay and Phinneys Bay is shown to be flooded during all 2070 SLR scenarios.

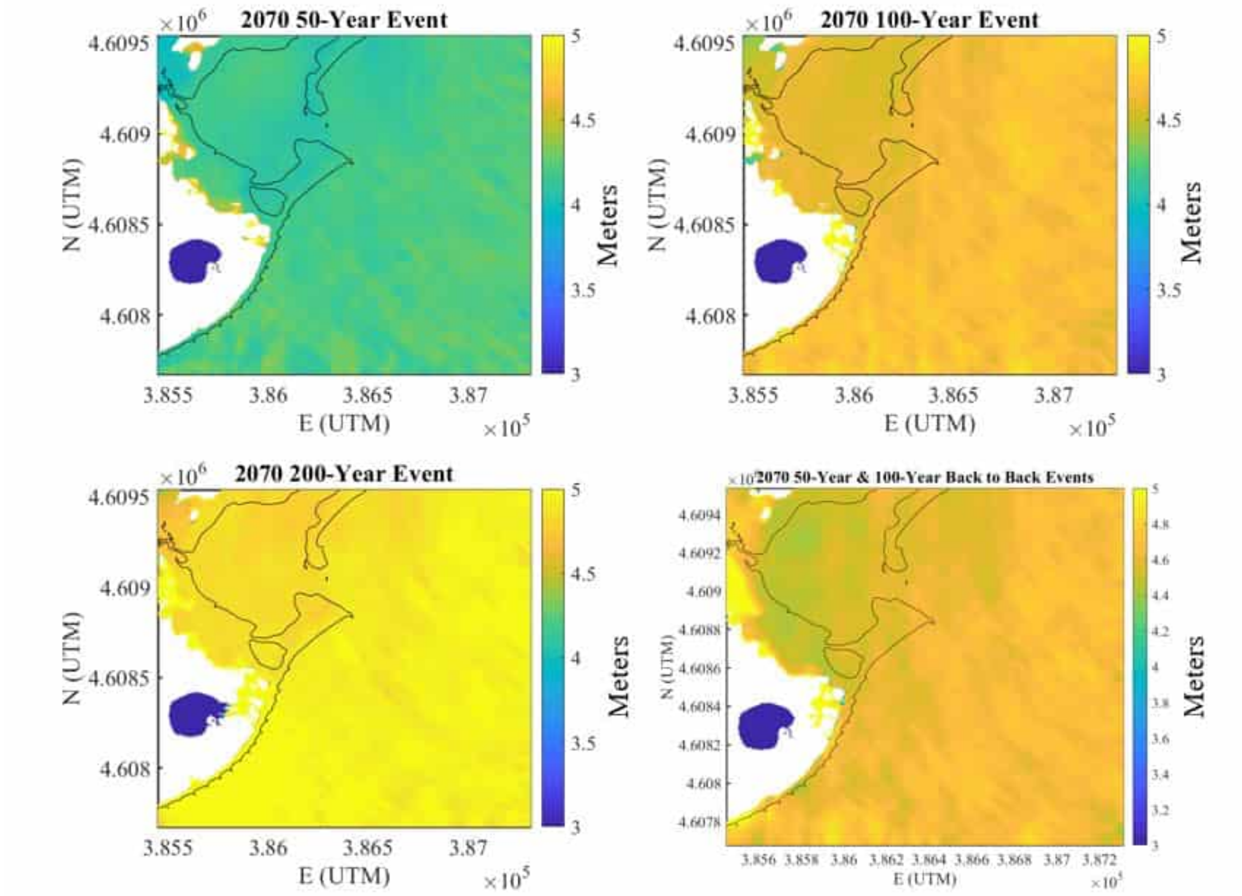


**Figure 4-38: Maximum water level (m) that occurred over each grid cell over the domain throughout the modelled 50-year (top-left), 100-year (top-right), 200-year (bottom-left), and 50 & 100 – year back to back storm (bottom right) scenarios for 2070 SLR projections.**

The mapped maximum simulated wave force (Figure 4-39) shows the effects of bathymetry on wave character and in turn erosional patterns. Similar to the 2050 SLR storm scenarios, the 2070 SLR scenarios modelled the greatest amount of wave radiation stress at the seaward boundary as well as along the shoreline. This can be attributed to abrupt shoaling in bathymetry that occur at these two locations (Figure 3-2) that induce wave instability and breaking as waves propagate over these areas. As the water levels become higher, whitecapping of waves offshore can spread out to a larger area, while, compared to the 2050 conditions, the shore breaking zone is simulated to move further upland toward today's dune tow, rather than today's beach slope (Figure 4-39).

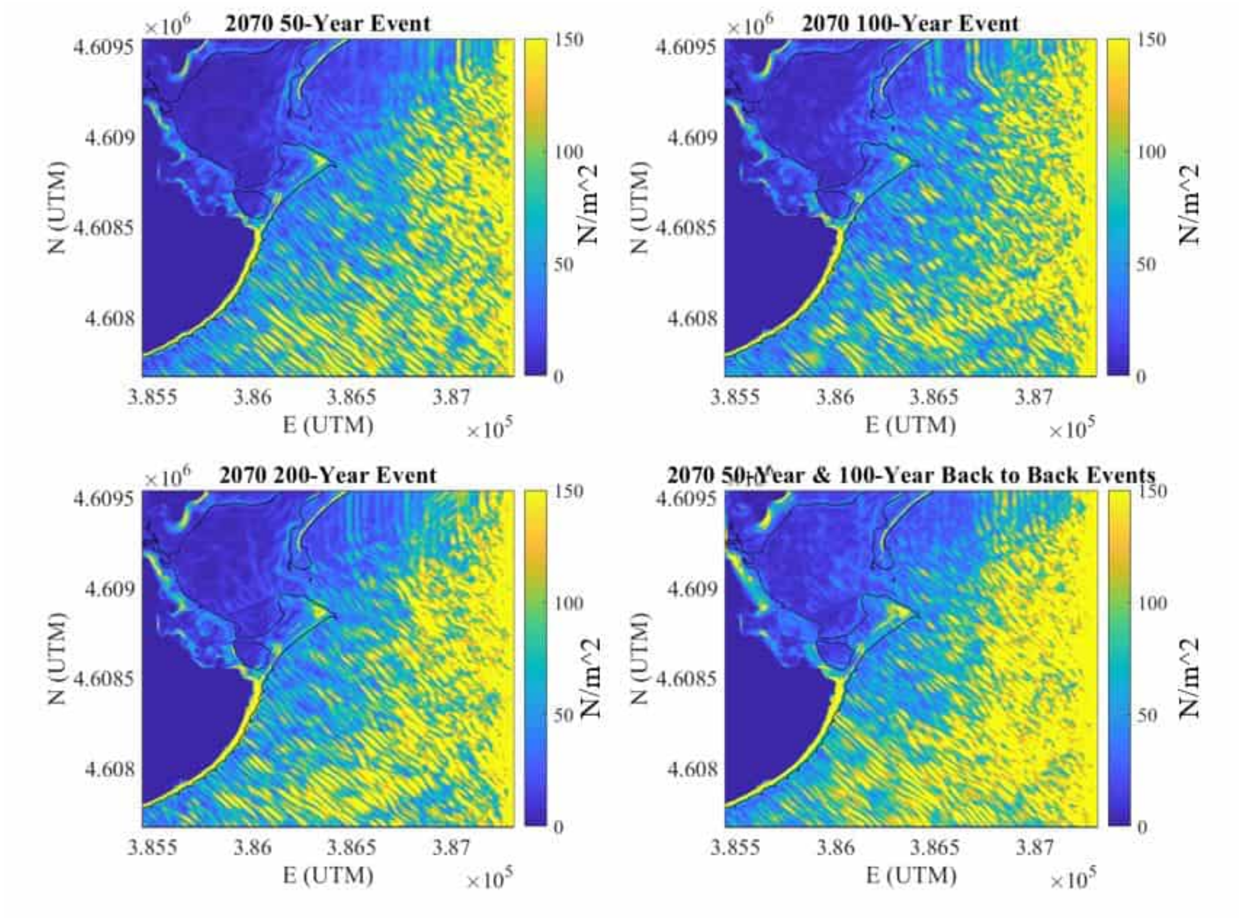


**Figure 4-39: Maximum wave force magnitude that occurred over each grid cell over the domain throughout the modelled 50-year (top-left), 100-year (top-right), 200-year (bottom-left), and 50 & 100 – year back to back storm (bottom right) scenarios for 2070 SLR projections.**

