Enhanced Modeling in Support of Recommended EWN/NNBF Measures and Efficacy in Providing Flood/Storm Risk Reduction

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June 2020

Prepared for USACE Philadelphia District
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Executive summary

Evidence suggests NNBF such as coastal wetlands and islands can reduce maximum water levels during storms through a combination of both wave and surge attenuation. However, the efficacy of these measures is a function of the configuration of the coastline, characteristics of the NNBF, and the characteristics of the storm itself such as the intensity, forward speed, size, and landfall location. Consequently, the effect of any proposed NNBF and/or structural measure should be examined under a suite of storms that represent a range of likely water level responses. To examine the effect of proposed large-scale NNBF in coastal New Jersey, we developed three implementations of very large scale NNBF measures to determine whether the NNBF concept could reduce water levels in the back bay areas adjacent to inlets when applied in conjunction with surge barriers (and instead of surge barriers at Little Egg and Brigantine Inlets): the Holgate region landward of Little Egg Inlet; the Brigantine region, influenced by both Little Egg Inlet to the north and the smaller Brigantine Inlet; and the Great Egg region landward of Great Egg Harbor Inlet. The NNBF configuration, topography, and roughness were developed in ArcMap 10.7 and used to modify the existing ADCIRC and STWAVE model domains for the region developed as part of the North Atlantic Coastal Comprehensive Study. A suite of 10 synthetic tropical storms were applied to the existing and modified model domains to determine how the proposed NNBF affected water levels in the back bay areas around the proposed NNBF.

The results indicated storm characteristics, particularly wind direction, strongly influenced water level response to the implementation of the proposed NNBF. Water level change attributable to NNBF for most NJBB domain was relatively modest (on the order of 10-30 with some areas up to 50 cm), for most storms regardless of the magnitude of base water level response; however, the duration of reductions in water levels was many hours and could potentially reduce flooding due to the prolonged reductions in peak water levels. In some areas, the NNBFs increased water levels, especially in situations that created strong north to south winds; additional analysis with re-designed NNBF should be considered to determine if the amplification of water levels attributable to the NNBF could be reduced. The results from this initial modeling study show NNBF could potentially provide some benefit to reducing coastal storm risk in the New Jersey back bays in some areas. While no configuration showed that the addition of NNBF measures were able to reduce water levels enough to reduce flooding during the largest storms without the implementation of additional perimeter NNBF and structural measures, the results do indicate that NNBF paired with the structural measures simulated in this study may show promise in reducing operation frequency of surge barriers or reducing the required height of cross-bay closures and perimeter flood walls and levees, which may not only reduced costs for those measures but may also be desirable to preserve the view shed for the residents of back bay communities.

Final decisions on the utility of the NNBF measures implemented in this report should be informed by economic models to determine if the maximum water level reduction and duration of reduction in these regions may translate to economic benefits either directly through reduction in damages or indirectly through reduction in height of perimeter structural measures or reduced operations of surge barriers. The authors of this report acknowledge that the NNBFs as modeled and described in this report would require very large volumes of sediment that would likely

render such features cost prohibitive. However, the modeling conducted in this study was not designed to determine if "medium" and "large" NNBFs, which utilize smaller footprints and/or lower elevations (i.e., less overall sediment volume), could sufficiently reduce water levels in critical parts of the back bays. Additional NNBF configurations and associated modeling would be required to ascertain how much initially estimated sediment quantities required to construct the "extra-large" scale NNBFs described in this study would be reduced. Additionally, the feasibility of utilizing sediment from routine maintenance dredging should be examined to determine if the required volume of "borrow source" sediment can be reduced. Further analysis with the PDT should provide additional information on the potential CSRM benefits. Moreover, quantification of additional benefits aside from National Economic Development (NED) benefits should be considered as NNBFs are designed to provide additional environmental, social, and economic benefits apart from benefits associated solely with CSRM.

1 Introduction

This report details the modeling and analysis efforts that were conducted as part of a larger report entitled "Assessment of Engineering With Nature® (EWN®) Strategies and Natural and Nature Based Features (NNBF) as Coastal Storm Risk Management Attributes for the Tentatively Selected Plan (TSP)" in support of the New Jersey Back Bays Coastal Storm Risk Management Feasibility Study led by the USACE Philadelphia District (NAP). The goal of the study was to identify and prioritize NNBF options and/or other EWN strategies on a systems level to support the comprehensive CSRM approach for the NJBB Feasibility Study. In order to achieve those goals and provide NAP with relevant evidence of the efficacy of proposed NNBF options to manage coastal storm risk, advanced modeling of a subset of NNBF options was required to better quantify the degree to which NNBF could reduce water levels in the back bay environment.

The New Jersey Back Bays Coastal Storm Risk Management Interim Feasibility Study and Environmental Scoping Document was released for public comment in March 2019 and stakeholder feedback indicated a desire for the NJBB Product Delivery Team (PDT) to evaluate options that fully integrate NNBF measures into the tentatively selected plan and Draft Feasibility Report (anticipated April 2020). In July 2019, the NAP PDT (including representatives from the New Jersey Department of Environmental Protection, ERDC, and members of the Dredge Research Collaborative (DRC) assembled in Philadelphia to brainstorm NNBF options in the back bays. Several areas were identified as likely candidates for implementation of large-scale NNBF. However, the degree to which these options could potentially affect water levels in the back bay alone or in combination with structural measures was not known, necessitating this modeling study.

Evidence suggests NNBFs such as coastal wetlands and islands can reduce maximum water levels during storms through a combination of both wave and surge attenuation (van Berchum et al., 2019; Leonardi et al., 2018; Narayan et al., 2017; Lopez, 2009). However, the efficacy of these measures is a function of the configuration of the coastline, characteristics of the NNBFs, and the characteristics of the storm itself such as the intensity, forward speed, size, and landfall location. Consequently, the effect of any proposed NNBF and/or structural measure should be examined under a suite of storms that represent the full range of likely conditions. The large-scale NNBF concepts developed during the July 2019 workshop likely would affect both storm surge and waves, requiring both to be evaluated by adapting existing models developed for the North Atlantic Coast Comprehensive Study (Cialone et al., 2015). The ERDC modeling team developed a modeling proof-of-concept approach to determine if what is referred to as extra large-scale NNBFs (on the order of >50% of the back bay cross-section area occupied by NNBF) produced changes in water levels significant enough to potentially produce CSRM benefits. These extra large-scale features were also rendered into drawings developed by the DRC to illustrate what NNBF at these scales would look like. Some of these renderings are presented within this report but for more details, please refer to the report entitled "Engineering With Nature® and Landscape Architecture: New Jersey Back Bays".

2 Methods

2.1 Configuration description

Three areas were targeted to add extra large-scale NNBF measures to determine whether the NNBF concept could reduce water levels in the back bay areas adjacent to inlets in addition to the reduction from surge barriers. The Holgate region landward of the Little Egg Inlet is the northernmost proposed NNBF area. Within this region two types of NNBF features were proposed: a horizontal levee along Great Bay Boulevard along the Tuckerton Peninsula and expansion of the island complex landward of Beach Haven (Figure 1) utilizing the "surge filter" concept described in the Engineering With Nature® and Landscape Architecture: New Jersey Back Bays report (Figure 2). The horizontal levee concept was developed in the San Francisco Bay region and consists of a traditional levee material core with a shallow ecotone slope atop the side slopes designed to provide more habitat zones transitioning from intertidal areas to upland areas (Leo et al., 2019). The added benefit of a longer and more gradual slope is enhanced wave attenuation along the ecotone slope, which may reduce wave overtopping under some conditions.

The goal of the NNBF measures in this region is to slow or block surge and waves that would propagate from Little Egg Inlet northward into Barnegat Bay.

