APPENDIX V

STORM RESPONSE SIMULATION

Delft3D Storm Response Simulations
With and Without a Terminal Groin

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Introduction

A calibrated, depth-averaged Delft3D model was utilized to predict the physical performance of the terminal groin following passage of a low-frequency tropical storm event. The model was run for both with- and without-terminal groin conditions in order to draw relative conclusions on storm response. Both scenarios include the placement of approximately 1.2 Mcy of beach nourishment and simulate beach conditions following or concurrent with project construction. Spatial distribution of the beach fill varied between scenarios according to specific project needs. Both models consider the existing sand-filled geotextile tube groins. The storm-response results suggest that the terminal groin improves the performance of the placed beach nourishment sand without causing significant negative impacts to the downdrift shoreline.

The terminal groin is modeled as "leaky" using porous plates which are by definition infinitely high, semi-permeable numerical structures. The permeability of porous plates is numerically controlled by a friction term which was set to 4.5 for these simulations, roughly representing a level of permeability between about 10 and 30 percent. The existing tube groins are described as thin dams in the model, which act as impermeable, infinitely high barriers to sediment transport.

Storm conditions simulated in the model are similar to those identified during the June 10-14, 1996 passage of Hurricane Bertha. The model does not seek to expressly model Hurricane Bertha, and damages caused by local high winds and inland flooding are not described in the model. Rather, the tropical event simulated herein is akin to a Bertha-like event. Hurricane Bertha was, at its peak intensity, a Category 3 storm which made landfall as a Category 2 storm in the immediate vicinity of Bald Head Island. Hurricane Bertha's track is mapped in **Figure 1**.

Waves, Water Levels, and Bathymetry

The storm model was run in real time, for the 4 day period June 10 - 14, 1996. A time series detailing significant wave height, wave period, wave direction, and wind velocity for this time period were obtained from data published by the U.S. Army Corps of Engineers Wave

Information Studies (WIS). Specifically, data from offshore WIS station 63320 were used. The location of this station is shown in **Figure 1**. WIS station 63320 is very near both the seaward row of the numerical wave grid and the NOAA buoy used to generate input conditions for the calibrated long-term morphological model. As such, the WIS time series data were input directly into the model as-is. The offshore wave time series is plotted in **Figure 2**. Hurricane Bertha represents the third largest wave heights in the 20-year WIS record covering the period 1980-1999.

A time series of measured water levels for this period was specified using tide data collected at Oak Island, NC. Hourly tide measurements were obtained from NOAA's National Ocean Service station 8659182, which is located in the Atlantic Ocean off Oak Island, NC. The hourly water level time series used for model input is plotted in **Figure 3**.

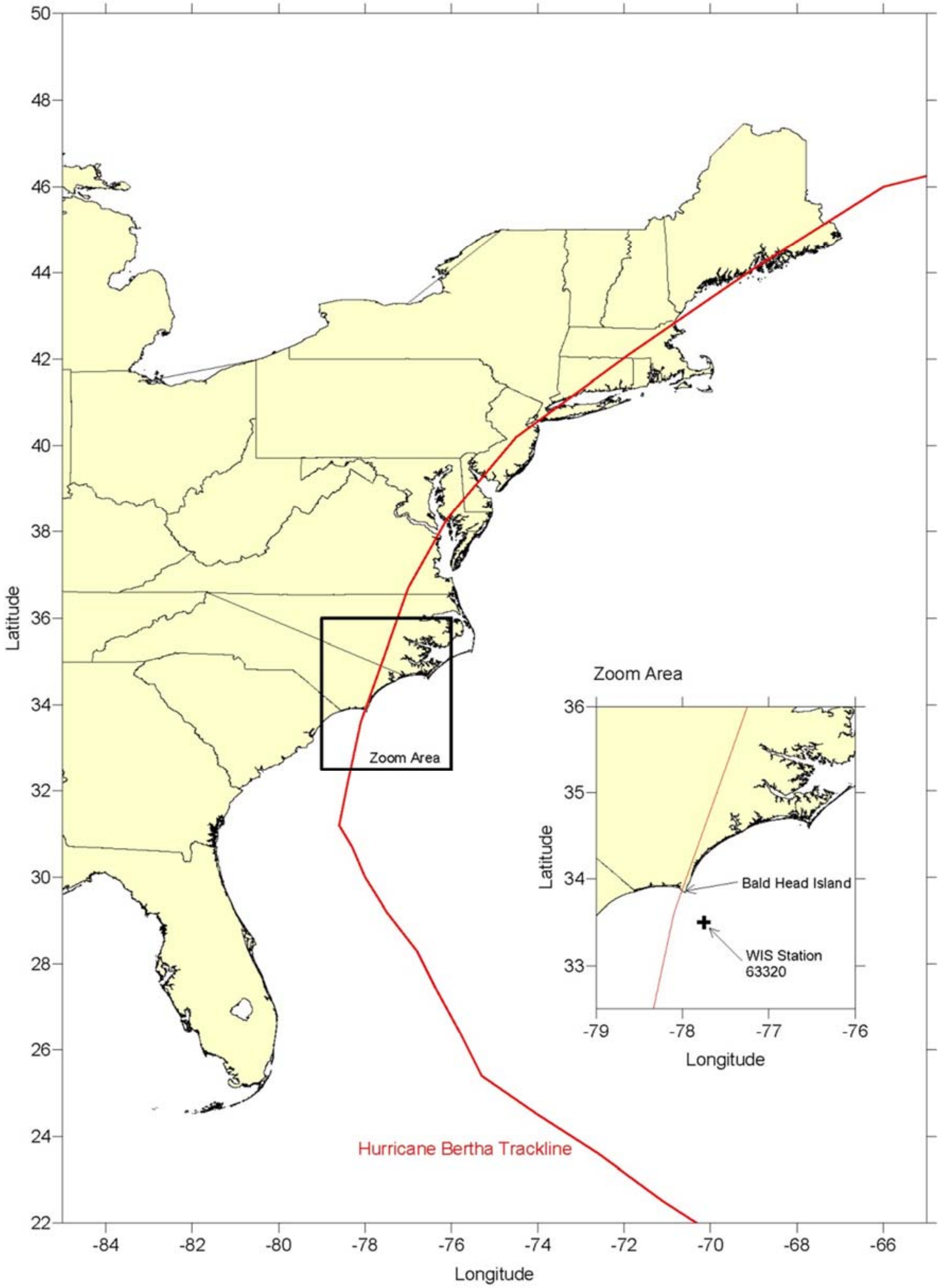

Figure 1: Track of Hurricane Bertha (1996).

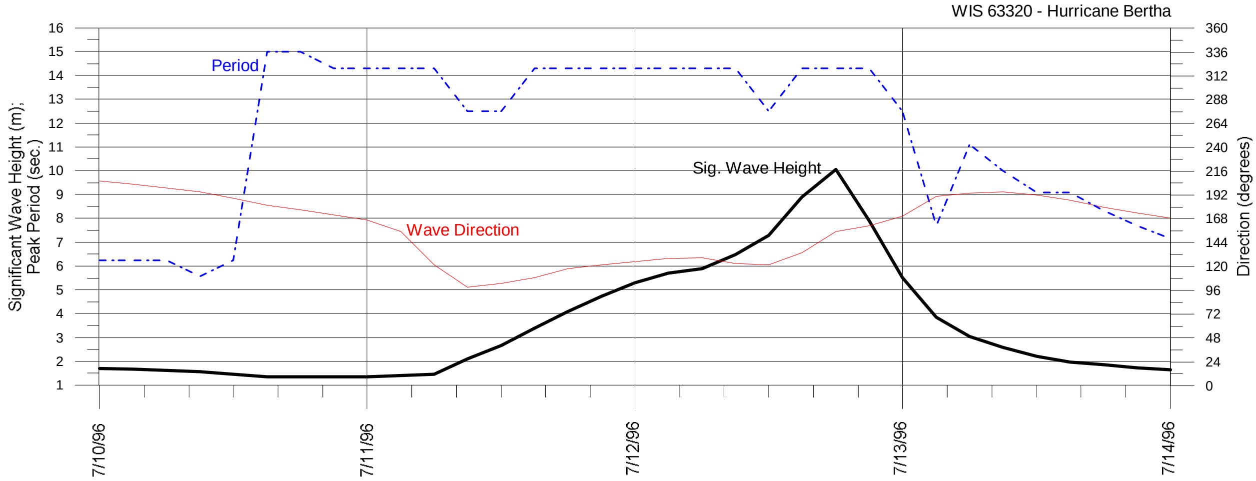

Figure 2: Input offshore wave time series obtained from WIS Station 63320.