Simulated maximum wave force along the cable transects and causeway revealed that the maximum wave force is high at the offshore boundary and quickly reduces in magnitude along the shoreline. In many cases the force induced by breaking waves reduces under 50 $N/m^2$ past the cable causeway intersections ( Figure 4-40 to Figure 4-43). The most substantial increase in wave force compared to 2050 respective conditions is simulated to be for the back-to-back scenario.

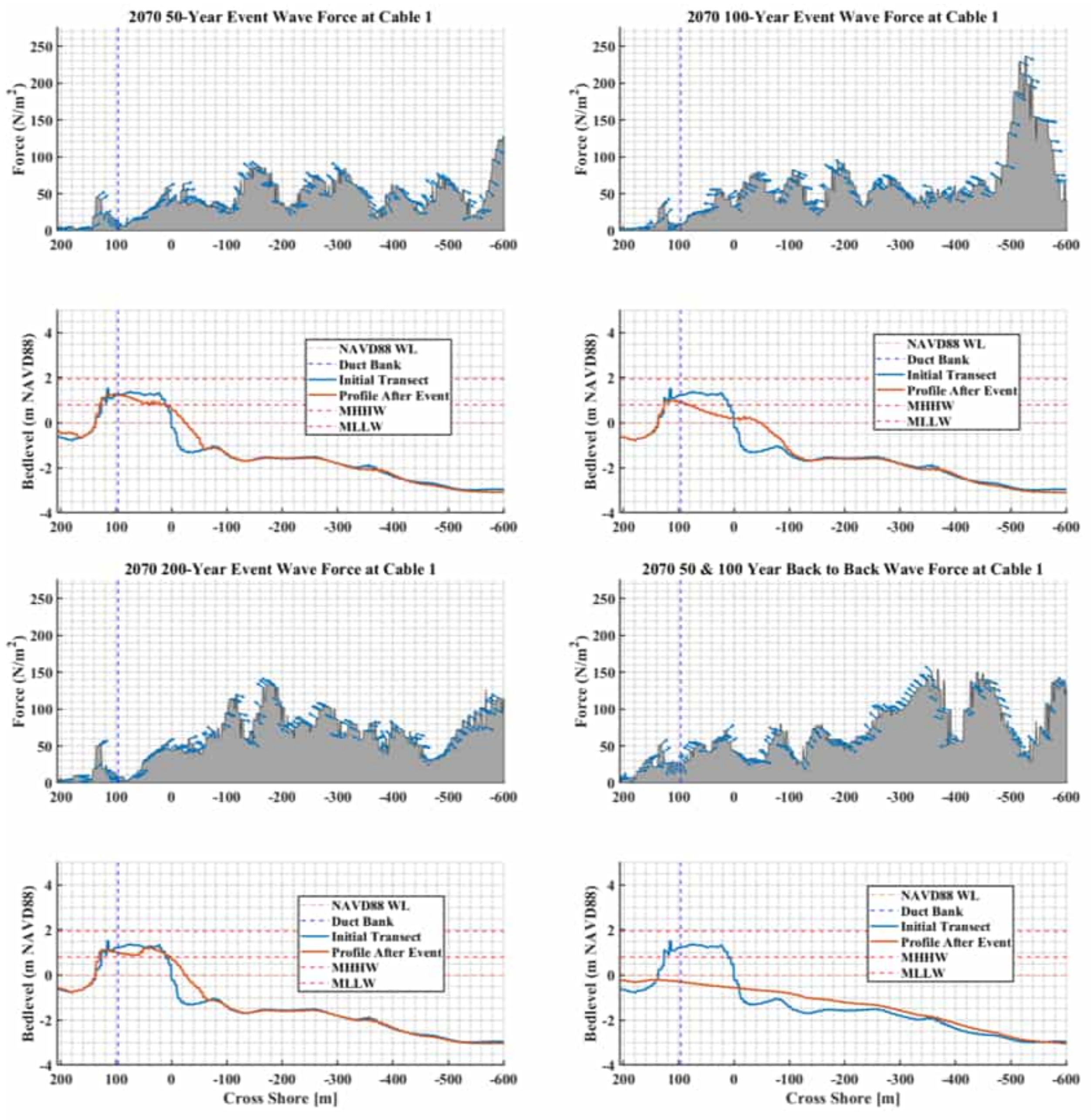


**Figure 4-40: Simulated initial and post-storm cross-shore transect at Cable 1 (bottom) with corresponding maximum wave force magnitude and direction (normalized arrows) along transect (top) for projected 2070 conditions during 50- year (top-left), 100-year (top-right), 200-year (bottom-left), and 50 & 100 – year back to back storm (bottom right) scenarios.**