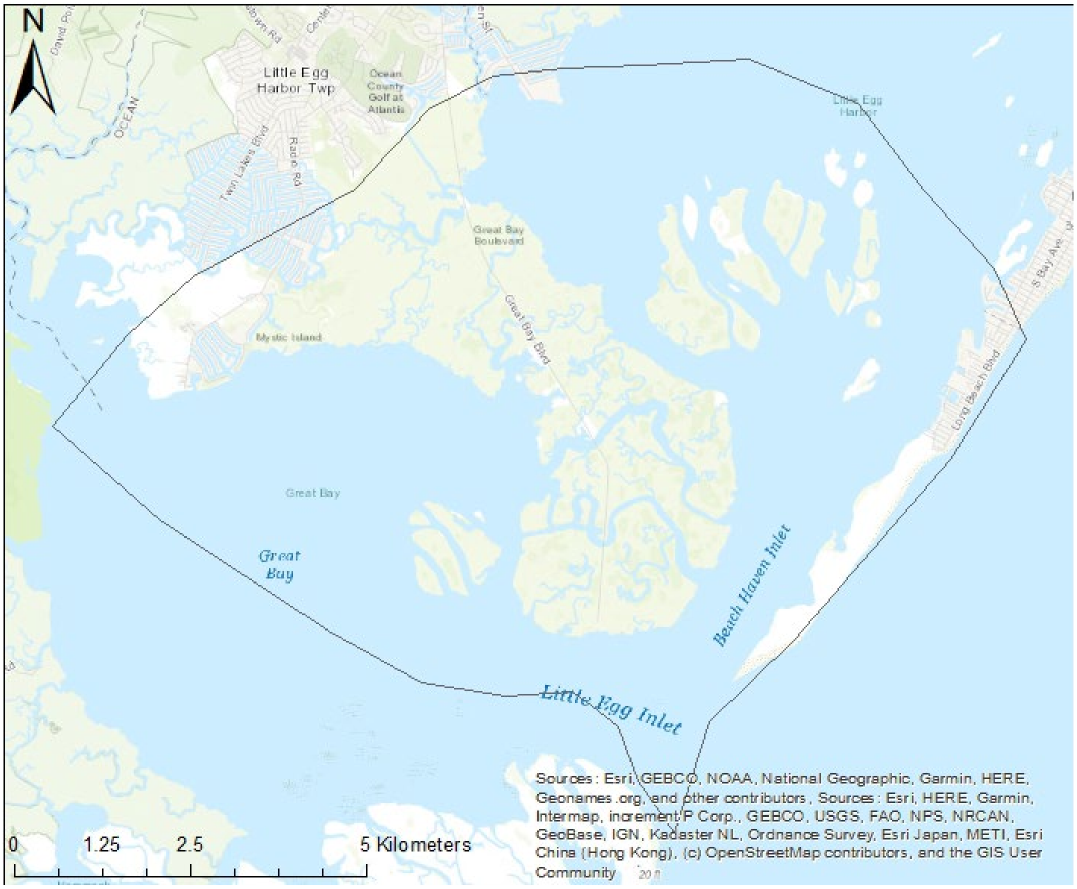


Figure 1 Map of Holgate NNBF area

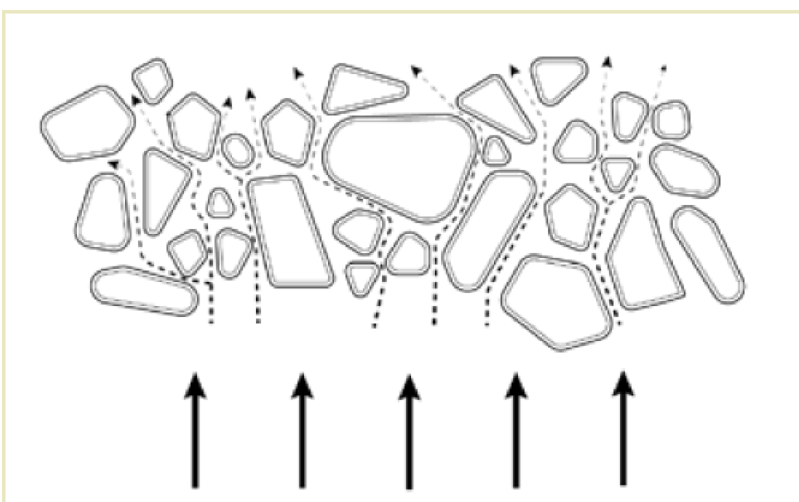


Figure 2 Surge filter concept diagram from Engineering With Nature® and Landscape Architecture: New Jersey Bay Bays report

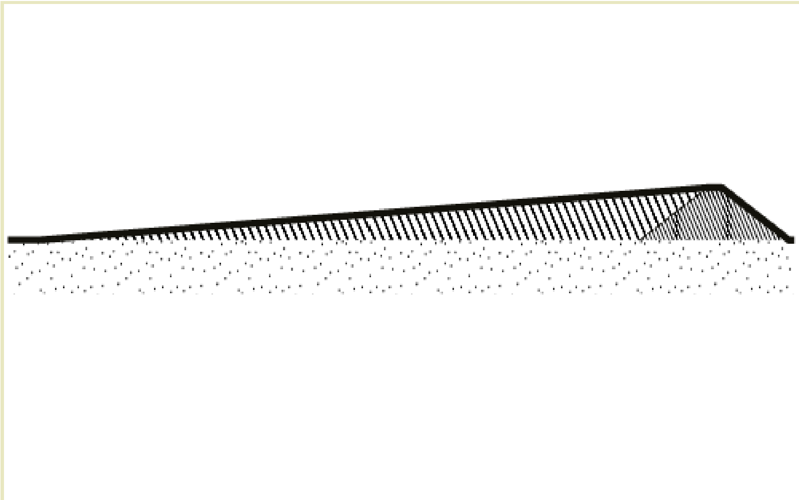


Figure 3 Horizontal levee concept diagram from Engineering With Nature® and Landscape Architecture: New Jersey Back Bays report

The Brigantine region is influenced by both Little Egg Inlet to the north and the smaller and more southern Brigantine Inlet (also referred to as Little Egg/Brigantine), both of which are not stabilized and Absecon Inlet, which is stabilized with jetties (Figure 4). The region is dissected by a number of navigational channels, some of which cut through existing marsh, and the existing marsh islands are mostly low-lying and fragmented by mosquito ditching, potentially impacting the capability to attenuate surge and wave propagation. The NNBF measures proposed in this area also utilize the "surge filter" concept and include expansion and elevation of existing marsh islands with a focus on creating more sinuosity in open water areas of the back bay.

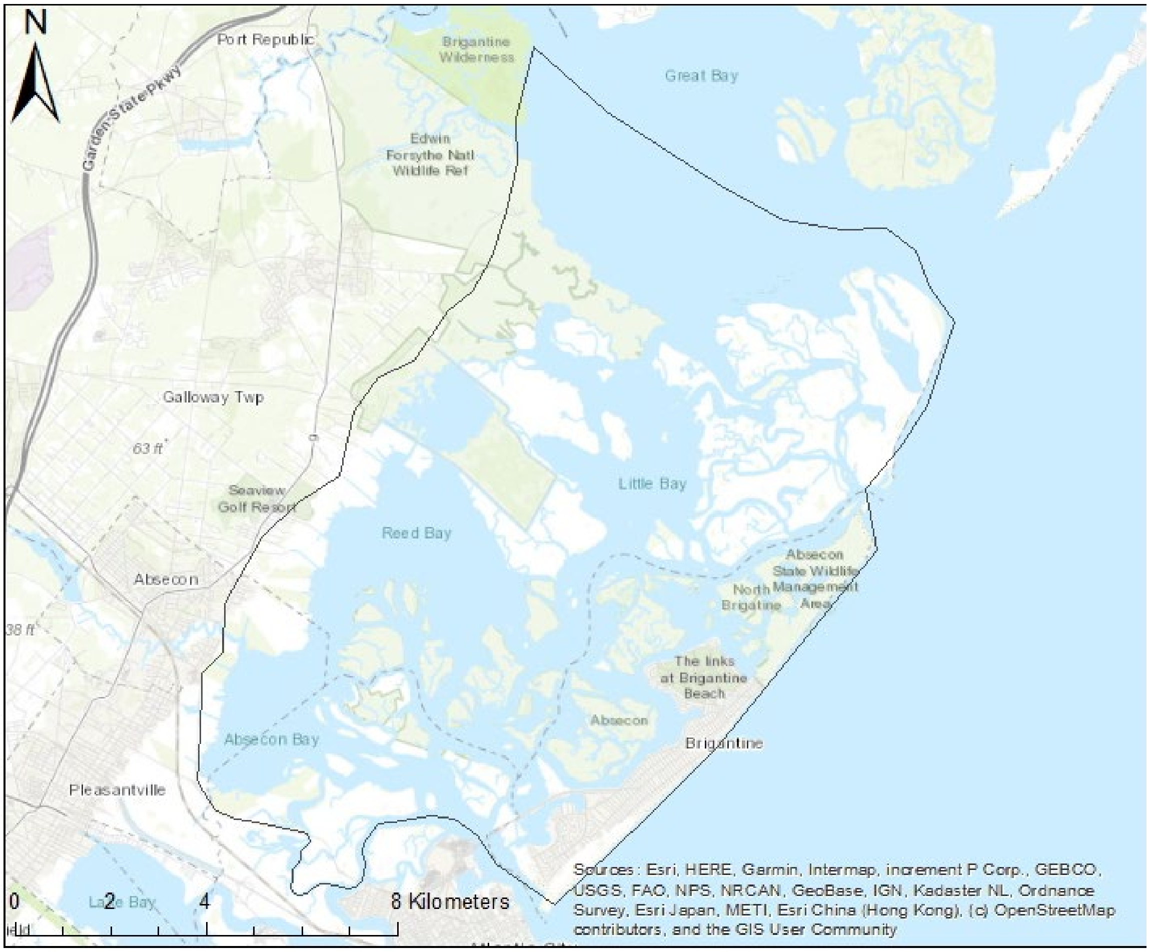


Figure 4 Map of Brigantine NNBF area

The Great Egg region is the most southern NNBF evaluation area and is focused on preventing surge and waves from propagating into the back bay through Great Egg Harbor Inlet (Figure 5). The NNBF measures proposed also utilize the “surge filter” concept and are similar to those in Brigantine: expand and elevate existing marsh islands and construct new islands to further reduce flow into the back bay. The northern portion of this area is characterized by a large number of wetland islands in the back bay as opposed to the southern portion, which has relatively fewer wetland islands and a larger proportion of open water areas.