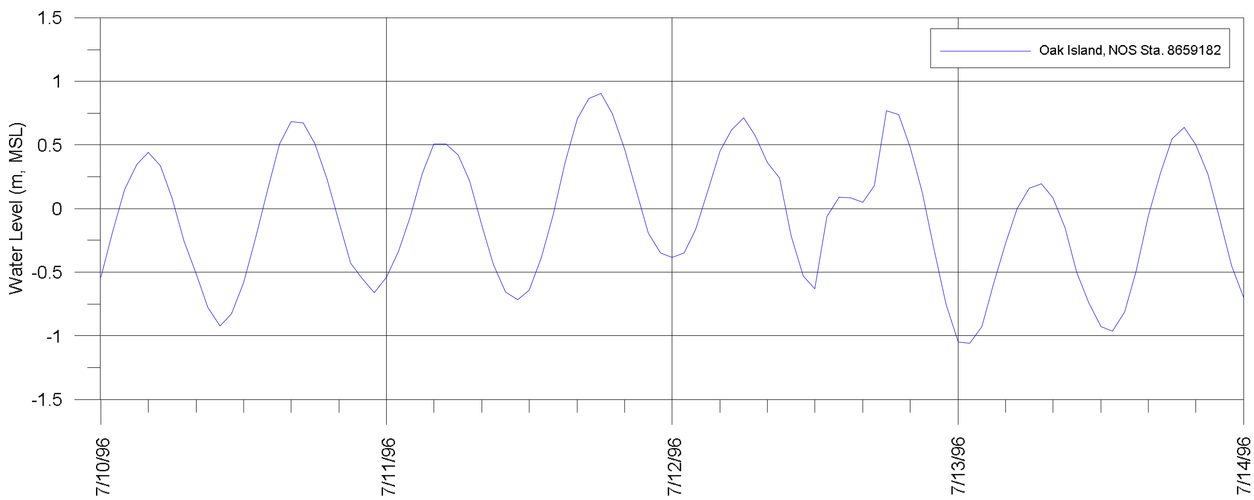

Figure 3: Input water level time series obtained from NOS Station 8659182, Oak Island, NC.

Figure 4 depicts the input bathymetry for the beach fill only condition (without terminal groin). This modeled scenario represents a typical sand placement (disposal) project along Bald Head Island. The project includes placement of about 1.2Mcy of sand extending from the Point eastward to about Station 166+00. A typical nourishment event of this volume will bury, and deactivate, the existing tube groins. The beach fill only scenario was run as a baseline condition in order to form the basis for relative comparison to the terminal groin (with fill) simulation.

Figure 5 plots the input bathymetry for the semi-permeable terminal groin scenario. The modeled bathymetry includes placement of a similarly sized beach fill placement project. The 1.2Mcy nourishment is distributed from the terminal groin to about Station 130+00 where it begins to taper into the existing profile. The distribution of the fill increases in sectional density towards the west in order to pre-fill the fillet along the updrift side of the terminal groin.

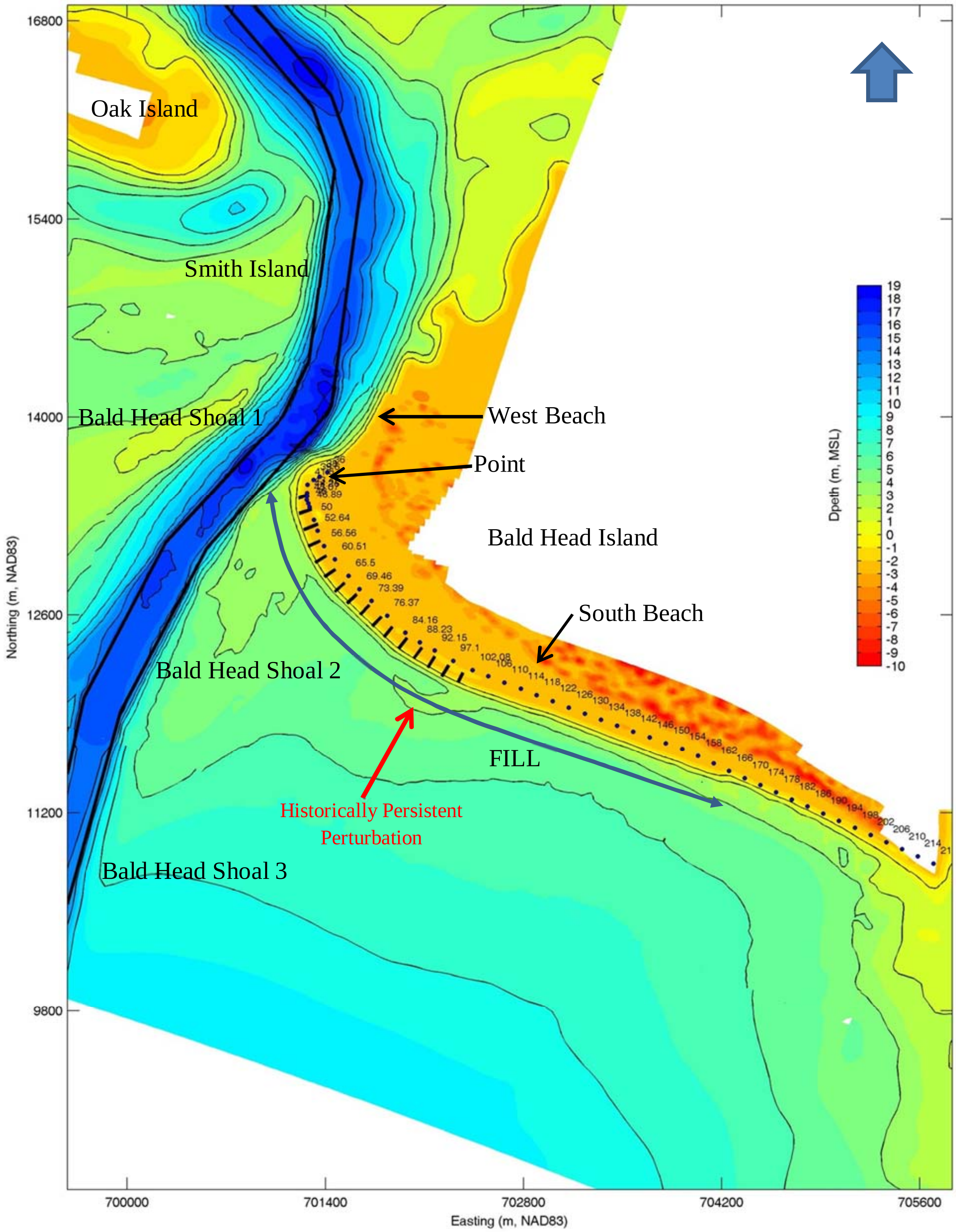

Figure 4: Nearshore bathymetry used for model input in the beach fill only simulation.

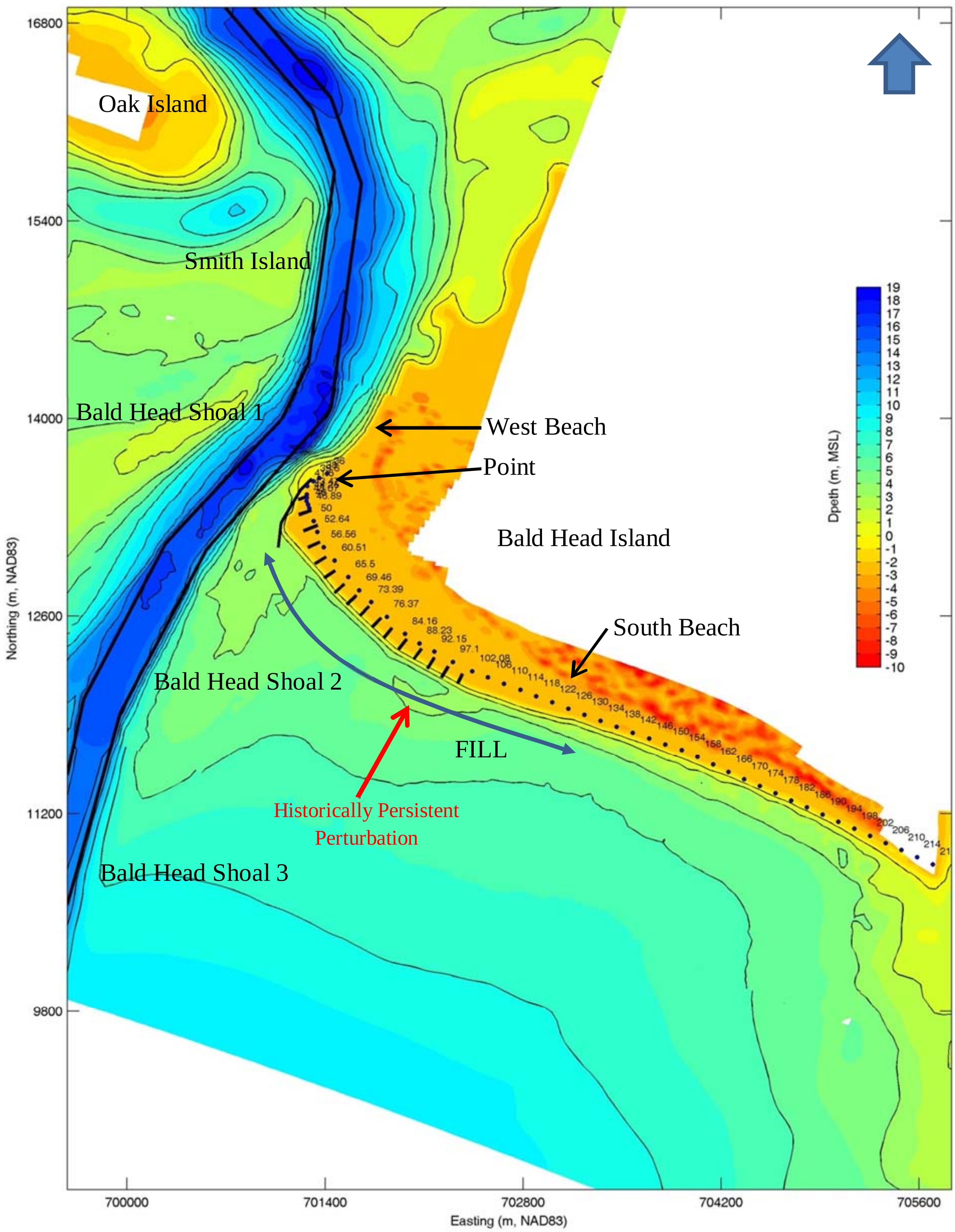

Figure 5: Nearshore bathymetry used for model input in the semi-permeable terminal groin simulation.