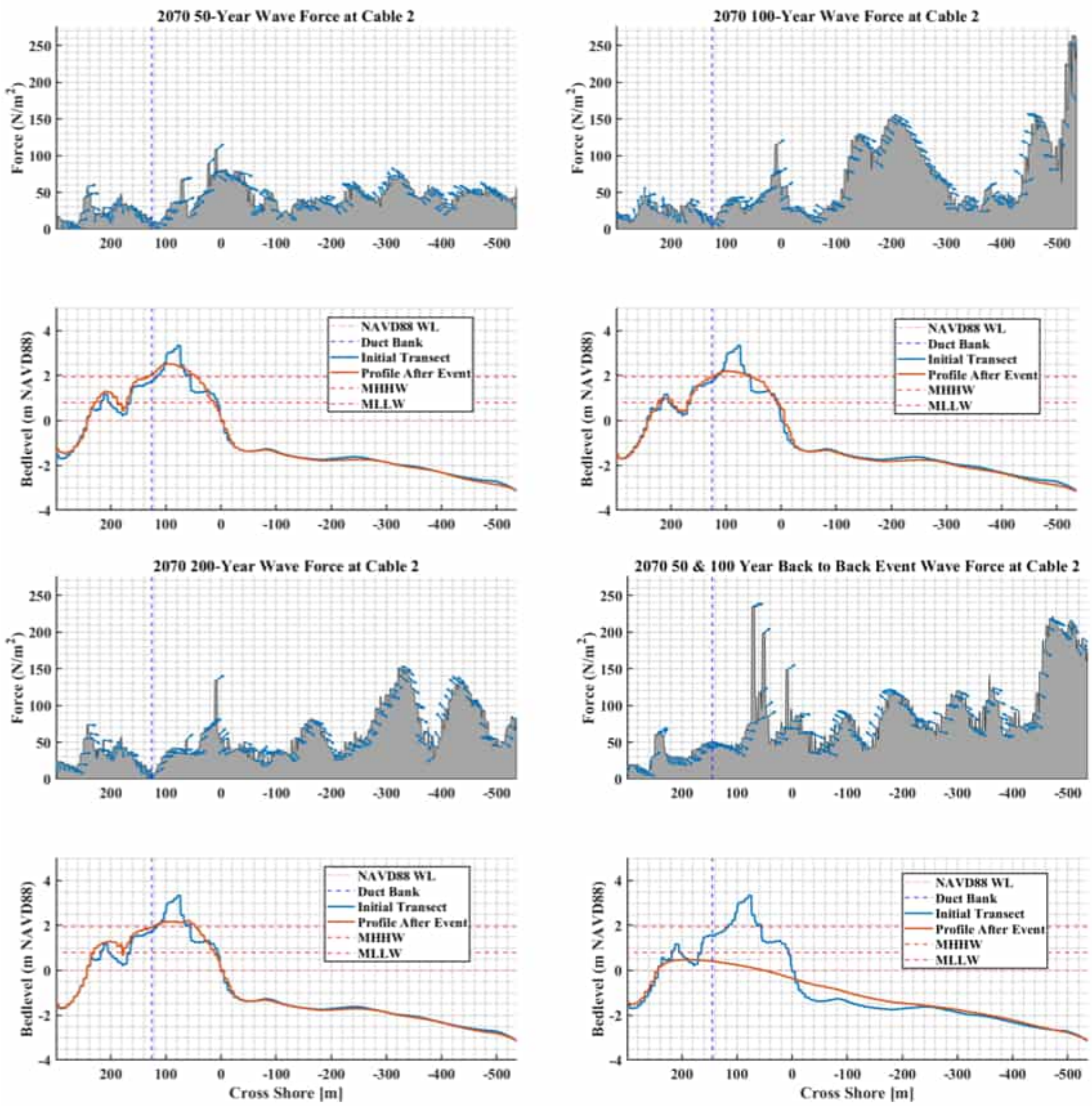


**Figure 4-41: Simulated initial and post-storm cross-shore transect at Cable 2 (bottom) with corresponding maximum wave force magnitude and direction (normalized arrows) along transect (top) for projected 2070 conditions during 50- year (top-left), 100-year (top-right), 200-year (bottom-left), and 50 & 100 – year back to back storm (bottom right) scenarios.**

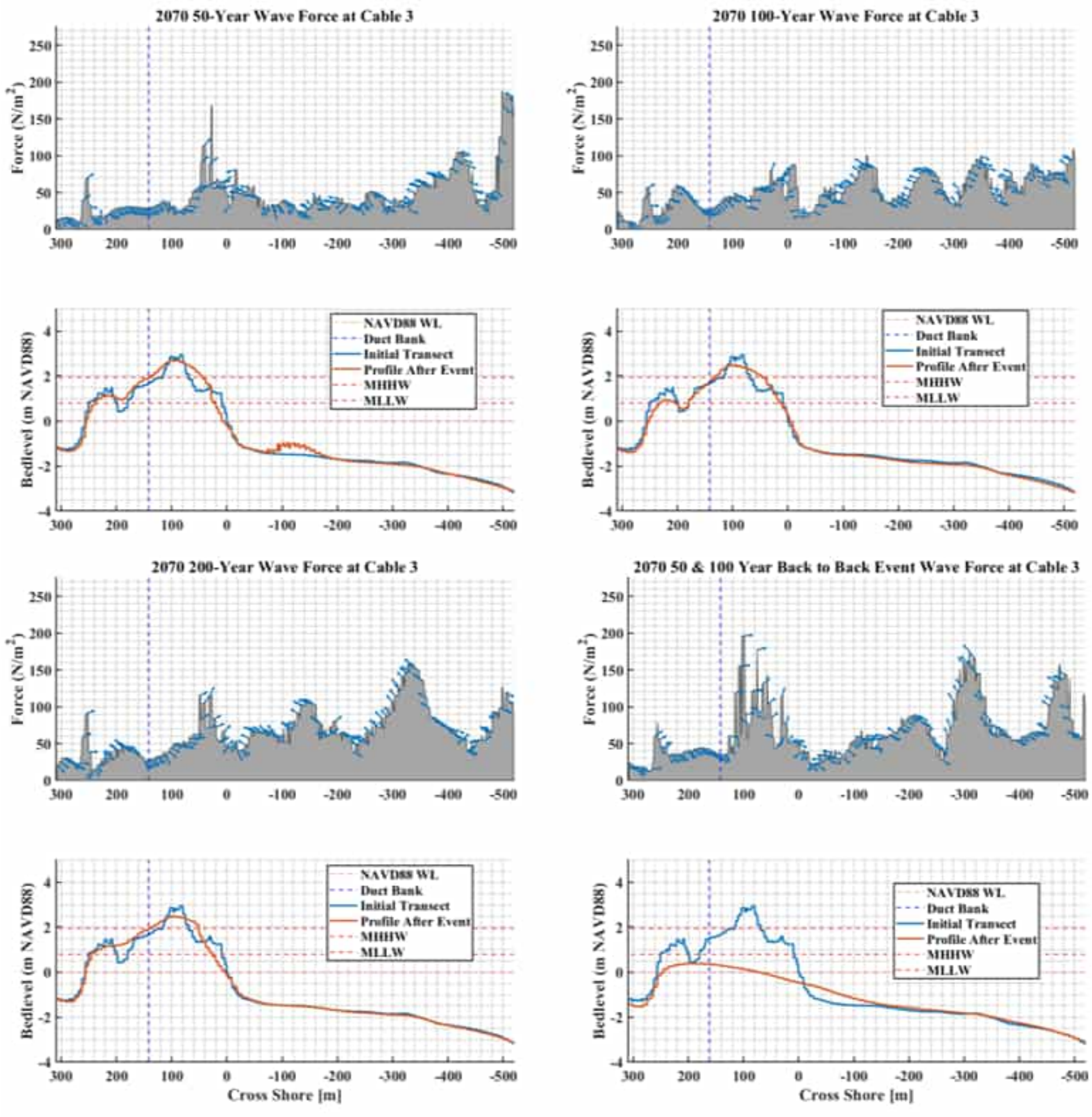


**Figure 4-42: Simulated initial and post-storm cross-shore transect at Cable 3 (bottom) with corresponding maximum wave force magnitude and direction (normalized arrows) along transect (top) for projected 2070 conditions during 50- year (top-left), 100-year (top-right), 200-year (bottom-left), and 50 & 100 – year back to back storm (bottom right) scenarios.**