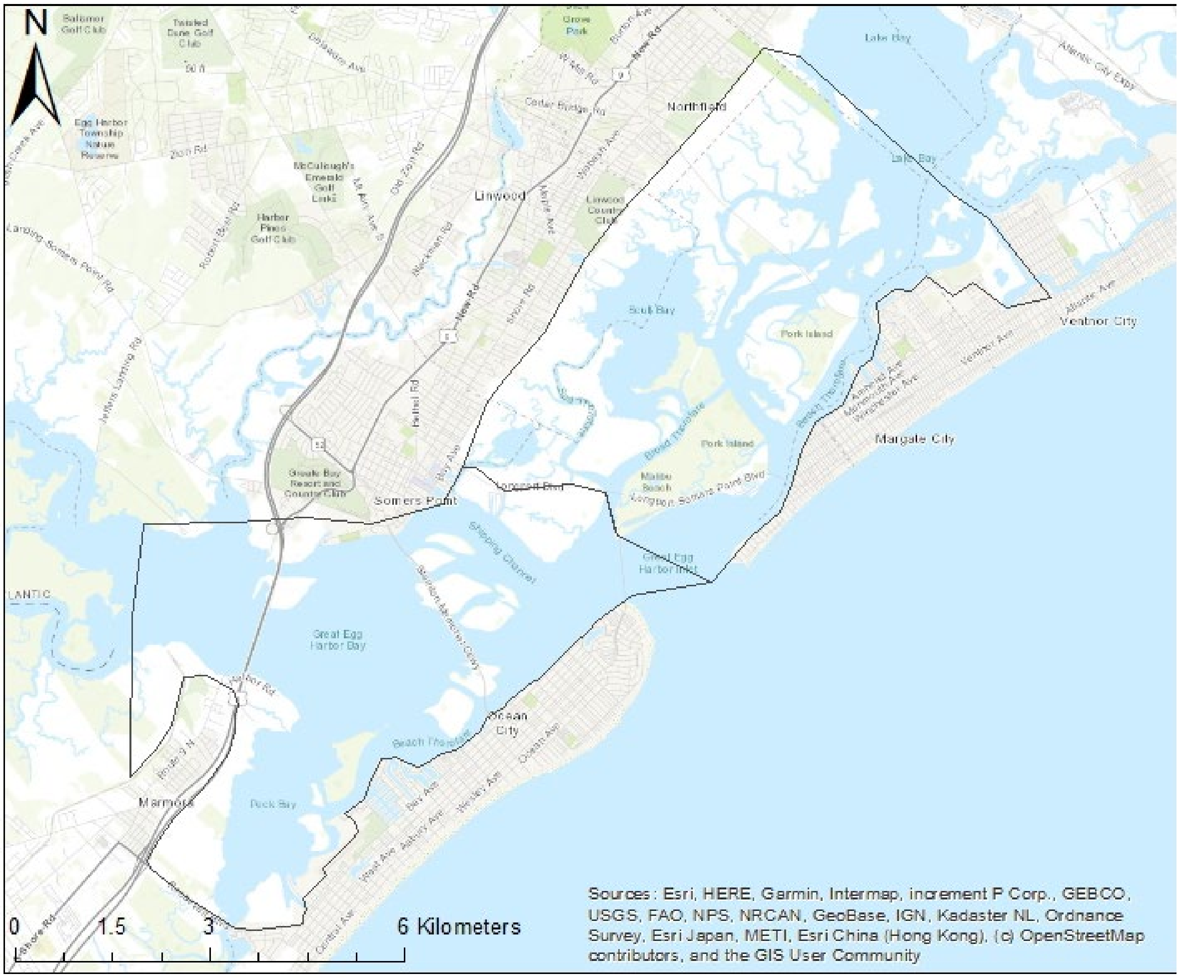


Figure 5 Map of Great Egg Harbor Inlet NNBF area

The effects of extra large-scale NNBF were assessed in two model configurations: Configuration 8, which included storm-surge barriers at Manasquan Inlet and Barnegat Inlets, expansion of the island complex west of Beach Haven in the Holgate region of the E.B. Forsythe National Wildlife Refuge, a horizontal levee along Great Bay Boulevard, and expansion of the wetland island complex landward of and to the north and south of Great Egg Inlet (Figure 6) and configuration 5, which included storm-surge barriers at Great Egg and Absecon Inlets and wetland island expansion in the back bay region west of Brigantine (Figure 7). Note that NNBF measures in the Holgate and Great Egg regions were combined into one configuration because the proposed interventions were spaced far enough apart that their effects were independent of each other as determined from the earlier hydrodynamic evaluation of surge barrier combination (Slusarczyk et al. 2020) so only two model configurations were required to assess the efficacy of NNBF in three areas of the NJBB domain. These NNBF with surge barrier configurations were compared with two surge-barrier-only configurations, Configuration 3 and North, that only included the structural measures described above; Configuration 3 was compared with Configuration 5 and North was compared with Configuration 8. The purpose of this comparison was to determine how the proposed NNBF affected water levels (surge only in the case of North and Configuration 8 and surge and waves for Configurations 3 and 5) in the three areas.

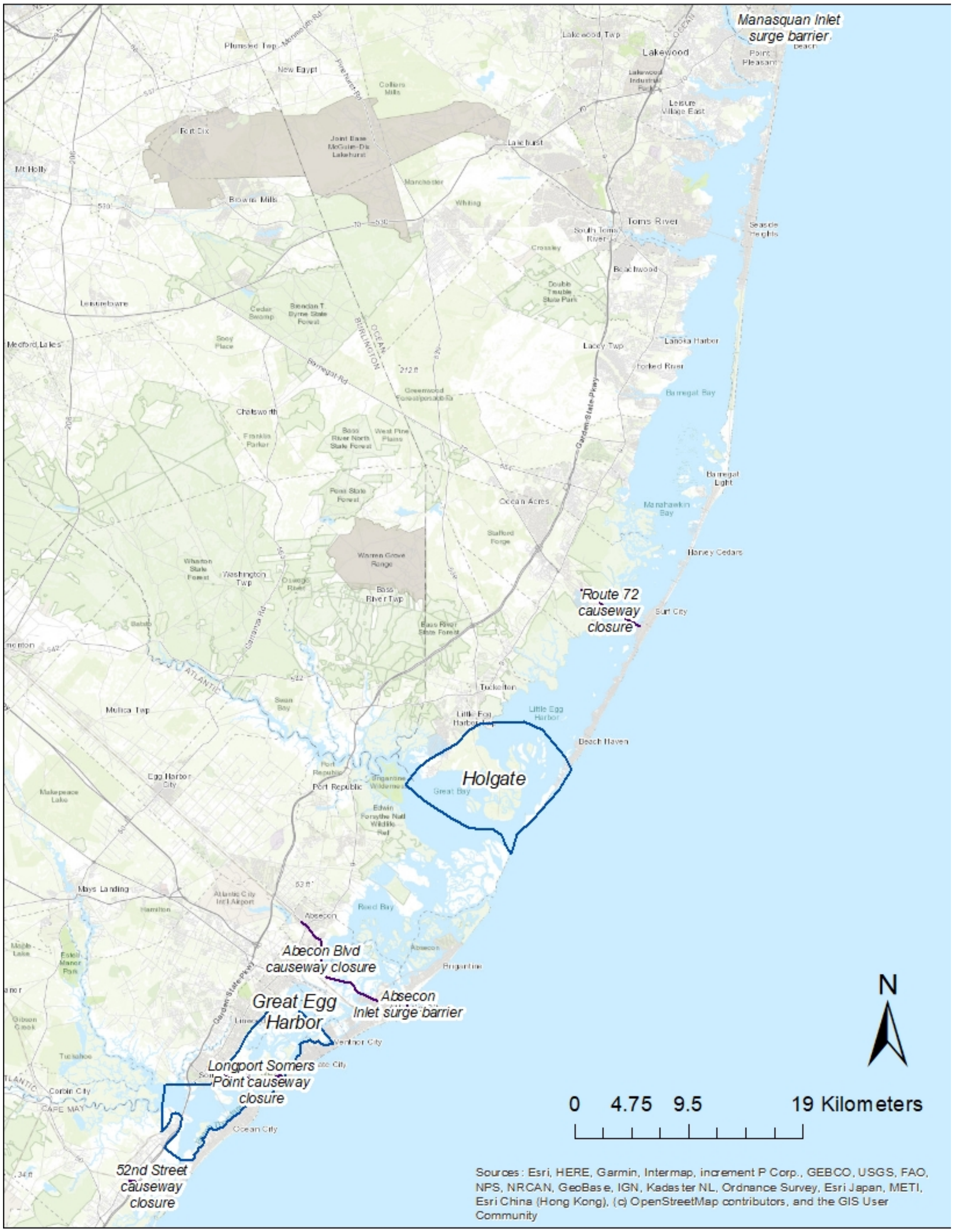


Figure 6 Configuration 8 included NNBF measures in the Holgate and Great Egg Harbor areas as well as surge barriers at Manasquan and Absecon Inlets