Model Results

Figures 6 and **7** present cumulative erosion and sedimentation patterns predicted for both without- and with-terminal groin simulations, respectively. Blue shading represents sedimentation (accretion) whereas red/yellow shading represents erosion (seabed deflation). The vectors on each plot describe mean total sediment transport over the four day simulation and are scaled identically for both with- and without-terminal groin conditions. **Figure 8** directly compares cumulative erosion and sedimentation magnitudes without mean transport vectors for increased readability. The beach fill only condition is shown on the top pane of the figure with the terminal groin result below.

Under both scenarios there is a storm-induced acceleration of transport, and subsequent erosion, immediately updrift (east) of the geotextile groin field. This is suggestive of an erosional "hot spot" which results in transport off the beach with deposition just offshore of the eastern tube groins. This pattern has been verified by field observations and is generally accurately predicted by the model. Further, the bathymetric record suggests a persistent sandy, subaqueous perturbation extending seaward at this location (demarked by a red arrow in **Figure 4**) which precedes the tube groin field and likely evidences previous erosion/accretion events like that described above.

Both simulations predict storm-related cross-shore equilibration of the south-facing (South Beach) shoreline. This is reflected by the blue shading immediately offshore of the intertidal beach. It is characteristic of sandbar formation commonly measured by survey along Bald Head Island. The western extent of sandbar formation differs between the two results, however. In the beach fill only condition, sediment is not deposited in the nearshore zone in the far western reaches of the tube groin field. The shoreline here is oriented nearly north-south and the model indicates accelerating erosion towards the inlet with no formation of a stabilizing bar. Eroded sediments are deposited into the inlet channel or large shoal off the Point and are ultimately lost from the island's littoral system.

With the terminal groin in place, however, there is relatively uniform sandbar formation throughout the project area along with predicted impoundment eastward of the structure. There is very little sediment movement predicted in the lee (west) of the terminal groin, excepting a localized area of erosion associated with a northward push of the existing Point sediments.

Both simulations predict storm-induced shoaling within the navigation channel, principally in the central portion of the Bald Head Shoal 1 cut. This shoal feature is much more spatially expansive under the fill only condition. The addition of the terminal groin appears to result in localized focusing of transport off the seaward end of the structure towards the channel. This process appears to greatly reduce the migration of the Point shoal towards the channel during the simulated storm event but results in some level of temporal scour at the seaward tip of the terminal groin, as expected.

In the beach fill only scenario with no terminal groin, the model indicates an acceleration of erosion throughout the western end of the tube groin field. The seabed erosion accelerates further north of the last groin. This suggests a strong possibility for failure of said groin, particularly considering the fact that the model describes conditions immediately after fill placement when the beach is technically at its least vulnerable. Increased erosion and recession along the Point is wholly consistent with observations from monitoring conducted over the last 10 years.

The simulations additionally suggest that the addition of the terminal groin results in an overall lower rate of sediment transport along the western South Beach shoreline of Bald Head Island. This is primarily associated with a reduction of the shoreline angle relative to the incident wave direction via prefilling the terminal groin. The apparent eastern extent of the “hot spot’’ at the east end of the groin field is potentially reduced by about 2,400 feet (+/-) under the with-terminal groin scenario (though some of this apparent benefit may be related to differences in the fill sectional densities between the two alternatives). The Point continues to migrate northward under both with- and without-terminal groin scenarios via erosion of its southern beach and subsequent deposition of this sediment further north, towards West beach (see **Figure 8**).

An accounting of sand lost within the respective areas of fill placement suggests that the addition of the terminal groin reduces net volume losses within the construction template by about 57 percent over the beach fill only condition (without terminal groin). More specifically, the construction template in the fill areas lost, in the net, about -97,400 cy without the terminal groin versus approximately -55,350 cy with the terminal groin. The fate of the higher losses from the beach fill only scenario is predominantly manifest as deposition north and west of the Point. Previous numerical analysis and physical monitoring observations suggest that this sand is effectively lost from the beaches’ littoral system to the navigation channel.

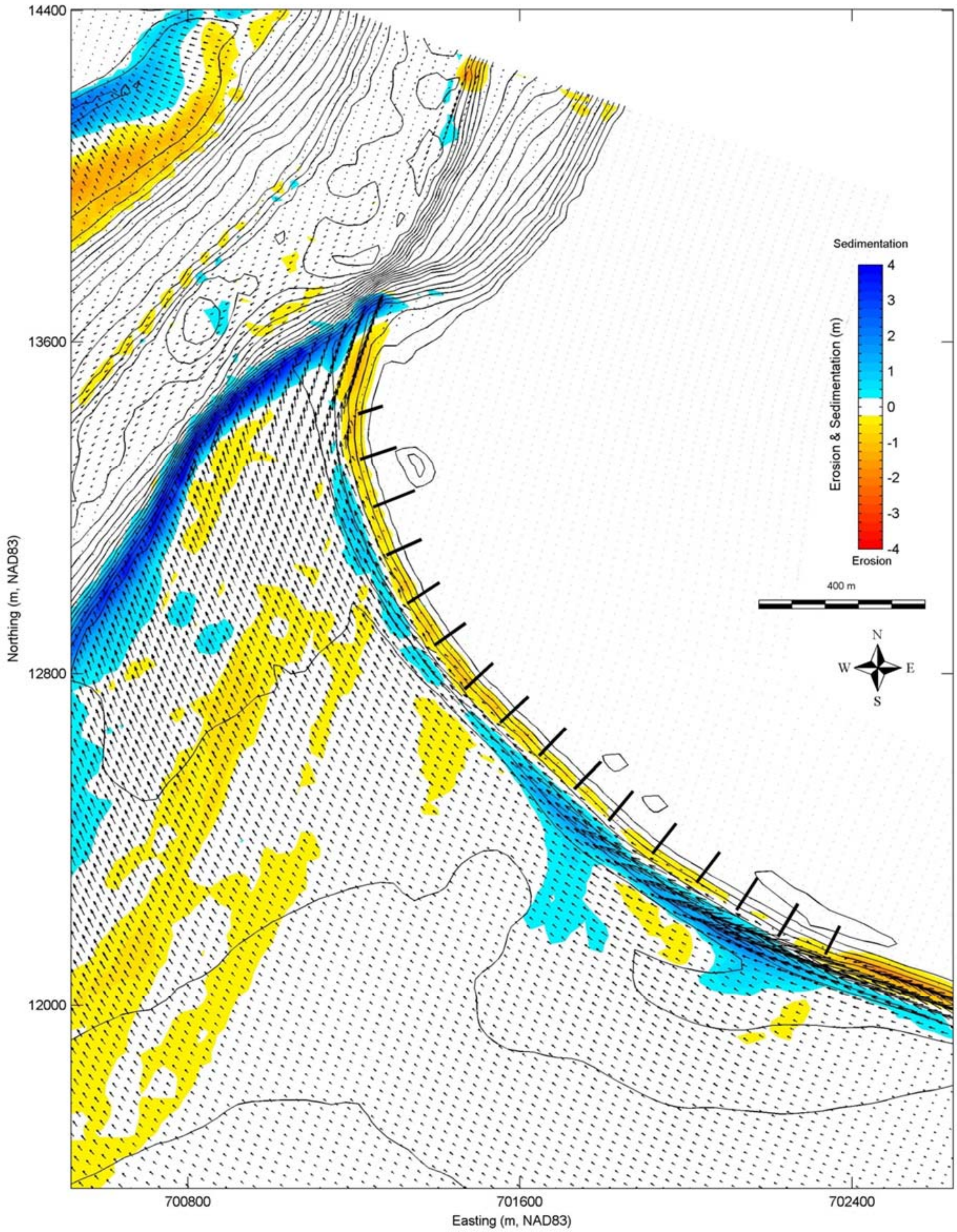

Figure 6: Cumulative sedimentation and erosion patterns and mean transport directions for the beach fill only condition following a Bertha-like tropical storm event.