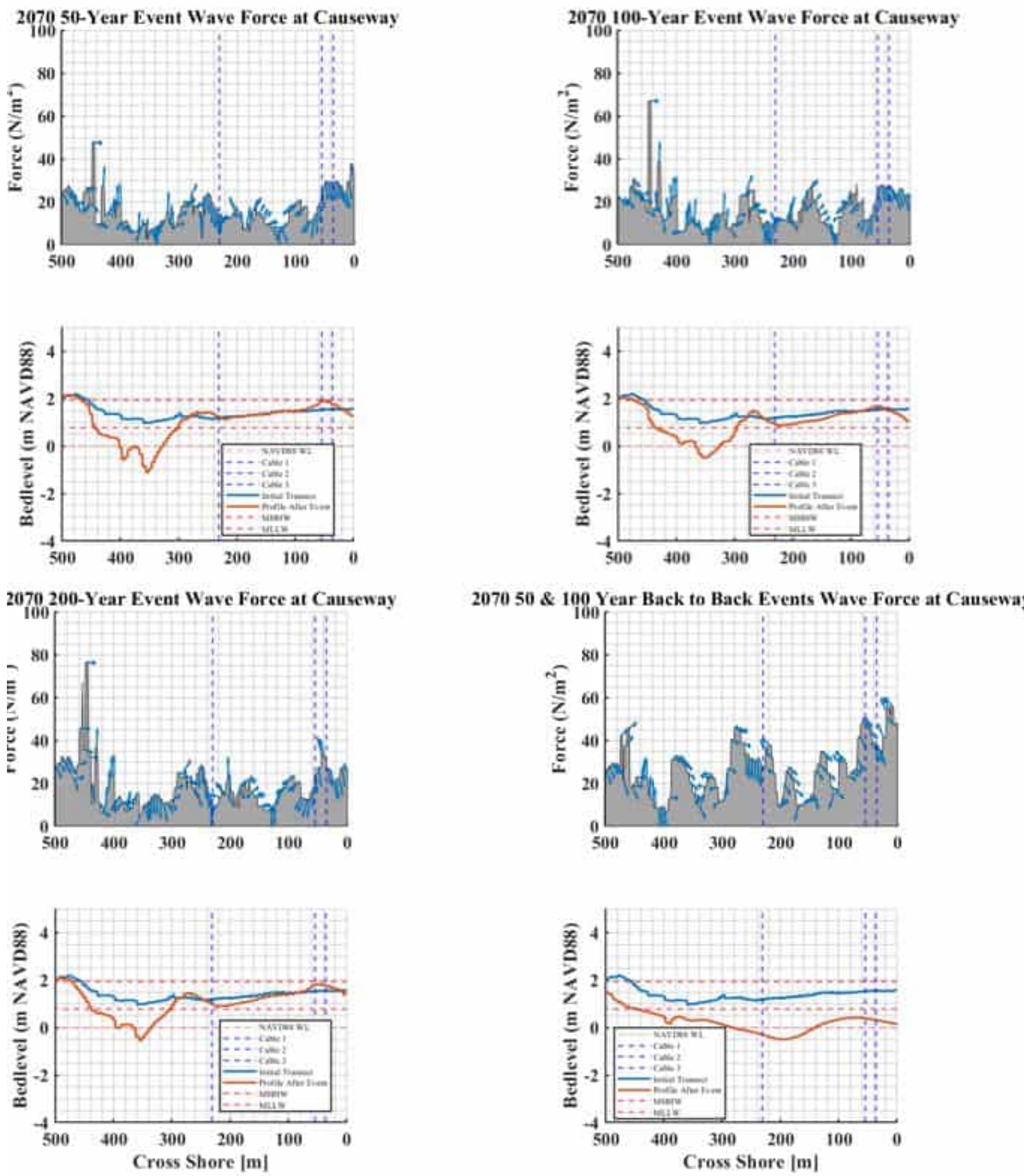


**Figure 4-43: Simulated initial and post-storm cross-shore transect at Causeway (bottom) with corresponding maximum wave force magnitude and direction (normalized arrows) along transect (top) for projected 2070 conditions during 50- year (top-left), 100-year (top-right), 200-year (bottom-left), and 50 & 100 – year back to back storm (bottom right) scenarios.**

Transect analysis of wave induced storm forces (Figure 4-40 to Figure 4-43) display how wave forces differ while propagating across a varying bathymetry. Much like in 2050 SLR scenarios, 2070 SLR scenarios a majority of the wave force is dissipated by Dowses beach's natural dune system. As the large amount of wave force is already reduced by the time the wave hit the back dune, wave force at the causeway cable intersection is quite low.

# 5. CONCLUSIONS

RPS conducted hydro-morphodynamic numerical simulations at the area of Dowses Beach, MA using the 2D model XBeach to assess the potential erosion at the landing sites of three offshore wind cables and the associated causeway connection cable to the upland grid during future storm conditions (in 2030, 2050, and 2070). A set of assumptions was made in this study as listed in Section 3.4. The model simulated the storms' flow and wave propagation, the associated sediment transport and the resulting change in bathymetry and topography. Simulations were performed for a range of future storms including, 2030 (+0.39 m), 2050 (+0.76 m), and 2070 (+1.31 m) SLR. The sediment transport was modeled for 50-year, 100-year, and 200-year extreme events. A sequential 50-year and 100-year back-to-back scenario was also simulated for 2050 and 2070 conditions.

Global climate change is occurring rapidly and features SLR and increased storm frequency that pose profound threats to coastal areas. Cape Cod has over 580 miles of coastline that are typically sandy, low-lying and vulnerable to flooding and erosion. The Town of Barnstable alone has 104 miles of coastline and has approximately 15 square miles (9,834 acres) of property that is within hurricane inundation zones (Woodard & Curran, 2022). Future inundation on Cape Cod is expected to require that adaptation and resiliency strategies be developed and iteratively implemented over time (e.g., identifying adaptation options for assets). The increasing magnitude and frequency of future storm events is predicted to cause extensive coastal flooding and erosion throughout the Town of Barnstable and Cape Cod.

It is important to consider the severity of the events modeled to support conservative design decisions. The likelihood of a 50-year extreme event occurring is inherently that of 2% annually; similarly, that of a 100-year event is 1% annually. Combining these events in a back-to-back event in the same year significantly reduces the probability of occurrence (~0.02% annually) and leads to the creation of an extremely rare event. Over the past century, the only recorded back-to-back hurricane events in the area were that of Hurricanes Carol and Edna which occurred in 1954. Hurricane Carol was a category 3 hurricane and made landfall about 90 miles west of the Barnstable area. Hurricane Edna, the latter of the two, was a category 2 hurricane and crossed through the town of Barnstable as it made landfall (NOAA, n.d). The two events had a landfall 11 days apart. Each event followed a different trajectory and path which resulted in varied severity of impact to different localities: One locality may have experienced a 50yr flood while another a 10yr flood. Therefore, the back-to-back events simulated in this study, a near-coincidence of a 50yr and 100yr local event at Dowses Beach in the same year, literally back to back, are extremely rare to occur. If the extremely unlikely back to back storm events simulated in this modelling analysis were to actually hit Dowses Beach, the flooding, erosion and vast associated damage would be devastating to a much larger area on the south coast of Cape Cod and its barrier beaches.

Coupled SLR projections and predicted storm events for the decades of 2050 and 2070 were predicted by the model to result in more extreme erosion than in 2030. For 2050 and 2070 conditions, the extreme back-to-back events were predicted by the model to show the greatest changes in the topography with the most significant erosion at the landing sites. Many scenarios predicted a significant lowering of the dune and recession of the dune crest. Cable 1 and Causeway locations predicted the most morphological change during extreme events due to low lying elevation and lack of dune protection in these areas. Throughout all modeled storm events, areas of higher dune elevation (Cables 2 and 3) displayed more resilient behavior to sediment transport due to their natural protection. Simulations showed at these cable locations that the shoreline would be significantly eroded, especially during 100-year, 200-year, and back-to-back events occurring in the future [2050; 2070].

The initial dune crest at the Cable 2 transect was projected by the model to be eroded by a maximum of 3.2 m due to the simulated back-to-back event in 2070; the dune was predicted by the model to be completely leveled and a new dune was not created in that extreme scenario. Significant erosion was also seen in the back dune (Causeway intersection and parking lot area); bed-level change was simulated to be almost 2 m in this area. Wave forces for Cable 2 during this extreme event show large spikes (over 200

$N/m^2$) at the foredune and dune area. The causeway intersection at Cable 2, about 74 m behind the dune crest is shown to benefit from its location and is exposed to a maximum of only 50 $N/m^2$ of wave force as the dune absorbs a brunt of the wave radiation force.