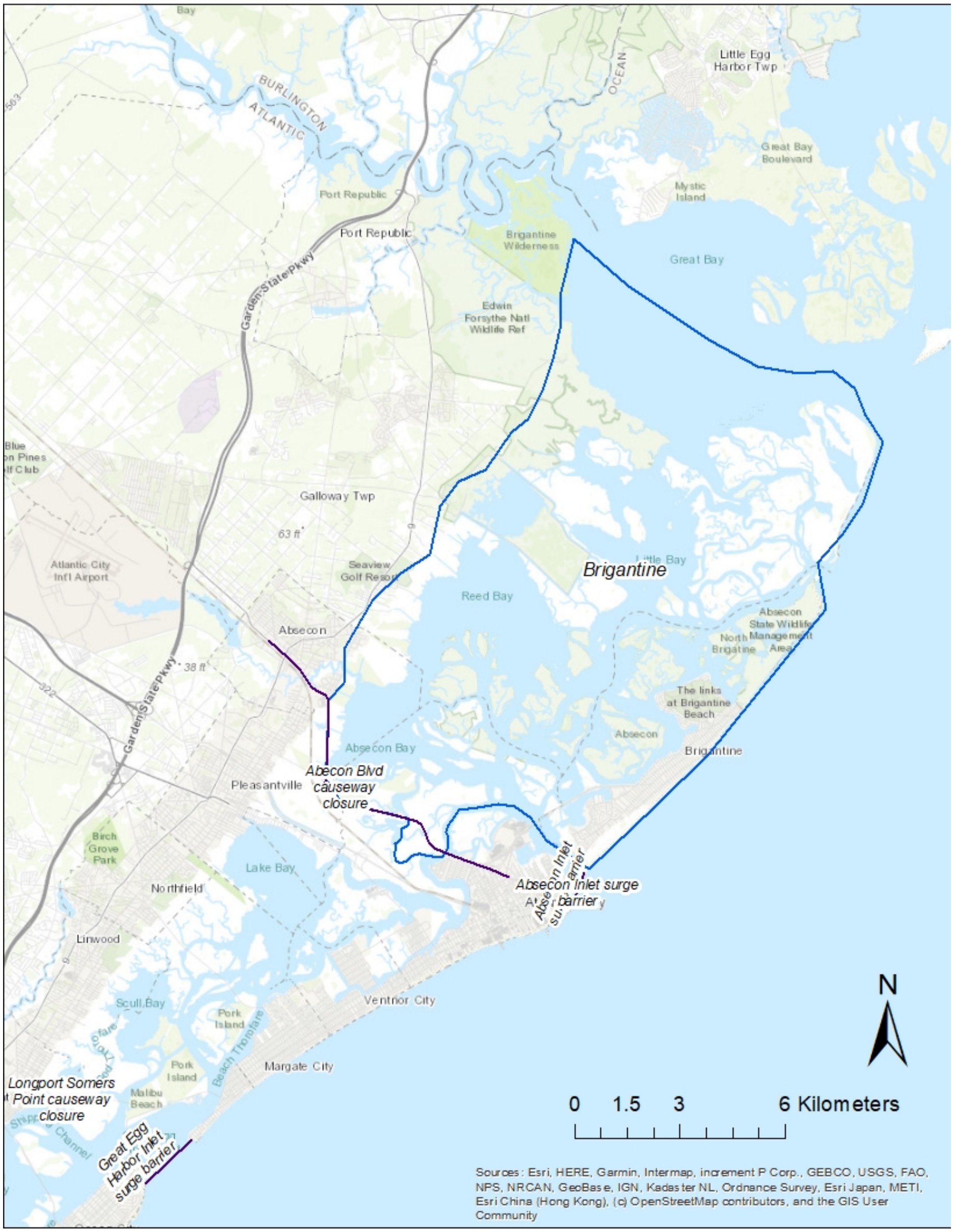


Figure 7 Configuration 5 included NNBF within the Brigantine NNBF area as well as a surge barrier at Absecon Inlet

2.2 Development of NNBF characteristics

The NNBF feature configurations were developed in ArcMap 10.7 using the Continually Updated Shoreline Product available from NOAA (2018) to define the present land-water interface. Existing elevation data were used to define the existing topography and bathymetry from USGS Coastal National Elevation Database (2015). The existing island boundaries were manipulated using ArcMap 10.7 Editor through a combination of scaling existing islands, merging adjacent smaller islands into larger islands, and creating new islands. Edge elevation was assigned as the mean elevation of existing shorelines in the NNBF area. The elevation of the islands was determined by assigning a constant slope to the feature, typically 0.5%, increased to 1% for small islands. For large features, once the elevation exceeded 3 m, the slope was further reduced to 0.25%.

The vegetation type and corresponding roughness value of the vegetation was inferred from the elevation using the rules adapted from Correll et al. (2018) for vegetation communities in coastal New Jersey. Four vegetation communities were assumed to occupy the proposed NNBF: low marsh, characterized by elevations ranging from mean sea level to mean higher high water and occupied by *Spartina alterniflora*; high marsh, characterized by elevations ranging from mean higher high water to the extent of the highest astronomical tide and occupied by *Spartina patens Distichlis spicata, Juncus gerardii,* and short form *Spartina alterniflora*; transitional marsh characterized by typical elevations from highest astronomical tide to maximum flood and characterized by *Typha angustifolia, Iva frutescens, Baccharis halimifolia, Solidago sempervirens, Scirpus robustus, and Spartina pectinata*; and coastal shrub-scrub, characterized by elevations greater than the maximum flooding extent and occupied by *Juniperus virginiana* and other woody species stunted by proximity to the coast. Local mean sea level and mean higher high water for each region were estimated using NOAA's Vdatum version 4.01 software (NOAA, 2019) and the highest astronomical tide and maximum flood level recorded at the Atlantic City, NJ NOAA water level gage were used for all areas. The vegetation communities were selected to correspond with the existing inventory of Manning's n roughness coefficients compiled in Bunya et al. (2010) and represented the majority of natural land areas in the back bay region excluding urban and developed areas.

The horizontal levee geometry was developed using the Feature Stamping tool in SMS version 13.0. The centerline of the levee followed the existing centerline of Great Bay Boulevard. The levee height was +3.1 m (10 ft) NAVD88 with a top width of approximately 30 m corresponding to the ADCIRC mesh resolution. The side slopes ranged from 2 to 3.3% depending on the available area. Major creeks were not blocked by the horizontal levee and instead were designed to be closed off only during storm conditions using gates.

2.3 Storm suite selection

In Phase 1 of the NJBB study (Slusarczyk et al., 2020), CHL selected an initial subset (10) of the 1050 synthetic tropical cyclones that were designed and simulated in the North Atlantic Coastal Comprehensive Study (NACCS) using Gaussian process metamodeling (GPM) and a design of experiments (DoE) approach. This 10-storm subset (Storms 99, 349, 350, 357, 433, 434, 469, 524, 636, and 646) was used to simulate the response of the proposed NNBF to varying storm conditions such as intensity, direction, and translational speed. The storm characteristics of the ten storms are listed in Table 1 and the storm tracks are shown in Figure 8.