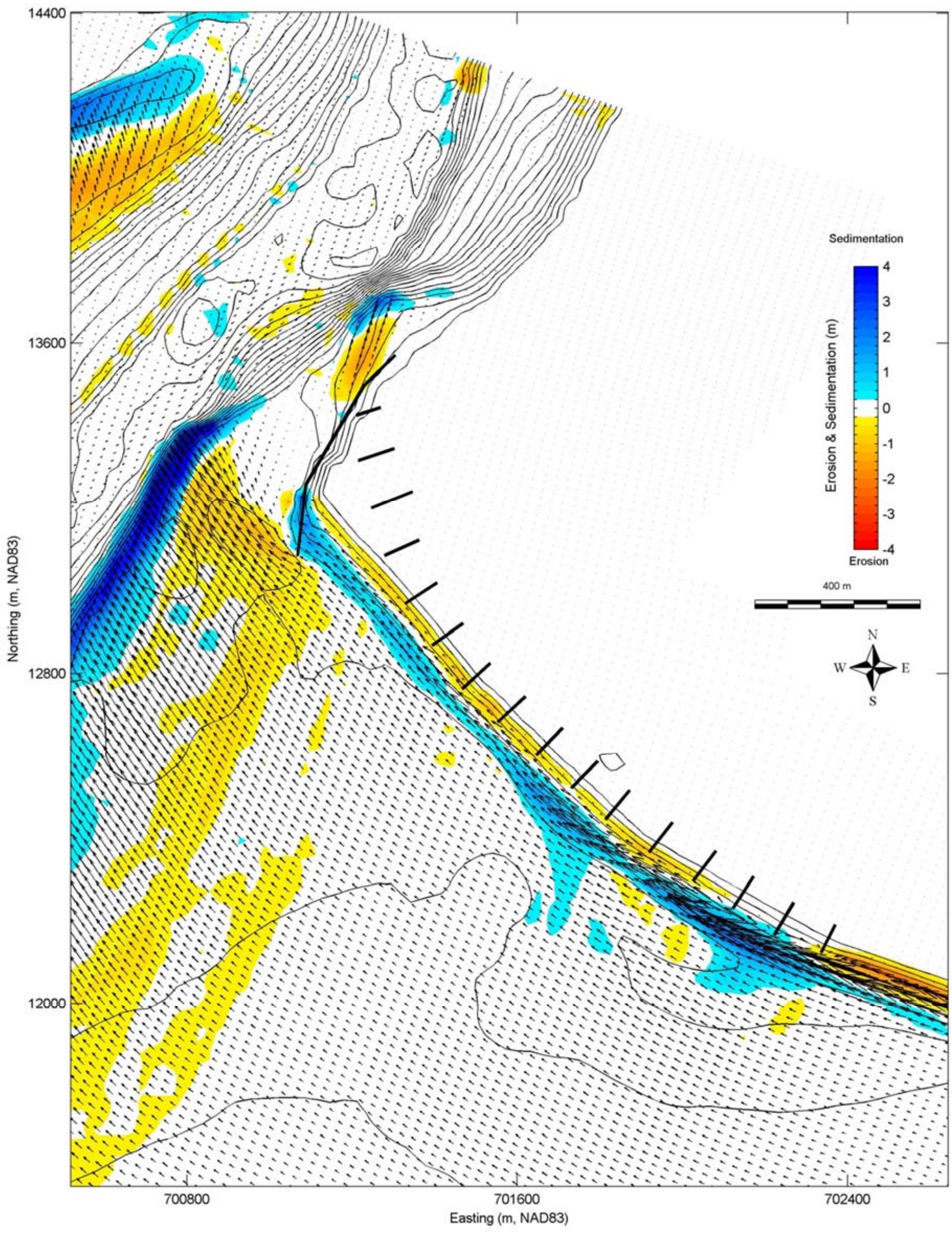

Figure 7: Predicted cumulative erosion and sedimentation patterns and mean transport directions for the with-terminal groin simulation following a Bertha-like tropical storm event.

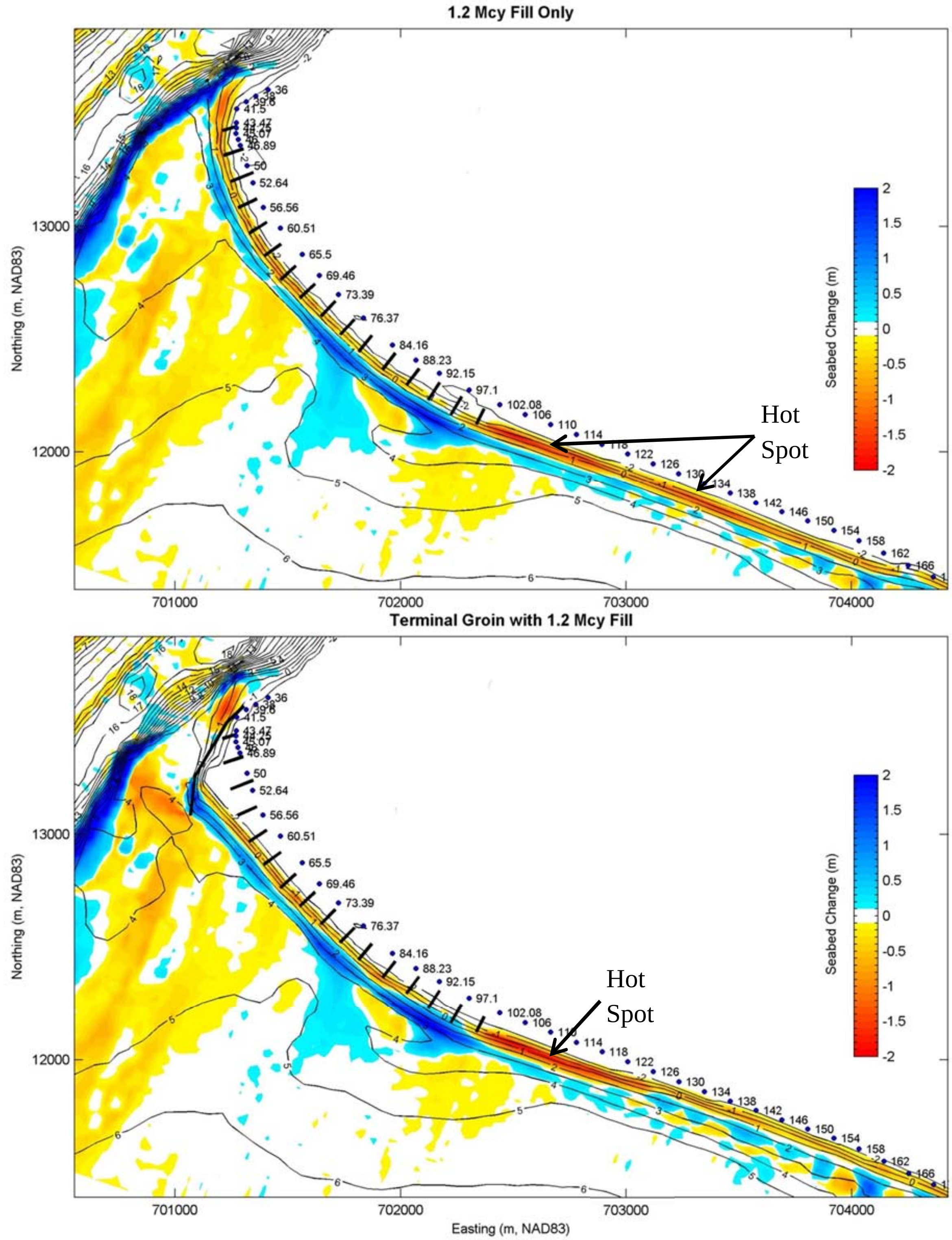

Figure 8: Predicted cumulative erosion and sedimentation patterns following a Bertha-like tropical storm event. Upper – without terminal groin; lower – with terminal groin.

The model results indicate an increase in sediment transport at the seaward tip of the terminal groin along with some scour at the tip of the jetty – as intuitively expected during the storm event. Longer term model simulations performed for the broader analysis of the terminal groin indicate a marked decrease in channel shoaling following construction of the terminal groin, particularly within the Bald Head Shoal 1 cut. The results of this storm simulation indicate that the apparent increase in transport towards the channel (at the structure's seaward end) is beneficially offset by a decrease in transport into the channel at the Point. The latter has been documented as an area of historically persistent shoaling.

Figure 9 plots the difference between the post-storm (final) bathymetries predicted under with and without terminal groin conditions. Yellow and red shading in the figure indicates areas where the seabed is lower due to the terminal groin and its corresponding beach fill, while blue shading represents a raised seabed attributable to the terminal groin and its fill. The dark blue fillet in the upland -- east of the terminal groin -- includes the beach fill sand that was initially added to pre-fill the terminal groin. Further seaward, the blue shading represents beneficial impoundment of material and/or deposition owing to reduced sediment transport rates along South Beach following terminal groin installation. The direct impoundment effect of the terminal groin appears to extend eastward to about Station 66+00 thence tapering off in magnitude until about Station 76+37. Much of the yellow shading in the lee (west and north) of the terminal groin represents reduced accretion and shoaling relative to the beach-fill only (no groin scenario. The model does suggest increased erosion along a small area at the landward end of the terminal groin, which is not unexpected. This is manifest as a modest increase in shoreline recession. The model results do not indicate any volume changes attributable to the terminal groin along West Beach, north of the Point.