All simulated cases of 2050 and, especially, 2070 conditions displayed breaching and overwash which indicated that these events could impact and damage the causeway and causeway intersection. In the cases of future extreme events (2070) the stronger wave action resulted in dune erosion of almost 4 m along Dowses Beach. Sediments were simulated to be overwashed behind the causeway and the lowered dune crest transgressed landward. Cable 1, unprotected by a dune, shows the worst-case post storm elevation with areas of change 2 m below the existing grade.

Along the causeway cable transect, most sediment transport was consistently simulated to occur at the areas unprotected by a dune. The causeway between East Bay and Phinneys Bay was predicted to be eroded most during the simulated storms as it is a relatively low-lying area with risk of frequent flooding. The simulated storm forces caused lowering of the causeway in this area. It is suggested and recommended to reinforce and support this area if cable-related placement will be occurring. Methods of turning this roadway into a truly non-erodible structure (i.e., armoring, rubbling, etc.) may offer support to this at-risk area. It is suggested to adapt the low-lying causeway area for future flooding and erosional patterns that are predicted to occur in future decades. Scour protection measures as well as flood protection measures should be considered and are highly recommended.

While an increase in wave height, wave period and water levels represent the physical variable impacting foreshore erosion, the duration of the event and the time of exposure are directly controlling the amount of erosion. Amongst all scenarios, the 2070 storm scenarios featured the highest significant wave height and caused most of the simulated erosion at each landing site, compared to other scenarios. In addition, the back-to-back events have provided more dune exposure to a longer stormy sea-state resulting in larger erosion and posing the most threatening conditions to the cable landing sites.

In conclusion, the sediment transport at the site is heavily influenced by environmental conditions, and the site-specific wave climate should be assessed when designing infrastructure. Extreme events are predicted to induce overwash and breaching in the study area. Overwash and breaching cause landward migration of the dunes and leveling of the initial dune crests, which threatens existing coastal topography as the top layers of sediment on the shore are predicted to migrate. Wave and other loads (sediment, tidal, current) to the proposed infrastructure need to be carefully considered.

The results and conclusion presented above are conservative in nature. This conservatism is due to the assumptions applied in this analysis, including, (1) the pavement of the causeway and beach parking lot is erodible, and can be removed by storm action, leaving the underlying sediment exposed to current and wave action; (2) the waves generated at the peak of the 50-year, 100-year, and 200-year storm event will come primarily from the southeast as occurred during Hurricane Sandy; and (3) the beach will not keep up naturally with sea level rise and the Town will not conduct any beach or dune nourishment along Dowses Beach over the next 50-years; (4) a conservative grain size on the lower threshold of medium sand was used to drive the model; (5) the events considered, especially a 50-yr&100-yr back-to-back event, are rare to extremely rare in nature. This report is not intended to be construed as an engineering evaluation on the ability of the project to withstand predicted erosion and waves forces but is a modeling effort to predict potential erosion at the proposed sites. An evaluation of the design and operation of the project to successfully mitigate impacts of the storm events modeled is outside the scope of this report and could be completed as part of a subsequent engineering analysis.

# 6. APPENDIX


**Figure 6-1: Map of cross shore referenced cable and causeway locations. Measured in meters across Dowses Beach and along causeway.**

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# Q2 Coastal Design Memo

Stantec

# Memo

| | | | |
|---|---|---|---|
| To: | Avangrid Offshore Wind / Commonwealth Wind LLC<br>125 High Street, 6th Floor, Boston, MA 02110 | From: | Stantec Consulting Services Inc.<br>300 Crown Colony Drive, Suite 110, Quincy, MA 02169 |
| Project/File: | 198804104 | Date: | June 29, 2023 |

**Reference: Engineering Evaluation of Coastal Storm Modeling Results for Dowses Beach Area**

Avangrid Offshore Wind / Commonwealth Wind LLC (Avangrid) engaged environmental consulting company RPS Group (RPS) to model extreme worst-case coastal storms to predict potential impacts to the Dowses Beach area planned to be used for the New England Wind 2 Connector/Commonwealth Wind (CWW) Project landfall site and proximate duct bank route. Avangrid subsequently requested Stantec Consulting Services Inc. (Stantec) evaluate RPS's coastal storm modeling results, provide engineering recommendations, and identify potential design upgrades to enable the Project infrastructure to withstand the predicted conditions. This memo outlines the results of Stantec's evaluation.

**<u>Interpretation of RPS Data</u>**

Modeling results from RPS were used to examine the potential erosion, wave forces, and water level where Project infrastructure is proposed at the landfall site and proximate area. Results of the 2050 storm modeling analysis were used as the basis of the engineering evaluation since they presented the most severe conditions during the Project design life and, accordingly, would result in the most conservative design.

Figure 1 illustrates predicted worst-case post-storm bed level change (in feet) from the 2050 back-to-back storm scenario by comparing pre- and post-event ground elevations; negative values indicate erosion, and positive values indicate accretion. Figure 2 presents potential wave forces (lb/ft$^2$) on a structure using the Goda equation (USACE Coastal Engineering Manual Table VI-5-53) with the modeled peak wave conditions from the 2050 200-year storm event. Proposed structure locations are shown in red. As set forth in the RPS reports, this worst-case storm scenario is very severe and would damage the coastline in many parts of Cape Cod, not just Dowses Beach, and would do so regardless of the project.

Erosion values along proposed structure locations is predicted to be as high as 8.9 feet (2.7 meters), but this value is isolated to a single area on the causeway that is likely minimally erodible. At the South Transition Joint Bay, the maximum modeled erosion is 3.6 feet (1.1 meters). Maximum potential wave forces at proposed structure locations range from 250 to 410 lb/ft$^2$. Additionally, the RPS modeling predicted that the 2050 200-year still water level could potentially reach a maximum of 14.6 feet (4.4 meters) NAVD88, which includes sea level rise, tides, and storm surge. At this elevation, the entire Dowses Beach Area, including its causeway and parking lot, would be submerged.