Table 1 Storm characteristics of the ten storm suite used to model response in the study domain

TROPICAL CYCLONE ID	NACCS SUBREGION	MASTER TRACK ID	Θ (DEG)	ΔP (HPA)	RMAX (KM)	VF (KM/H)
99	3	31	-40	88	65	16
349	2	9	-60	78	125	65
350	2	9	-60	68	52	26
357	2	10	-60	58	88	28
433	2	55	-20	88	55	62
434	2	55	-20	78	82	27
469	2	76	0	78	74	38
524	2	98	20	78	73	38
636	2	120	40	78	47	14
646	2	121	40	83	67	59

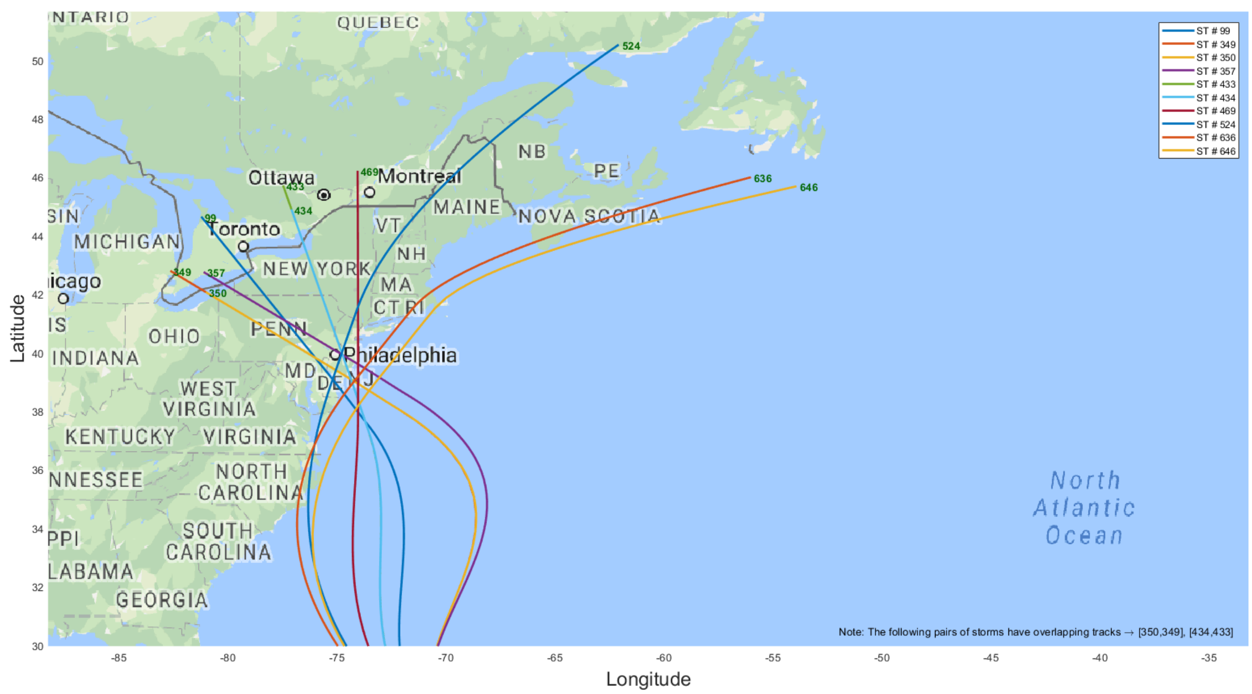


Figure 8 Synthetic storm tracks for the ten storms simulated

Table 2 shows a full summary of the water level responses (surge and waves) and associated annual exceedance probabilities (AEPs) for selected save points in the NNBF interest areas as interpolated from the AEP water level response curves reported in the Coastal Hazards System (Melby and Green, 2015). These AEPs represent the water level responses due to the ten synthetic tropical storms if no CSRM measures (structural or NNBF) were in place based on modeling that occurred after Hurricane Sandy and are intended to help the reader get a sense for the relative likelihood of the water level responses induced by these ten storms.

For most save points, storms 99 and 433 produced the greatest water level response at all save points, and storms 357 and 646 produced the smallest responses. The save point locations are shown in Figure 19, Figure 22, and Figure 24 in the Results section. Note that these water levels and associated AEPs were from previous modeling efforts associated with the North Atlantic Coastal Comprehensive Study and published to the Coastal Hazards System (Melby and Green, 2015). For New Jersey Back Bays study, the model geometry was updated to include changes in bathymetry and restoration of barrier islands, which will alter the water level and AEP values reported in Table 2. The peak water level response data for the modeling scenarios included in this study are found in Tables 6 and 7 in Section 3.2.

Table 2 Summary of the water level responses (surge+waves) and associated annual exceedance probabilities within the NNBF areas without any structural or NNBF measures implemented (from Coastal Hazards System; Melby and Green, 2015)

AREA			HOLGATE			BRIGANTINE		GREAT EGG HARBOR		
SAVE POINT ID (THIS STUDY)			61	73	33	59	50	49	117	111
CHS SAVE POINT ID			11399	11459	13580	11369	11316	11315	13513	13496
STORM ID	99	WL elev. MSL (m)	2.34	3.09	3.00	3.00	3.94	3.79	3.39	3.36
		AEP	4.0E-03	1.9E-03	3.7E-03	3.9E-03	1.6E-03	1.7E-03	4.1E-03	2.6E-03
	349	WL elev. MSL (m)	2.23	2.43	2.77	2.54	2.68	2.64	2.61	2.32
		AEP	4.8E-03	7.8E-03	5.5E-03	9.0E-03	1.3E-02	1.1E-02	1.8E-02	2.5E-02
	350	WL elev. MSL (m)	2.29	3.04	2.83	2.76	3.31	2.79	2.37	2.48
		AEP	4.3E-03	2.2E-03	4.8E-03	6.0E-03	4.5E-03	8.8E-03	3.1E-02	1.6E-02
	357	WL elev. MSL (m)	1.57	1.67	1.73	1.83	1.72	1.43	1.44	1.63
		AEP	1.5E-01	1.5E-01	1.7E-01	1.3E-01	2.5E-01	3.7E-01	4.0E-01	3.0E-01
	433	WL elev. MSL (m)	2.78	3.01	3.78	3.63	3.40	3.33	3.78	3.20
		AEP	1.2E-03	2.4E-03	7.8E-04	9.8E-04	4.0E-03	3.7E-03	1.9E-03	3.6E-03
	434	WL elev. MSL (m)	2.54	2.95	2.85	2.92	3.38	3.09	2.88	2.89
		AEP	2.3E-03	2.8E-03	4.7E-03	4.4E-03	4.1E-03	5.0E-03	1.1E-02	6.6E-03
	469	WL elev. MSL (m)	2.10	2.37	2.49	2.70	3.04	2.70	2.71	2.67
		AEP	1.0E-02	8.8E-03	9.4E-03	6.9E-03	7.1E-03	9.9E-03	1.5E-02	1.0E-02
	524	WL elev. MSL (m)	1.11	1.67	2.09	1.84	2.21	2.46	2.36	2.17
		AEP	5.4E-01	1.5E-01	4.6E-02	1.3E-01	4.7E-02	1.5E-02	3.1E-02	4.2E-02
	636	WL elev. MSL (m)	1.83	2.19	1.94	2.09	2.79	2.11	2.16	2.37
		AEP	4.9E-02	1.6E-02	8.6E-02	4.6E-02	1.0E-02	3.8E-02	4.4E-02	2.0E-02

	646	WL elev. MSL (m)	1.33	1.45	1.66	1.93	2.07	1.71	2.22	2.20
		AEP	3.2E-01	2.9E-01	2.1E-01	8.9E-02	8.6E-02	1.6E-01	4.0E-02	3.8E-02

2.4 Implementation in ADCIRC

The ADvanced CIRCulation (ADCIRC) model was used to simulate the surge and circulation response to storms. Two ADCIRC meshes (North and Central 1) developed in the NJBB Phase 2 study (Slusarczyk et al., 2020) as part of the NJBB Feasibility Study were modified to accommodate the proposed NNBF by increasing the resolution where the NNBFs were to be placed. In these areas, the bathymetry and the Manning's n values were also modified to match the elevation and Manning's n values assigned in ArcMap 10.7 (ESRI, 2018). The minimum node spacing after the grid refinement in the area of interest is approximately 30 m, which is approximately double compared to the original grid resolution. An example of changes to the mesh for the Brigantine region to accommodate the proposed NNBF is shown in Figure 9. Mesh changes in the Holgate and Great Egg Harbor region are found in Appendix A.