As noted above, some of the differences in the project performance depicted in **Figure 9** reflect requisite differences in the initial beach fill geometry for the with- and without-terminal groin scenarios. **Figure 10** numerically removes these differences. That is, Figure 10 depicts the residual differences in the post-storm seabed elevations between the with- and without-terminal groin cases after accounting for (subtracting) the differences between the two cases' initial beach fill elevations. Again, yellow shading indicates areas where the post-storm seabed is lower due to the terminal groin – and blue shading indicates areas where the post-storm seabed is higher due to the terminal groin – relative to the beach fill only (no terminal groin) scenario. The direct effects of the terminal groin upon the beach and beach fill are evident in **Figure 10**. There is a net, substantial increase in sand volume retained along the west end of South Beach – within 750 meters updrift of the terminal groin. This is manifest as a reduction in erosion along the shoreline (blue band closest to land), cross-shore equilibration of sand placed and retained near the terminal groin (yellow/blue band in the middle of fillet), and some accumulation of sand at the terminal groin (blue band near the end of the terminal groin). At the same time, there is a reduction in sand volume that would otherwise accumulate along the Point and seabed nearest the channel (yellow/red areas westward and north of the terminal groin). Overall, reclaiming the shoreline under the terminal groin scenario results in a seaward shift of the beach equilibration process.

Figure 11 compares the approximate post-storm mean sea level (MSL) contours for with- and without-terminal groin conditions. Because Delft3D is a volume based model, the precise location of a tidally referenced shoreline should not be interpreted literally. That is, the Delft3D model predicts changes in seabed volumes, not shoreline locations. Comparatively speaking, the model results indicate the shoreline along South Beach remains much further seaward and more stable with the terminal groin relative to the beach fill only condition. This is attributable to the differences in placement of the initial nourishment and the ability of the terminal groin to quasi-stabilize the sand fill while impounding additional material.

The model suggests a localized difference in post-storm shoreline position at the Point, in the lee of the terminal groin. Specifically, a modest amount of additional Point shoreline recession is predicted under the with-terminal groin condition. This additional shoreline recession is not predicted to propagate north of the Point onto West Beach; that is, the predicted post-storm shorelines are identical along this area. The model suggests that post-storm net volume loss associated with the reduction in sediment supply to the Point under the leaky terminal groin scenario is about -5,100 cubic yards.

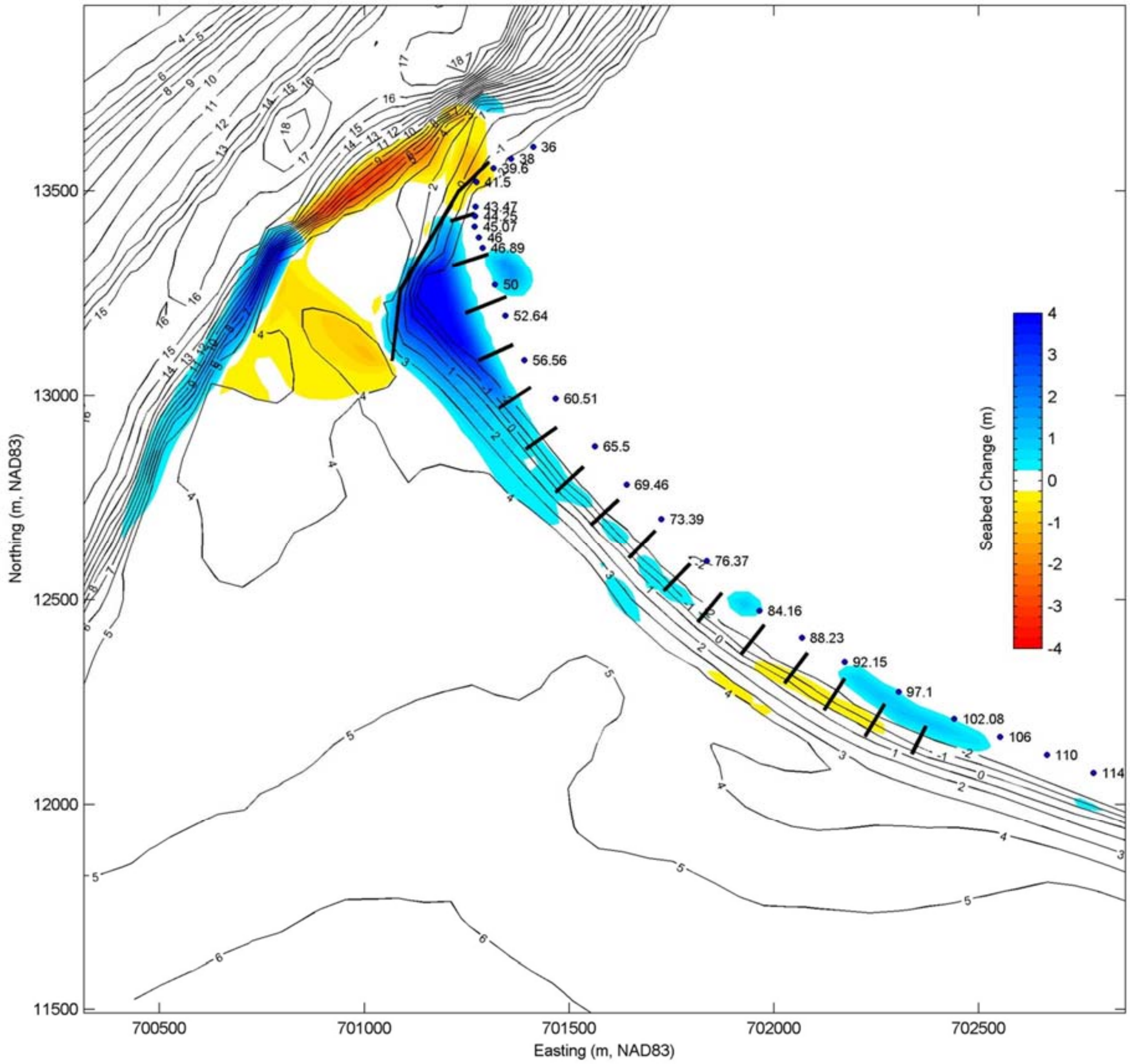

Figure 9: Predicted seabed differences attributable to the terminal groin following a Bertha-like storm event -- computed as the difference between post-storm (final) bathymetries for with- and without-terminal groin conditions. The effects of different initial beach fill geometries are included in the figure. Post-storm bathymetric contours are shown for the with-groin scenario and indicate that sediment was impounded by the terminal groin during the simulation.