**Reference: Engineering Evaluation of Coastal Storm Modeling Results for Dowses Beach Area**

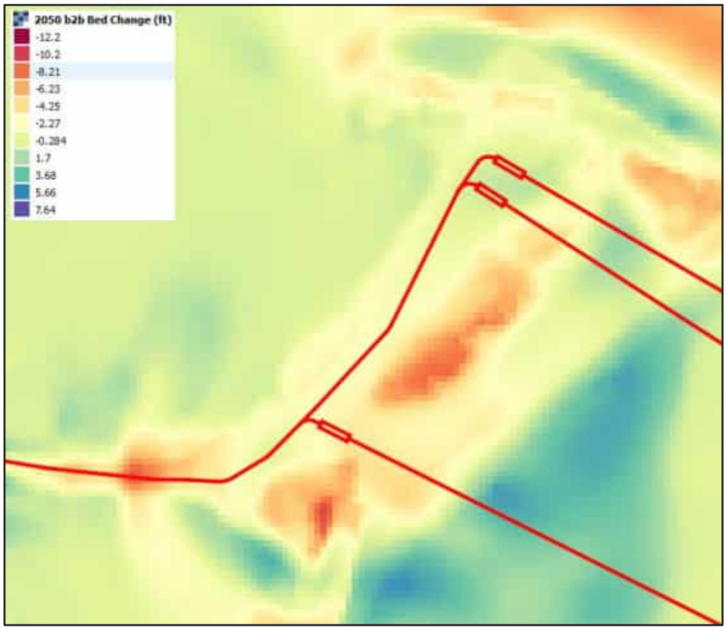



Figure 1 – Bed Level Change, 2050 Back-to-Back Storm Event Scenario

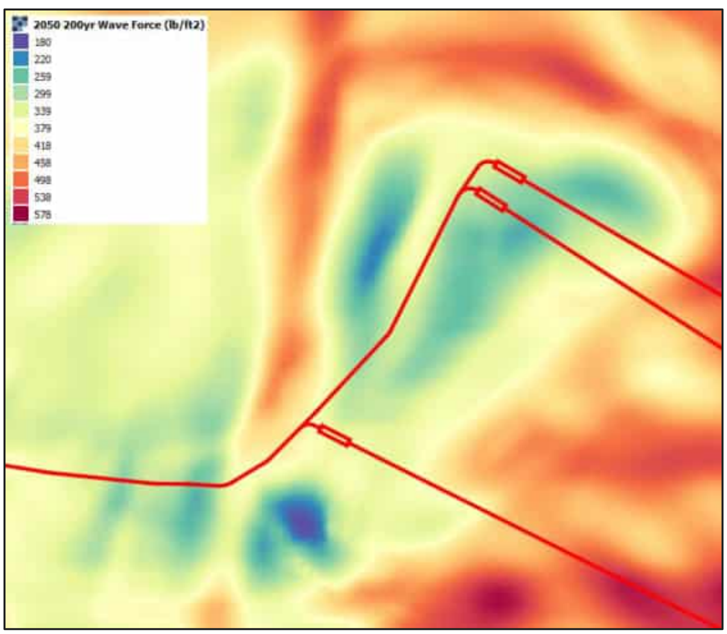



Figure 2 – Maximum Wave Force on Structure, 2050 200-Year Storm Event Scenario

## Engineering Evaluation of Infrastructure

***Transition Joint Bays in the Paved Parking Lot:***

A conservative (i.e., tending to overestimate the actual impact) interpretation of the erosion illustration (Figure 1) indicates the maximum erosion at the South Transition Joint Bay (vault) to be 3-4 feet at the east end of the vault. The North and Center vaults experience minimal (less than one foot) erosion or accretion. The maximum wave pressure illustration (Figure 2) indicates a force of 400 $lb/ft^2$ at the vault locations. The vaults included in the Project's current conceptual design are 8.5 feet in height and are placed 2 feet below grade. Each includes two access hatches that are connected to the vaults by extension collars. Erosion on the order of 3-4 feet would, therefore, leave up to the top 1-2 feet of the vault exposed during the 2050 storm event.

The vaults are planned to be sourced from a manufacturer as "precast" structures that will be assembled on-site. Precast vaults are robust in design with reinforced walls, tops, and bottoms. The vault manufacturer, who will serve as the vault Engineer of Record, will design the vaults and their internal reinforcement to resist the wave pressure and static pressure resulting from storm surge. Manufacturers will be contacted during the next phase of design to refine these details. At the Dowses Beach Parking Lot, the vaults will be installed within a temporary retention structure using sheet pile walls and a bottom seal slab.

South Vault – Conservatively assuming that the South vault, after the predicted erosion occurs, will not contain water, the weight of the current conceptual vault arrangement may be inadequate for resisting flotation. Sliding and overturning resistance provided by the remaining embedment appears to be adequate for the horizontal wave forces on the exposed sides of the vault.

The preferred solution for the South vault includes the following:

1. Lower the South vault elevation so that the vault top at or below the predicted erosion level.
2. Extend the vault extension collars to the accessways to accommodate this vault elevation change.
3. Anchor the South vault to the bottom seal slab and design the slab to resist floatation uplift forces.
4. Coordinate the vault manufacturer's design to accommodate the hydraulic pressure resulting from the 14.6 feet water level plus the downward wave pressure acting downward on the top of the vault.

The lower vault elevation is not anticipated to worsen storm impacts, as the infrastructure is not expected to be exposed.

The following two alternative designs are available, if needed for project optimization:

- Alternative A - Coordinate the vault manufacturer's design to:
    a. Accommodate the wave forces resulting from the 1-2 feet of vault wall exposure due to erosion.
    b. Accommodate the hydraulic pressure resulting from the 14.6 feet water level plus the downward wave pressure acting downward on the top of the vault.

   c. Anchor the vault to the bottom seal slab and design the slab to resist floatation uplift forces.

- Alternative B – Install a permanent sheet pile enclosure around the south vault. Stone or flowable backfill would be placed between the sheet pile and vault wall to prevent erosion below the top of the vault and limit exposure to wave forces. This alternate solution for permanent storm protection would include leaving below-grade sheet pile in place and removing any temporary bracing. All structures will be installed below grade. The only visible structure would be the two accessways.

North and Center Vaults – The North and Center vaults will be subject to a relatively minor degree of sediment accumulation or minor erosion. The vault manufacture's detail design will need to accommodate the hydraulic pressure resulting from the 14.6 feet water level and accretion. The current vault placement is acceptable to accommodate the modeled storms. However, the project engineering, procurement, and construction can gain efficiency with identical vault design and elevation.

The above design concepts will be further evaluated and refined in the ongoing project design process.

***Duct Bank:***

The RPS modeling analysis indicates that the duct bank alignment, as initially proposed in the paved parking lot at the landfall site, could potentially experience a maximum of 3 feet of erosion. Assuming the Project typical 3.5 feet installation depth of the current design, the duct bank would not be exposed and, therefore, not subject to lateral wave forces.

The RPS model shows that some portions of the Causeway would be exposed to higher degrees of erosion under extreme worst-case storm event conditions. To remedy concerns about these conditions, the duct banks can be either be lowered or fortified as follows:

- Erosion levels up to 7 feet – The Project design has already developed a duct bank detail intended for utility crossings that places the top of the duct bank 7 feet below grade. This design can be implemented for portions of the 3-conduit wide (W) x 4-conduit high (H) duct bank for erosion levels up to 7 feet. The lowered duct bank is not anticipated to worsen storm impacts, as the infrastructure is not expected to be exposed. The deeper excavation for duct bank installation will likely require additional dewatering measures; however, with an appropriate plan in place, the deeper excavation and additional dewatering are feasible.

- Erosion levels greater than 7 feet – RPS modeling identified an isolated potential maximum 8.9-foot erosion depth at the east end of the causeway under extreme worst-case storm event conditions. Since the duct bank cannot be lowered deeper than 7 feet, protection can be provided by permanent steel sheet pile on the sides of the duct bank and a structural concrete top slab just above the duct bank. Refer to Attachment 1.

.

***Duct Bank Transition to Culvert Crossing:***

Figure 1 indicates that erosion in the vicinity of the existing causeway leading to the landfall site could be a maximum of 3.25 feet; under these conditions, the duct bank, in a 3W x 4H conduit configuration, would not become exposed. However, to cross the existing culvert within the causeway, the duct bank conduit would rise and transition from a 3W x 4H to a 12W x 1H configuration on their approach to the hollow core slabs that bridge over the culvert, and in this location would have a limited depth of cover under the roadway pavement and would become exposed with the maximum predicted erosion. This duct bank transition can be protected from wave forces by an enclosure of PZ40 steel sheet pile walls and a 15 inch cast-in-place top slab. The sheet pile would form permanent sides of the excavation for installing the conduits with customary installation techniques. Once the duct bank construction is completed and any temporary bracing removed, the structural concrete slab would be placed directly on top of the duct bank conduits. As the duct bank rises as it approaches the bridge crossing, the top of the slab would be just below the bottom of the roadway pavement. The reinforced structural concrete slab will be designed to support roadway traffic loads and be secured by steel angle segments welded to the sheet pile.

As the conduits achieve the 12W x 1H configuration just before entering the hollow core slabs, the structural slab will be cast around the ducts with reinforcement above and below the conduit. The cross section is similar to the post-tensioning tendons of the hollow core section except that it will be a conventional cast-in-place slab with reinforcement. The cast-in-place slab spans transversely and is supported by the sheet pile sides of the permanent protection. Please refer to Attachment 1 for a graphical depiction of this concept.