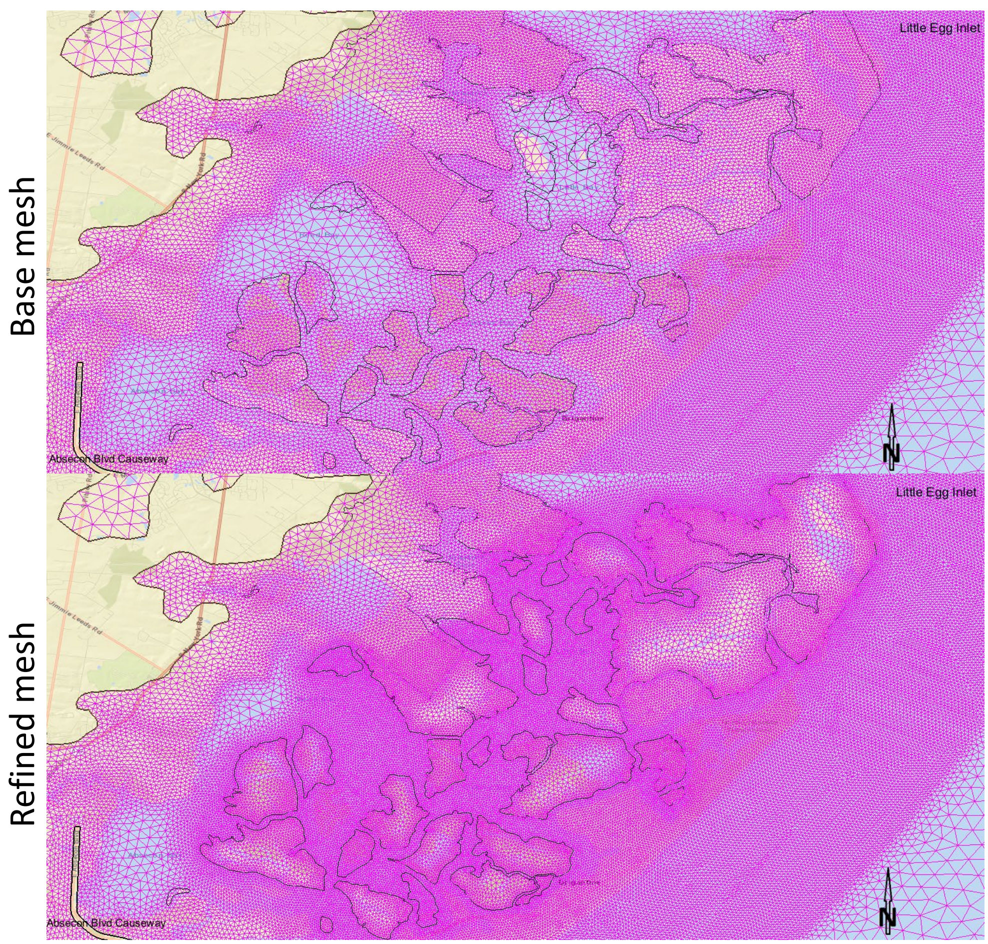


Figure 9 Change in mesh resolution in the Brigantine area to accommodate the NNBF

2.5 Implementation in STWAVE

2.5.1 STWAVE

STWAVE is a steady-state spectral wave model for nearshore wave generation, propagation, transformation, and dissipation (Smith et al. 2001, Smith 2007, Massey et al. 2011). STWAVE numerically solves the steady-state conservation of spectral wave action along backward-traced wave rays:

$$\left(C_g\right)_i \frac{\partial}{\partial x_i} \frac{C C_g \cos \alpha E(\sigma, \theta)}{\sigma} = \sum \frac{S}{\sigma} \tag{1}$$

where i is tensor notation for x- and y- components, Cg is group celerity, θ is wave direction, C is wave celerity, σ is wave angular frequency, E is wave energy density, and S is energy source and sink terms. Source and sink mechanisms included surf-zone wave breaking, wind input, wave-wave interaction, whitecapping, and bottom friction.

2.5.2 Coordinate System

STWAVE is formulated on a Cartesian grid, with the x-axis oriented in the cross shore direction (I) and the y-axis oriented alongshore (J), parallel with the shoreline. Angles are measured counterclockwise from the grid x-axis.

2.5.3 Grid Development

For simulation, two STWAVE domains (parent and nested) were developed to simulate wave growth, propagation, and transformation around the added NNBF features. The parent grid uses a 200-m resolution comprised of 452 cells in the cross-shore direction (I) and 1017 cells in the alongshore direction (J). However, finer resolution is needed in the areas of interest to resolve the NNBF features. Dictated by the geometry of the added features, the finer resolution was set at 50-m comprising of 672 cells in the cross-shore direction (I) and 1441 cells in the alongshore direction (J). The nesting approach will use the parent grid as the offshore domain using the boundary forcing already developed during the NACCS effort. This offshore domain will then be used to transform offshore waves to the boundary of a nearshore, high-resolution domain. The advantage of grid nesting is it minimizes computation requirements and increases accuracy due to a more accurate description of the bathymetry and topography

The developed parent grid extended offshore from the 80 m contour to the -70 m contour onshore and extends Northward to Fort Hancock and Southward to Cape May point. The developed child grid extended offshore from the 30 m contour to the -15 m contour onshore and extends to the North to Stafford Township and to the South to Sea Isle City, to capture the fetch around the NNBF features. The projection of the grid was UTM 18 with a vertical datum relative to NAD83. The properties of both STWAVE domains are provided in Table 3 and shown in Figure 10.

Table 3 STWAVE grid properties

GRID	PROJECTION	GRID ORIGIN (X,Y) [M]	AZIMUTH [DEG]	ΔX/ΔY [FT]	NUMBER OF CELLS I	NUMBER OF CELLS J
PARENT	UTM 18, NAD83 meters	(659306.740683, 4449647.677174)	154.23	200	452	1017
CHILD	UTM 18, NAD83 meters	(588858.409910, 4374090.260479)	140.14	50	672	1441

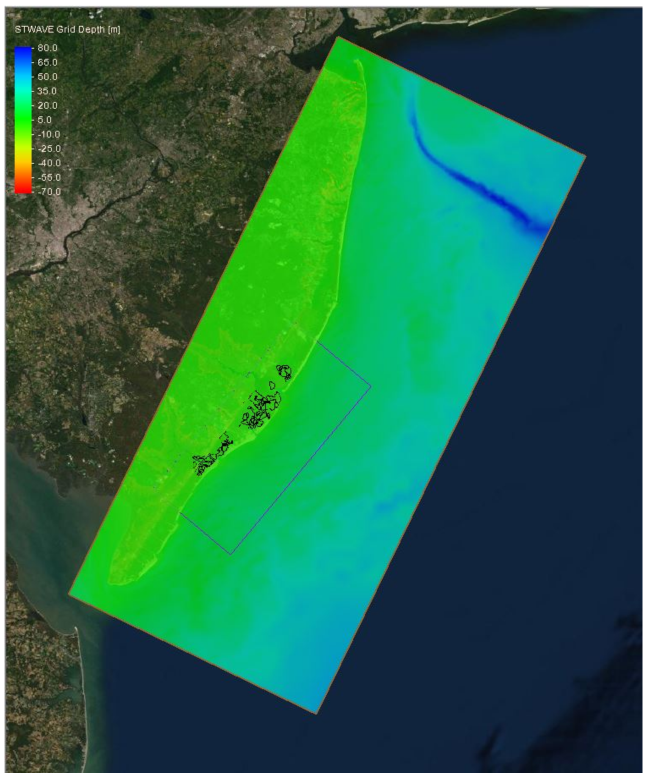


Figure 10 Parent Child STWAVE domains

The bathymetry, topography, and bottom friction Manning’s n values were interpolated from the ADCIRC mesh. The nested Child STWAVE domain is shown in Figure 11.

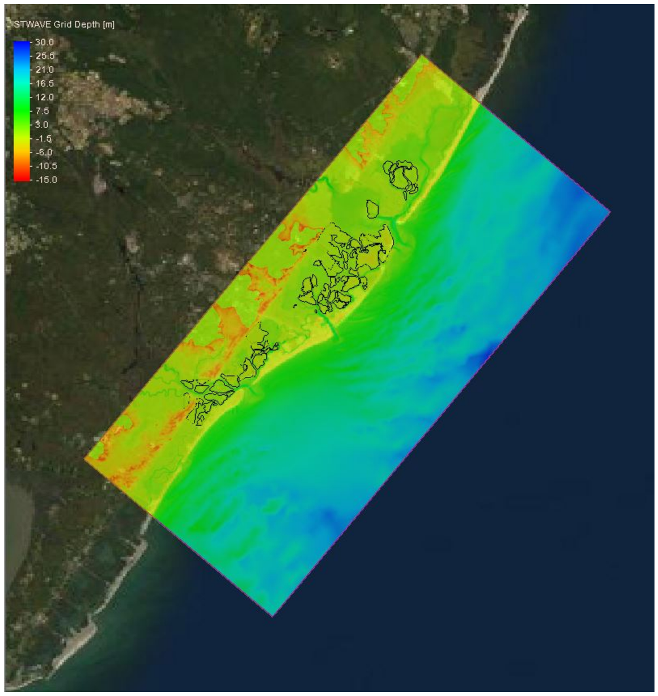


Figure 11 Child STWAVE Domain Extents

Two cases were modeled with the use of STWAVE, referred to as Configuration 3 and Configuration 5. The implemented design features of Configuration 3 were the storm surge barrier at Great Egg Inlet and the storm surge barrier at Absecon Inlet. The implemented design features of Configuration 5 were in addition to the storm surge barrier of Configuration 3, maximal island restoration in the Absecon/Brigantine wetlands. Given that the features included in the Configuration 3 design are also included in Configuration 5, Configuration 3 will be treated as the baseline condition and Configuration 5 as the test condition for analysis. The NNBF features included in the child domain are shown in Figure 12 below, and are depicted as a difference between the bathymetry of Configuration 3 (no NNBF) and Configuration 5 (with NNBF).