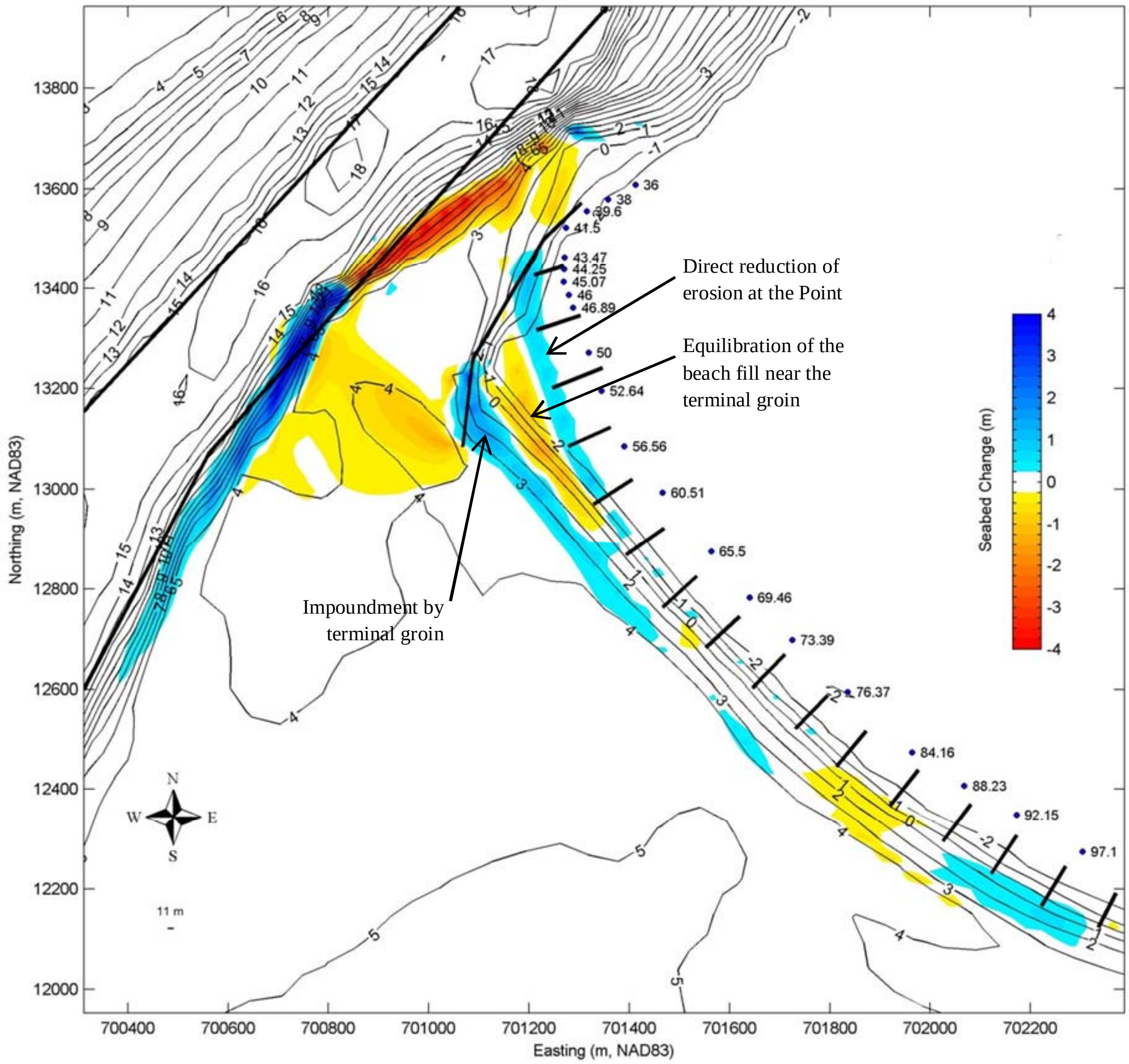

Figure 10: Predicted changes in the seabed attributable to the terminal groin following a Bertha-like storm event. Differences in the initial beach nourishment (between "with-groin" and "no terminal groin" scenarios) have been numerically removed from the results.

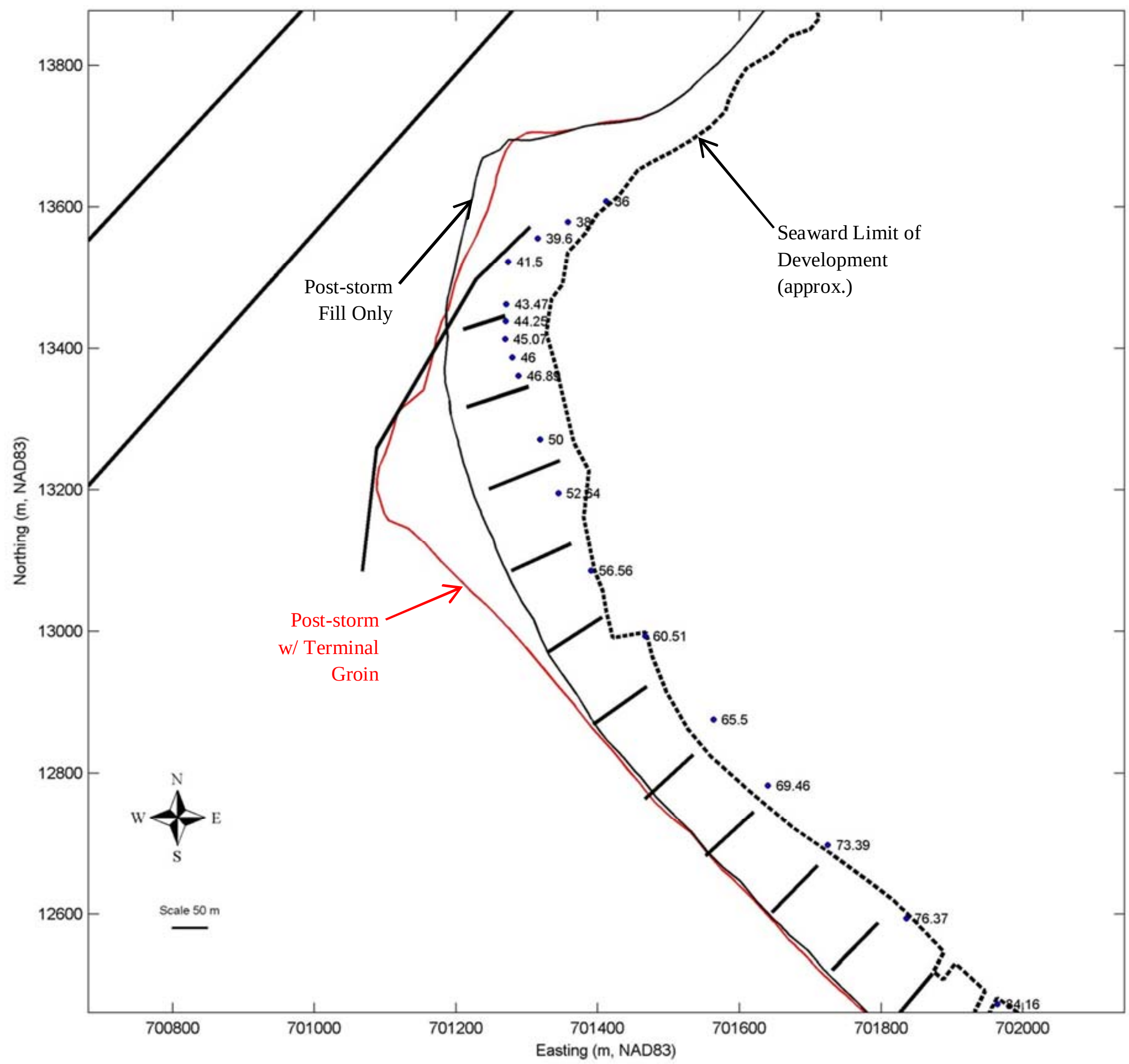

Figure 11: Approximate MSL shoreline response to a Bertha–like event for with- (red line) and without-terminal groin (black line) conditions.

Effect of Tube Groins

The scenarios described above were rerun to simulate the removal of all of the existing sand-filled tube groins along western Bald Head. The results were then directly compared to the "with tube groin" scenarios (described above) in order to determine the relative effect of the tube groins. All other parameters and initial conditions in the model remain the same. **Figure 12** compares the cumulative erosion and sedimentation patterns predicted under with and without tube groins for the beach fill only scenario (i.e., 1.2Mcy initial beach fill and no terminal structure). Vectors in the plots are identically scaled in both panes and represent mean total transport. An analysis of the volume change along Bald Head suggests that without the tube groins, the project is predicted to experience a net loss of approximately -105,300 cy within the limits of fill placement. In comparison, with the tube groins in place, the same fill limits were predicted to experience a net loss of about -97,400 cy, with the differences representing a direct benefit of the tube groins. Additional fill volume retained by the groin field is expectedly subtle in this simulation for two primary reasons:

- The initial bathymetry used as model input describes a post-nourishment condition which mostly buries the groin field thereby limiting the groins' exposure to incident waves, and
- The storm simulation is short in duration yielding less time for 'activated' structures to trap sediment once exposed by erosion.

That is, initiation of the storm simulation on an eroded beach (where the tube groins are initially exposed) would result in a proportionally larger effect (benefit) from the groins. Under this condition, the groins' ability to interrupt the alongshore transport of sediment would likely increase the downdrift erosion attributable to the groin field as well. The latter process is presently observable at the Point, immediately west of the tube groin field.

Figure 13 plots the difference between the post-storm (final) bathymetries predicted under with and without tube groins for the nourishment only condition. Yellow and red shading in the figure indicates areas where the seabed is lower due to the tube groins, while blue shading represents a raised seabed attributable to the tube groins. The results suggest a minimal lowering of seabed elevation at the Point and a modest decrease in material shoaling the channel due to the presence of the tube groins. Near the eastern limit of the groin field, however, the model predicts more significant differences in seabed elevation attributable to the tube groins. The model results suggest that the groin field physically interrupts the predicted nearshore erosional gradient extending east of about Station 92+15 (a historically erosional area), see **Figure 12**. The result is a predicted elevation increase across the easternmost three tube groins; i.e., retention of westerly-driven transport. The apparent seabed deflation immediately adjacent (west of) Station 92+15 due to the tube groins represents a decrease in sedimentation in the area where eroded sediments are deposited in the without tube groin model (Sta. 76+37 to 92+15).