The sheet pile would be installed a minimum 20 feet below all excavations. The sheet pile size and required temporary bracing for the construction will be determined during detailed design.

***Culvert Crossing:***

Over the existing culvert within the causeway, the conduits will be placed in precast concrete hollow core slabs that span over the culvert and are supported by new pile caps on each side of the culvert. The hollow core slabs and pile cap will form a structure, independent of and not connected to, the existing culvert. The ends of the hollow core slabs would be anchored and secured to the pile cap support with dowels placed between the plank joints and by end blocks on the pile cap to resist lateral and uplift forces. This new structure would allow for future repairs or replacement of the existing culvert while maintaining the conduits in place.

## Conclusion

This memo presents potential conceptual design enhancements to proposed Project infrastructure at the landfall site and along the proximate duct bank route that will enable the project to withstand the maximum predicted erosion, wave pressure forces, and storm surge indicated in the RPS coastal storm modeling analysis. We note that the modeled storm scenarios are very severe and would damage the coastline in many parts of Cape Cod and in Barnstable in particular, not just Dowses Beach. The predicted damage would be caused regardless of the project.

As a conservative measure, results of the 2050 coastal storm modeling analysis were used as the basis of the engineering evaluation since they presented the most severe conditions modeled during the project

**Reference: Engineering Evaluation of Coastal Storm Modeling Results for Dowses Beach Area**

design life and, accordingly, would result in the most conservative design. The RPS model results identified the following worst-case conditions to occur during the 2050 storm:

- Erosion Level – as high as 8.9 feet
- Storm Forces – as high as 250 to 400 lb/ft$^2$
- Water Level (sea level rise, tides, and storm surge) – as high as 14.6 feet

Based on engineering evaluation, the following potential design upgrades will enable the Project infrastructure to withstand the above predicted conditions:

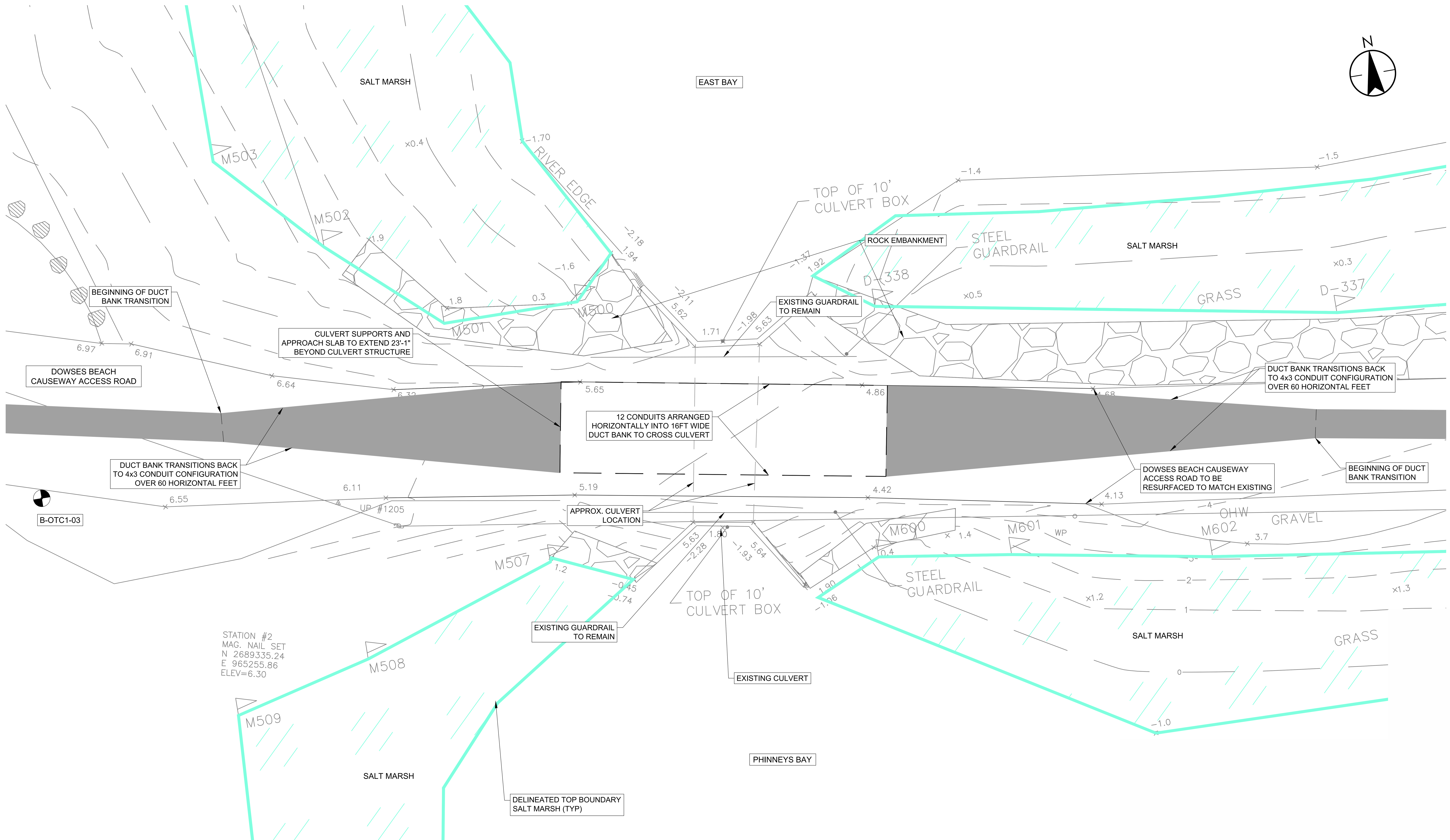
- Transition Joint Bays – The preferred design is to lower the South Transition Joint Bay below the modeled erosion level. This would not worsen storm impacts, as the infrastructure is not expected to be exposed.
- Alternate concepts, with the South Vault at its current elevation, include enhancing the vault structural design or installing the vault within a stone-filled sheet pile barrier. The North and Center Transition Joint Bays are not anticipated to require modification, either in design or placement.
- Duct Bank – Lower duct bank elevation below modeled erosion level, which would not worsen storm impacts, as the infrastructure is not expected to be exposed.
- Duct Bank Transition to Culvert Crossing – Install within sheet pile walls and secure with horizontal cast-in-place structural slabs,
- Culvert Crossing – Anchor and secure ends of the hollow core slabs to the pile cap support with dowels placed between the plank joints and by end blocks on the pile cap to resist lateral and uplift forces.

The above design concepts will be further evaluated and refined as the design progresses.