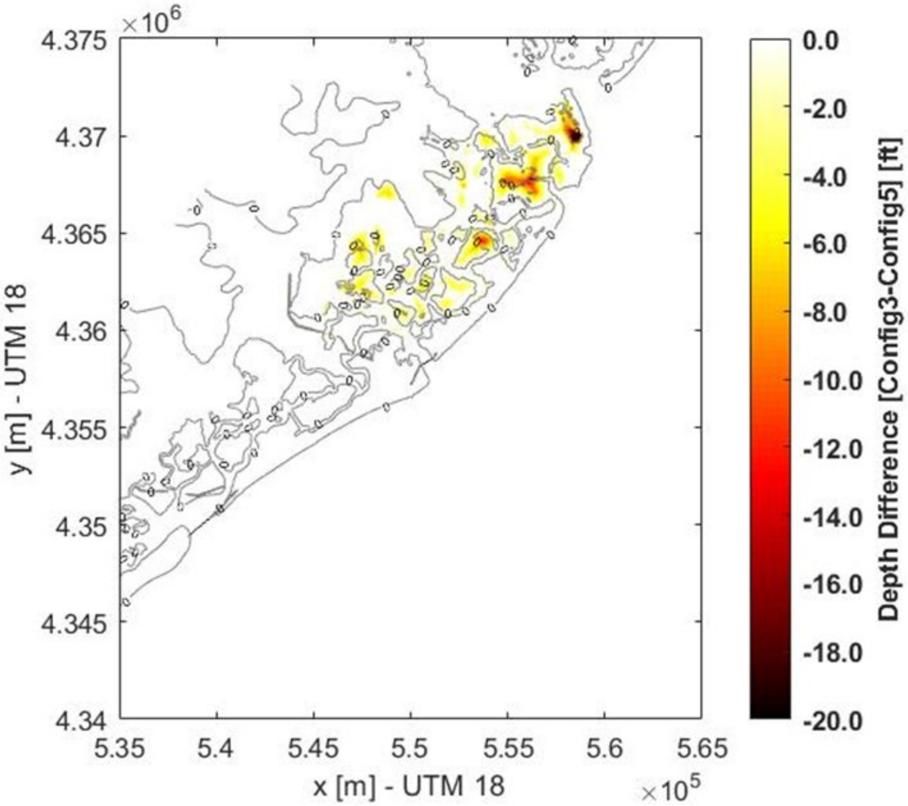


Figure 12 Implemented NNBF features and storm surge barrier included in the STWAVE child domains for Configuration 5. The NNBF are depicted as a difference between the bathymetry of Configuration 3 (no NNBF) and Configuration 5 (with NNBF.)

2.5.4 Boundary Spectra

Ten storms were identified for simulation in STWAVE. The parent grid was run with the NACCS resolved spectra, represented by 28 frequency bands, ranging from 0.031 Hz (32.2 sec) to 0.309 Hz (3.24 sec), and 72 angle bands, from an angle of 0 degrees to 355 degrees with respect to the x-axis (154.23). Each TMA spectrum within a simulation is an IDD. For simulation, the IDD type was selected as 'year/date' format with regularly spaced intervals of 15 min, the same as the NACCS modeling effort. The child grid was run with spectra generated at specified points from the Parent grid. These points were generated along the 65 ft (20 m) contour within the parent grid. The locations of these nested points are shown in Figure 13. The generated nesting spectra had identical time spacing and IDD formatting as the parent grid. Additional STWAVE inputs, such as winds and water elevations were included during coupling with ADCIRC.

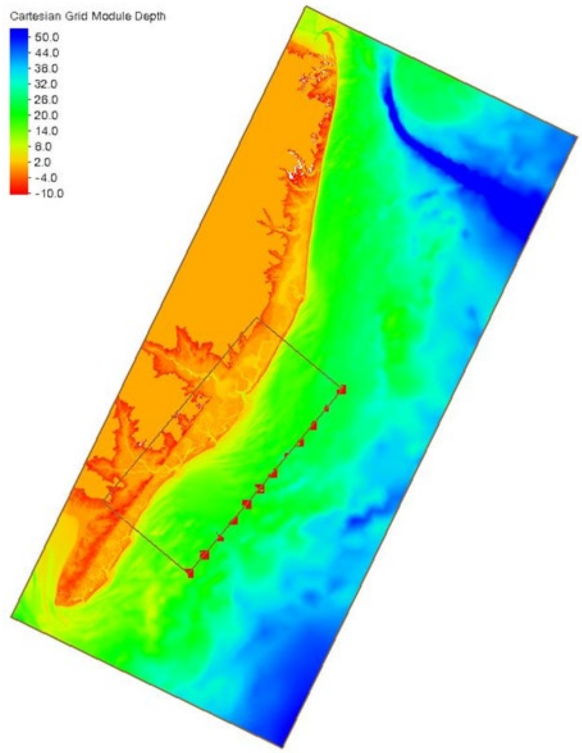


Figure 13 Nesting Locations inside the Parent grid Identified by the red dots along the child grid offshore boundary

2.5.5 Model Execution

Each STWAVE simulation conducted used the full-plane mode of STWAVE to allow for wave generation and transformation in a 360-degree plane. The full-plane version of STWAVE uses an iterative solution process that requires user-defined convergence criteria to signal a suitable solution. Boundary spectra information is propagated from the boundary throughout the domain during the initial iterations. Once this stage converges, winds and surges are added to the forcing, and this final stage iteratively executes until it also reaches a convergent state. The convergence criteria for both stages include the maximum number of iterations to perform per time-step, the relative difference in significant wave height between iterations, and the minimum percent of cells that must satisfy the convergence criteria (i.e., have values less than the relative difference.) Convergence parameters were selected based on a previous study by Massey et al. (2011) in which the sensitivity of the solution to the final convergence criteria was examined. The relative difference and minimum percent of cells were set as (0.1, 100.0) and (0.05, 99.8) for the initial and final iterations, respectively. STWAVE was set up with parallel in-space execution whereby each computational grid was divided into different partitions (in both the x- and y-direction), with each partition executing on a different computer processor. For the parent grid, the number of partitions in the x direction was 8, while the number of partitions in the y direction was 17. For the child grid, the number of partitions in the x direction was 12, while the number of partitions in the y direction was 25. The maximum number of initial and final iterations was set to a value of 25 and 32 respectively for the parent grid and a value of 45 for both the initial and final iterations for the child grid. For both the parent and child grid, this value is higher than the largest partition size.

Additionally 186 station locations from the ADCIRC station list were identified within the STWAVE domain for the parent grid, and 107 station locations were identified within the child grid. During the simulations, these stations recorded the significant wave height, mean wave period, mean wave direction, peak wave period, wind magnitude, wind direction, and water elevation for each time step. Station numbers 49, 50, 59,111, and 117 were chosen to produce time plot comparisons.

3 Results

3.1 NNBF configurations

The proposed NNBF were designed to attenuate surge and waves by increasing both elevation and roughness, which will lead to a change in the proportion of open water area and the habitat types of the areas. Table 4 summarizes the changes in the proportion of open water, the elevation of emergent land, and changes in open water, low marsh, high marsh, and shrub-scrub communities in each area. Note that the habitat changes are for the NNBF as modeled and were designed to be extra large-scale in both horizontal extent and elevation and do not reflect actual proposed changes in habitat types. As wetland elevation depends on mineral and biological accretion processes, any future predictions of wetland area in the future would require additional modeling to predict future accretion. However, habitat changes will be inevitable in the vicinity of any proposed CSRM measures. As sea levels rise, we expect coastal shrub-scrub area to convert to high marsh and high marsh to convert to low marsh and low marsh to convert to open water.