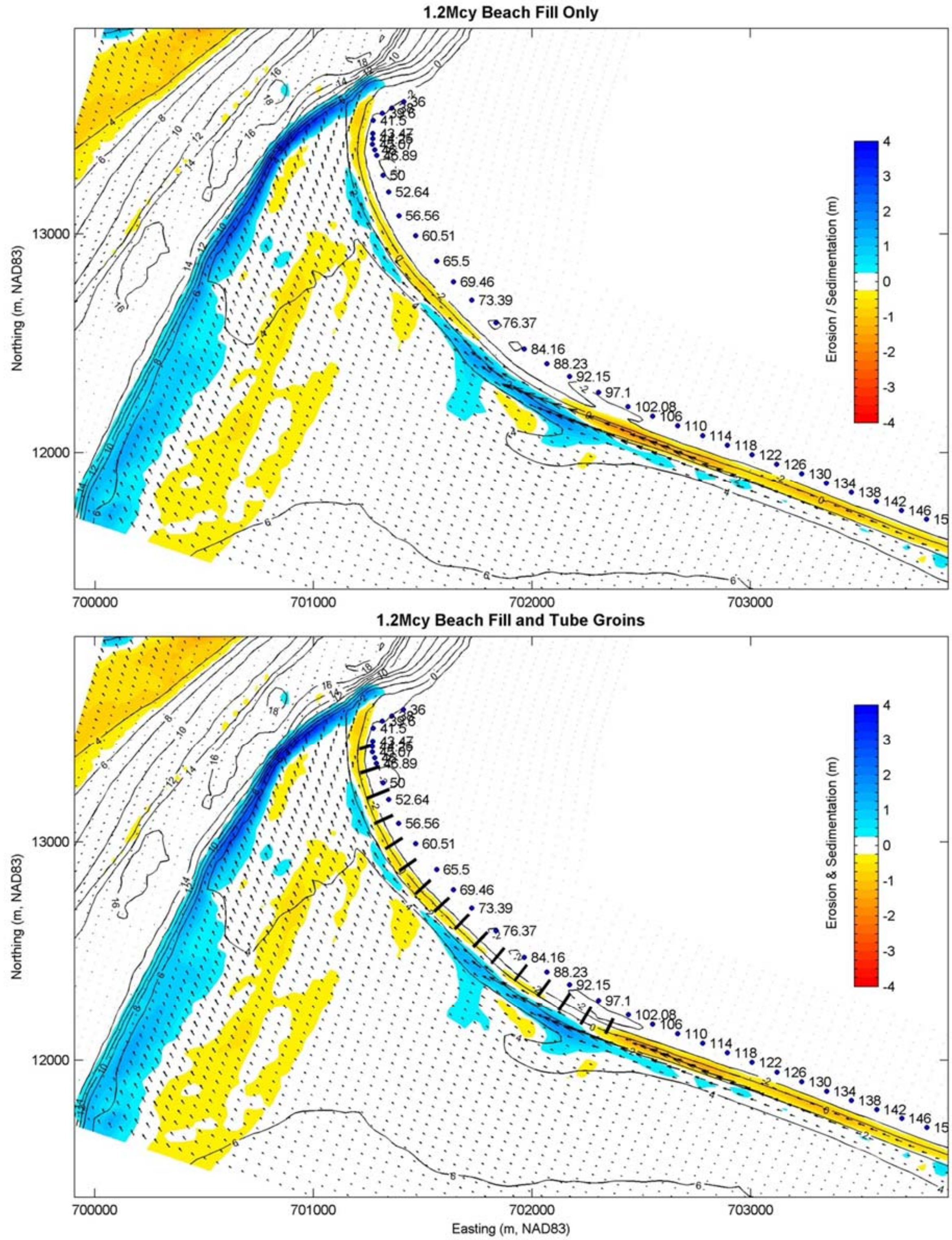

Figure 12: Comparison of predicted erosion/sedimentation patterns considering with and without the tube groins under the fill only scenario.

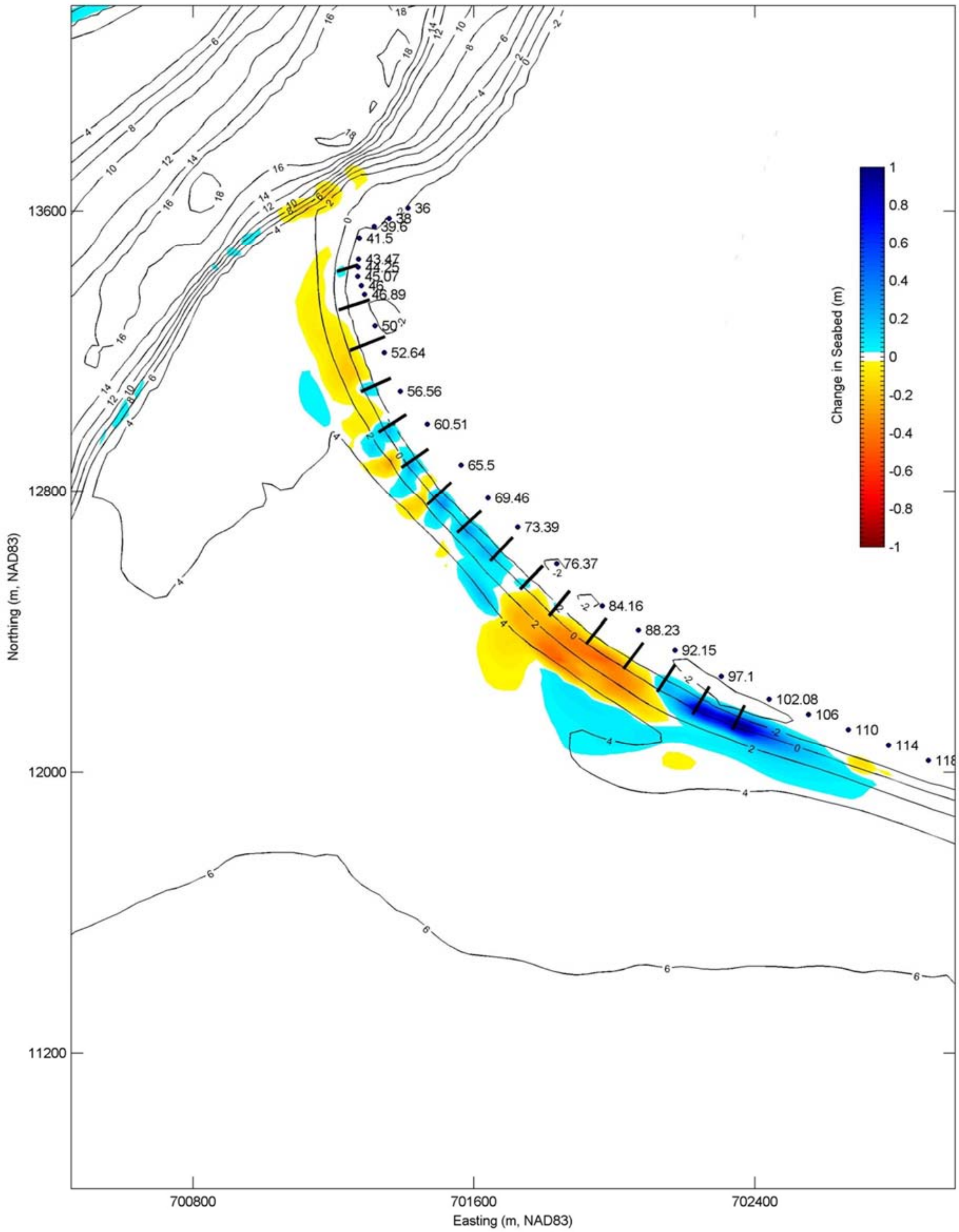

Figure 13: Predicted seabed differences attributable to the tube groins following a Bertha-like storm event following a 1.2Mcy fill -- computed as the difference between post-storm (final) bathymetries for with- and without-tube groin conditions. Yellow and red shading in the figure indicates areas where the seabed is lower due to the tube groins, while blue shading represents a raised seabed attributable to the tube groins.

Similar model simulations investigating the effects of inclusion and removal of the tube groins were completed for the with-terminal groin condition. **Figure 14** compares predicted erosion and sedimentation patterns under terminal groin with beach fill scenario both with and without the sand-filled tube groins. In the plots, yellow/red shading represents areas of erosion while blue shading represents sediment deposition resulting from the four-day storm. Overall, there are only minor differences in the predicted sediment transport pathways when the groins are not considered. Specifically, the presence of the tube groins appears to slightly slow sediment transport along western Bald Head Island. This is observable as moderate differences in color shading, particularly lesser shades of red/yellow east of the groin field and extending westward off the seaward end of the terminal groin; i.e., there is less predicted erosion/transport in these areas. Like the beach fill only example, these effects are expected to be stronger if the initial conditions did not represent a post-project beach in which the tube groins were mostly buried. The results suggest a net loss of approximately -58,450 cy from within the beach fill template without the tube groins. This represents a minimal increase in losses relative to the with tube groin condition where a net loss of about -55,350 cy was predicted within the same limits. Like the without terminal groin comparisons, the predicted decrease in sand losses with the tube groins in place is indicative of their net benefit, particularly considering they are not largely ‘active’ in this brief storm scenario.

Figure 15 plots the difference between the post-storm (final) bathymetries predicted with and without tube groins for the terminal groin and beach nourishment condition. Yellow and red shading in the figure indicates areas where the seabed is lower due to the tube groins, while blue shading represents a raised seabed attributable to the tube groins. Model results throughout the central and eastern portions of the groin field are similar to those discussed previously for the without terminal groin configuration. There are no significant changes in the post-storm seabed at the Point or on West Beach between the with- and without-tube groin scenarios.