Respectfully,

**STANTEC CONSULTING SERVICES INC.**

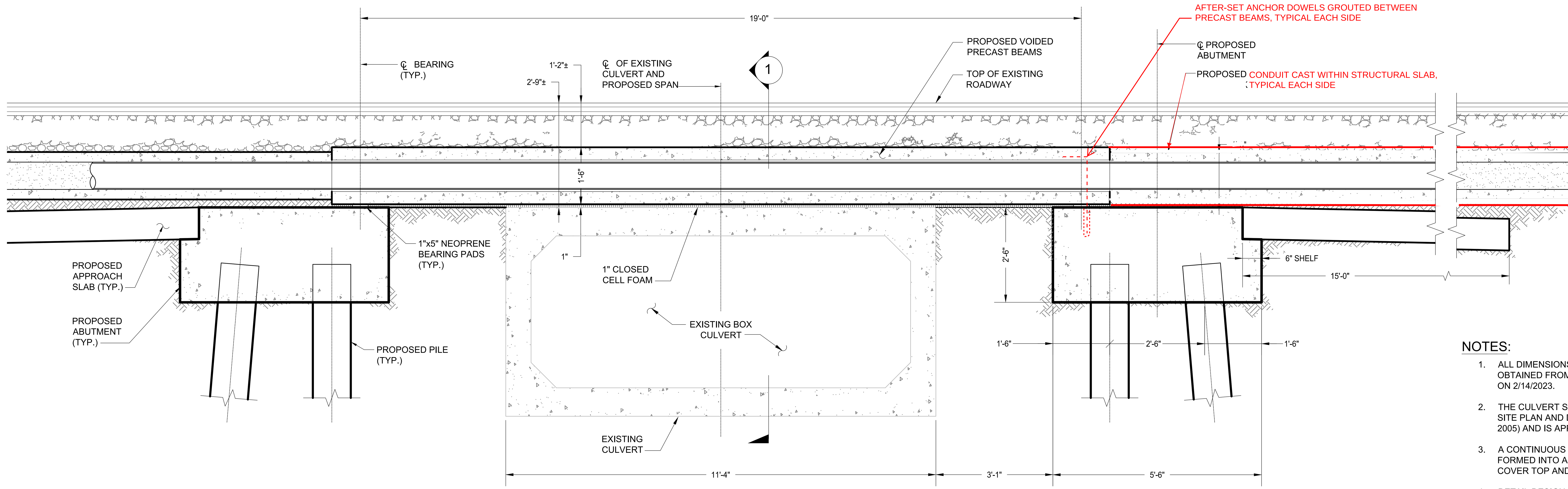
Attachment: Attachment 1 – Culvert Crossing & Duct Bank Transition




PLAN VIEW

SCALE: 1"=10'

# Attachment 1
# Culvert Crossing & Duct Bank Transition

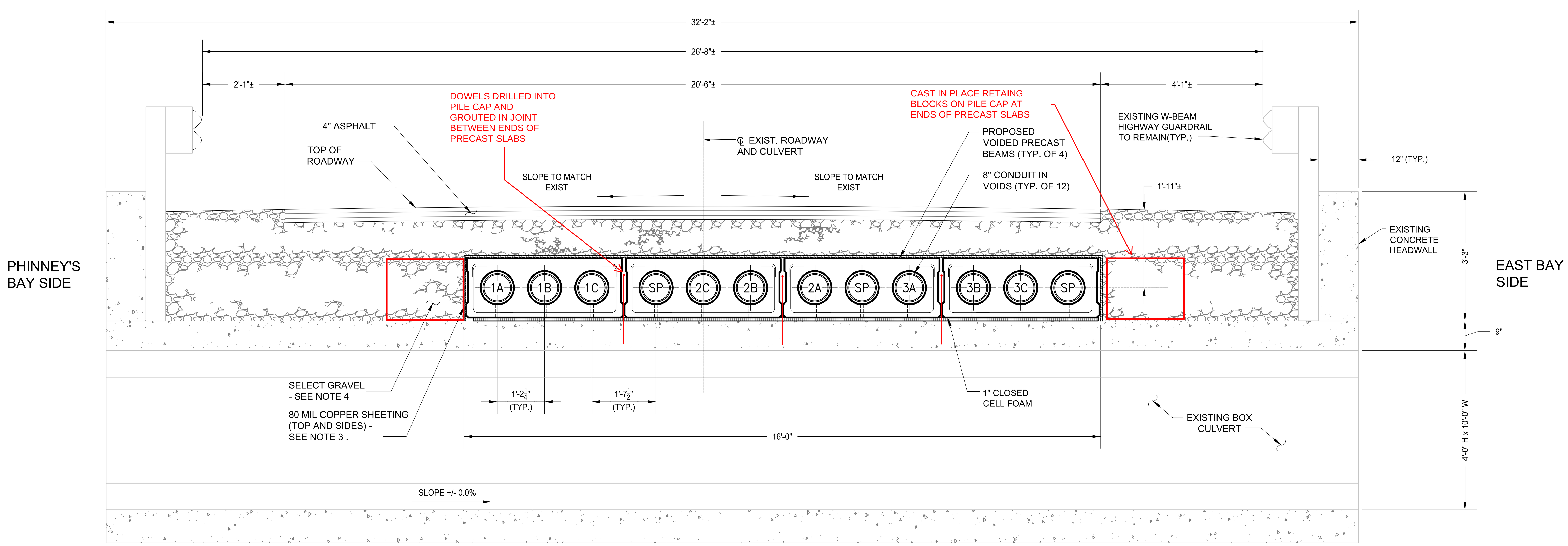



# LONGITUDINAL SECTION - PROPOSED STRUCTURE

SCALE: 1"=20"

## NOTES:

1. ALL DIMENSIONS OF EXISTING FEATURES WERE OBTAINED FROM FIELD MEASUREMENTS TAKEN ON 2/14/2023.
2. THE CULVERT SLOPE PROVIDED IS FROM DRAFT SITE PLAN AND DETAILS (DATED DECEMBER 2005) AND IS APPROXIMATE.
3. A CONTINUOUS METALLIC SHEET SHALL BE FORMED INTO AN INVERTED "U" SHAPE TO COVER TOP AND SIDES.
4. DETAIL DESIGN TO EVALUATE ANY REQUIREMENT FOR CATHODIC PROTECTION.




# 1 SECTION AT EXISTING CULVERT CROSSING

SCALE: 1"=20"


FINISH PAVEMENT
15" REINFORCED CONCRETE SLAB WITH TOP AND BOTTOM REINFORCING. BOTTOM BARS AND L WELDED TO SHEET PILE
VARIES
VARIES
DUCT BANK WIDTH AND HEIGHT VARIES ALONG TRANSITION
SECTION AT TYPICAL DUCT BANK
SECTION 1
CONTINUOUS SHEET PILE TO REMAIN IN PLACE
60'-0"
END OF TRANSITION
FLAT CONDUIT CROSSING OVER BOX CULVERT
START OF TRANSITION
END OF 3 OVER 4 DUCTBANK
11'-10 3/4"
PLAN
FINISH PAVEMENT
CAST IN PLACE REINFORCED SLAB WITH CONDUIT EMBEDED
SHEET PILE
L WELDED TO SHEET PILE FOR SLAB SUPPORT, TYP
BOTTOM BAR WELDED TO SHEET PILE, TYP
SHEET PILE
SECTION AT FACE OF HOLLOW CORE PLANK
SECTION 3
FINISH PAVEMENT
THICKENED CAST IN PLACE REINFORCED SLAB WITH CONDUIT EMBEDED
SHEET PILE
SHEET PILE
L WELDED TO SHEET PILE FOR SLAB SUPPORT, TYP
BOTTOM BAR WELDED TO SHEET PILE, TYP
SECTION AT TRANSITION FROM CONDUIT BELOW TO WITHIN REINFORCED SLAB
SECTION 2
CONDUIT IN DUCT BANK WITH STRUCTURAL SLAB ABOVE
THICKENED SLAB WITH REINFORCING TOP AND BOTTOM AND CONDUIT WITHIN SLAB
60'-0"
FLAT CONDUIT CROSSING OVER BOX CULVERT
START OF TRANSITION
END OF TRANSITION
GRADE
0.00
END OF 3 OVER 4 DUCTBANK
BRIDGE CROSSING
-2.00
DUCTBANK CENTERLINE
-4.25
SEC 2
SEC 3
SEC 1
ELEVATION
ORIGINAL SHEET - ANSI D