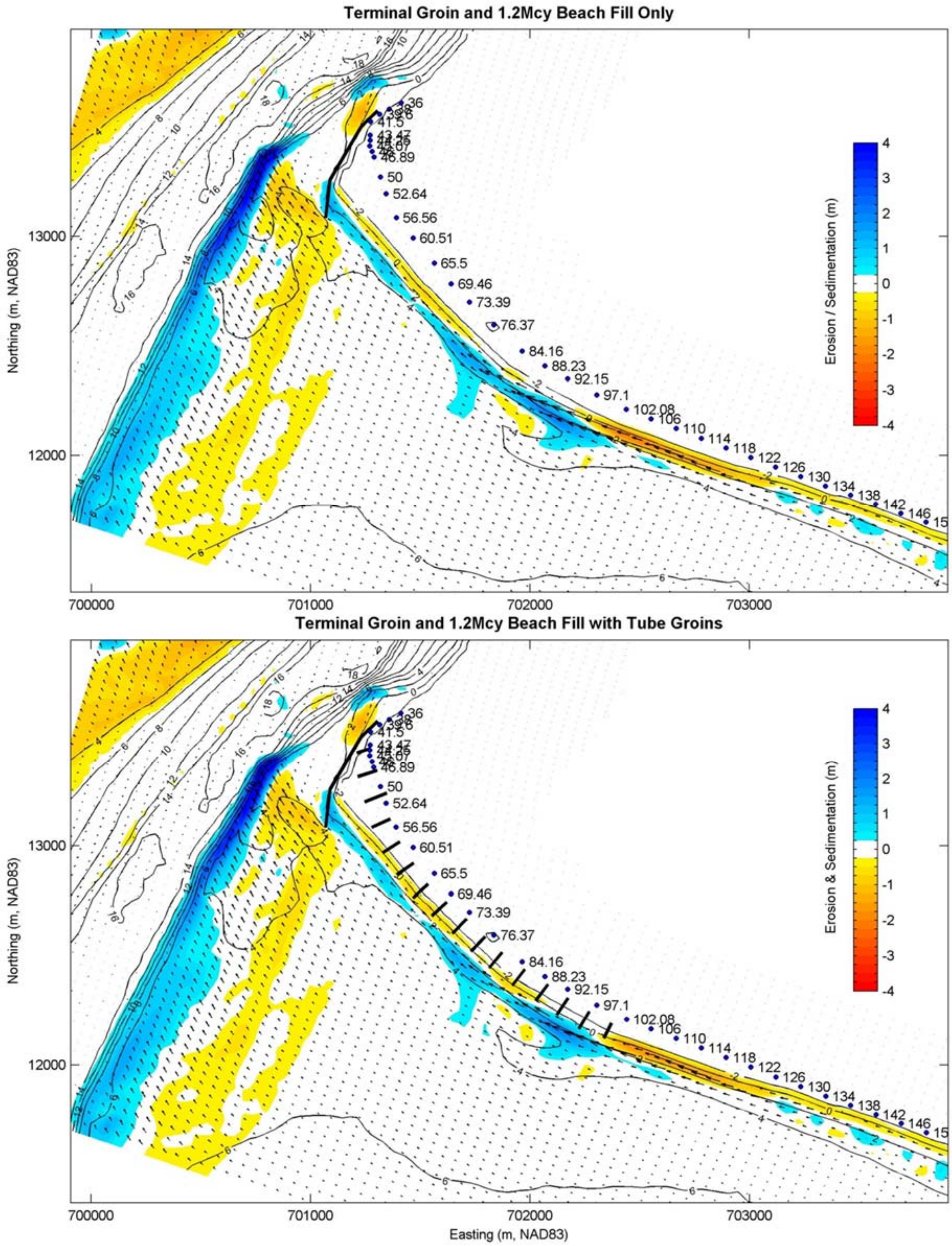

Figure 14: Comparison of predicted erosion/sedimentation patterns considering with and without the tube groins under the terminal groin with fill scenario.

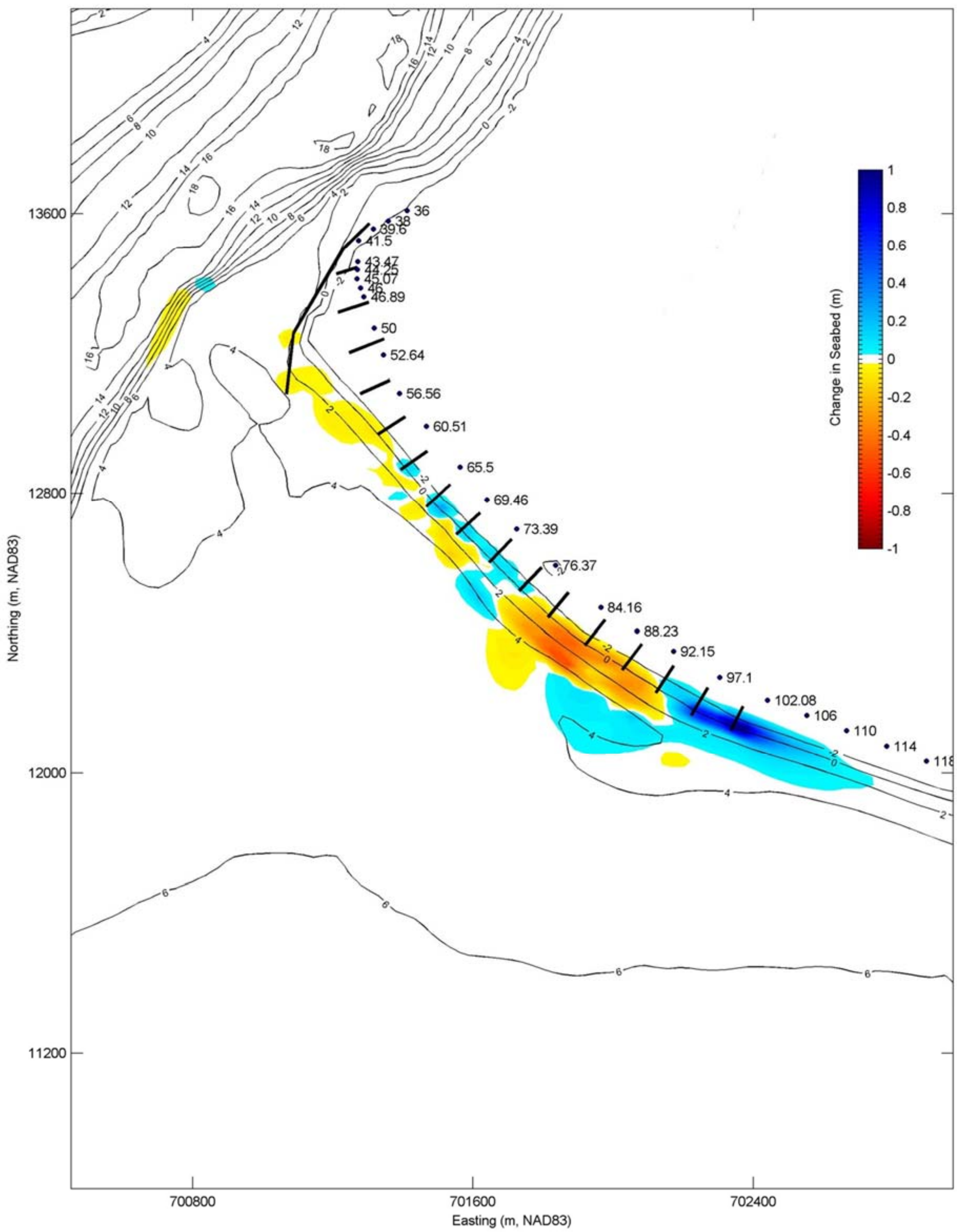

Figure 15: Predicted seabed differences attributable to the tube groins following a Bertha-like storm event following a 1.2Mcy fill with terminal groin -- computed as the difference between post-storm (final) bathymetries for with- and without-tube groin conditions. Yellow and red shading in the figure indicates areas where the seabed is lower due to the tube groins, while blue shading represents a raised seabed attributable to the tube groins.

In summary, the Delft3D model was used to simulate offshore storm conditions emanating from an event similar to the 1996 passage of Hurricane Bertha. The model results indicate that the terminal groin is capable of significantly reducing volume losses on South Beach while not meaningfully impacting the downdrift and West Beach shorelines, relative to a beach fill only condition. There is an indication of increased storm-related (seabed scour) erosion at the seaward tip of the terminal groin. Such scour is to be expected and will require attention in the detailed design phase to ensure long-term stability of the structure, typically through the use of a marine mattress foundation. Overall, the model predictions are generally consistent with those for typical annual conditions. The performance of the terminal groin and its beneficial effects upon both South Beach and neutral effects upon West Beach, relative to the without-terminal groin condition, are similar among both the severe storm and typical conditions. The presence of the sand-filled tube groins is predicted to have an overall positive (albeit limited) effect on the Island's ability to retain placed sediment when paired with the terminal groin. The limited nature of the tube groins' benefit in this simulation is principally due to the fact that the model simulates short-term morphological changes on a post-construction beach condition whereby the tube groins are largely buried in fill and do not significantly act upon the incident wave climate.