Table 4 Changes in habitat properties associated with implementation of proposed NNBF measures

PROPERTY	SCENARIO	HOLGATE ISLANDS	HORIZONTAL LEVEE*	BRIGANTINE	GREAT EGG
PROPORTION OPEN WATER	Base	66.9%	n/a	50.5%	50.1%
	NNBF	54.4%	n/a	42.5%	38.7%
MEAN ELEVATION (STANDARD DEVIATION) (M)	Base	0.55 (±0.95)	0.50 (±0.35)	0.27 (±0.61)	0.06 (±1.19)
	NNBF	1.06 (±1.02)	1.86 (±0.74)	1.21 (±0.82)	1.20 (±1.18)
OPEN WATER AREA (HA)	Base	1134.6 (73.6%)	26.9 (16.5%)	2199.2 (40.0%)	1382.0 (42.8%)
	NNBF	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
LOW MARSH AREA (HA)	Base	31.5 (2.0%)	11.4 (7.0%)	451.5 (8.2%)	277.0 (8.6%)
	NNBF	330.6 (21.4%)	1.7 (1.1%)	509.8 (9.3%)	1398.3 (43.3%)
HIGH MARSH AREA (HA)	Base	360.3 (23.4%)	110.7 (68.0%)	2608.7 (47.4%)	1316.2 (40.7%)
	NNBF	543.8 (35.3%)	19.5 (12.3%)	2672.4 (48.6%)	450.7 (13.9%)
TRANSITIONAL MARSH (HA)	Base	9.9 (0.6%)	11.6 (7.1%)	154.8 (2.8%)	146.6 (4.5%)
	NNBF	119.0 (7.7%)	36.6 (23.1%)	503.3 (9.1%)	325.9 (10.1%)
SHRUB-SCRUB AREA (HA)	Base	6.2 (0.4%)	2.1 (1.3%)	87.6 (1.6%)	109.3 (3.4%)
	NNBF	549.1 (35.6%)	100.8 (63.6%)	1816.3 (33.0%)	1056.2 (32.7%)

* Total area of habitat for the horizontal levee NNBF and base scenarios is slightly different due to rounding errors; shrub-scrub habitat area also includes road surface area

All proposed NNBF will require large volumes of sediment as proposed. Assuming a constant unit cost for sediment, sediment requirements can be used a proxy measurement for cost associated with construction of the NNBF. All NNBF configurations as proposed are assumed to be extra large-scale and are designed as proof-of-concept demonstrations of NNBF in the area. Based on the model results presented, the scale of any recommended NNBF will likely be reduced to minimize not only the volume of sediment required but also the changes in habitat and possible changes in estuarine circulation. As simulated, the Holgate region requires the least amount of sediment (123M yd^3 including both island expansion and the horizontal levee) while both the Brigantine and Great Egg Harbor regions are similarly sized.

Table 5 Summary of required volume of sediment required to construct extra large-scale NNBF measures

SITE	VOLUME OF SEDIMENT REQUIRED
HOLGATE	~114M yd^3 (87M m^3)
HORIZONTAL LEVEE	~9M yd^3 (7M m^3)
BRIGANTINE	~252M yd^3 (192M m^3)
GREAT EGG	~242M yd^3 (185M m^3)

3.1.1 Holgate-Beach Haven area

In the Holgate-Beach Haven area, an existing island complex and peninsula of wetland (Tuckerton Peninsula) already occupied a large proportion of back bay area to the north of Little Egg Inlet. To implement the proposed NNBF, the island complex was expanded (Figure 14). Existing islands were increased in size and elevation and new islands were created. The resulting modifications changed the percent open water from 66.9% to 54.4%, which is more open water than other regions.

Figure 14 Holgate area NNBF includes a horizontal levee along Great Bay Boulevard and island expansion and creation

The existing wetland peninsula on which the horizontal levee is located is dissected by a number of tidal creeks, which are designed to be closed by a gate during storm conditions, allowing free exchange of water during typical conditions. The horizontal levee along Great Bay Boulevard ranged in width from 137to 265 m (449 to 869 ft.), had side slopes ranging from 1:50 to 1:30, and increased the elevation from 0.50 m near the levee edges to 3.1 m at the levee crest (1.6 and 10 ft., respectively). The Engineering With Nature® and Landscape Architecture: New Jersey Back Bays report illustrates a typical cross-section for a potential horizontal levee design.

3.1.2 Brigantine

The Brigantine area was already characterized by extensive wetland islands; however, many had been dissected by navigation channels that provide conduits for easy transmission of surge into the back bay. Similar to the approach at Holgate, wetland islands were expanded, merged together, and created to reduce the total open water area and connectivity of the back bay (Figure 15). Island expansion was focused on areas of the back bay that had previously been wetland as far back as the 1930s. Other islands were created in areas of more extensive open water to prevent further wave generation where possible. The NNBF configuration (Configuration 5) included a storm surge barrier at Absecon Inlet and a cross-bay barrier along Absecon Boulevard.

Figure 15 Brigantine area NNBF included expansion and elevation of existing wetland islands

3.1.3 Great Egg Harbor Inlet

The area landward and to the north and south of Great Egg Harbor Inlet was characterized by a few wetland islands (Figure 16). The area south of the inlet had a higher proportion of open water, necessitating more island creation than the area to the north of the inlet or even the Brigantine and Holgate regions. The role of NNBF in these areas was to slow down surge entering the inlet and prevent it from propagating through the back bay and into Great Egg.

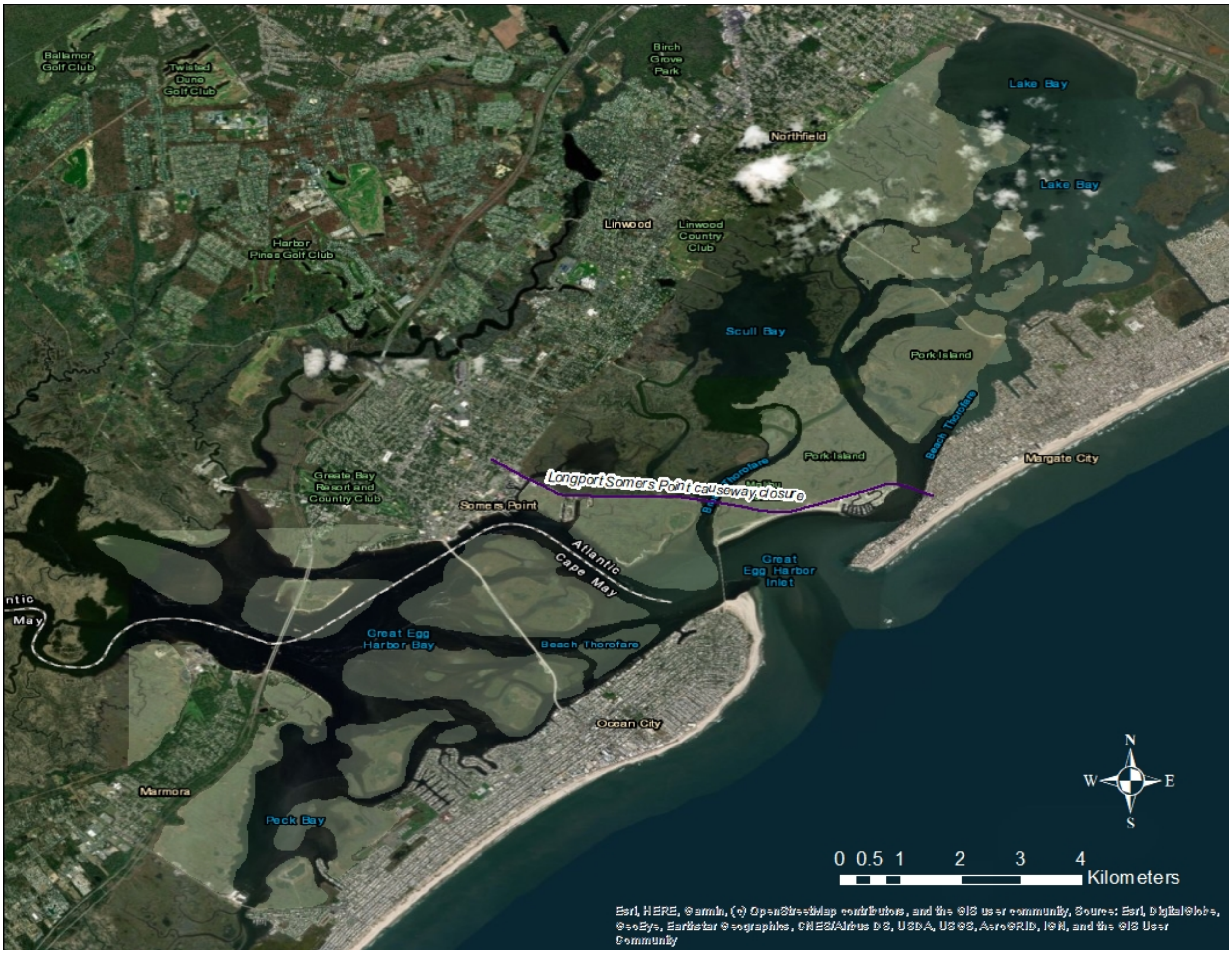


Figure 16 Great Egg Harbor Inlet area NNBF included mostly island expansion and creation south of the inlet

3.2 ADCIRC results

For both model configurations 5 (which includes the Brigantine NNBF) and 8 (which includes both the Holgate and Great Egg Harbor inlet NNBF), water level changes associated with implementation of the NNBF measures relative to the without NNBF (structural protection only) extended well beyond the area immediately adjacent to the proposed NNBF (Figure 17). Storms 350 and 636 showed two typical patterns of water level response to storms for most of the NNBF and surrounding areas. Notice that for both storm types and both configurations, there are areas of water level reductions (shown in cool blue colors) and areas of water level increases (shown in warm yellow and red colors). The water level responses in all three NNBF areas without any CSRM measures in place was greater for Storm 350 than Storm 636 (see Table 2). Storm 350 produced greater water level responses in the Holgate and Brigantine areas than the Great Egg Harbor area while Storm 636 produced the greater water level response in the Great Egg Harbor and Brigantine NNBF areas.

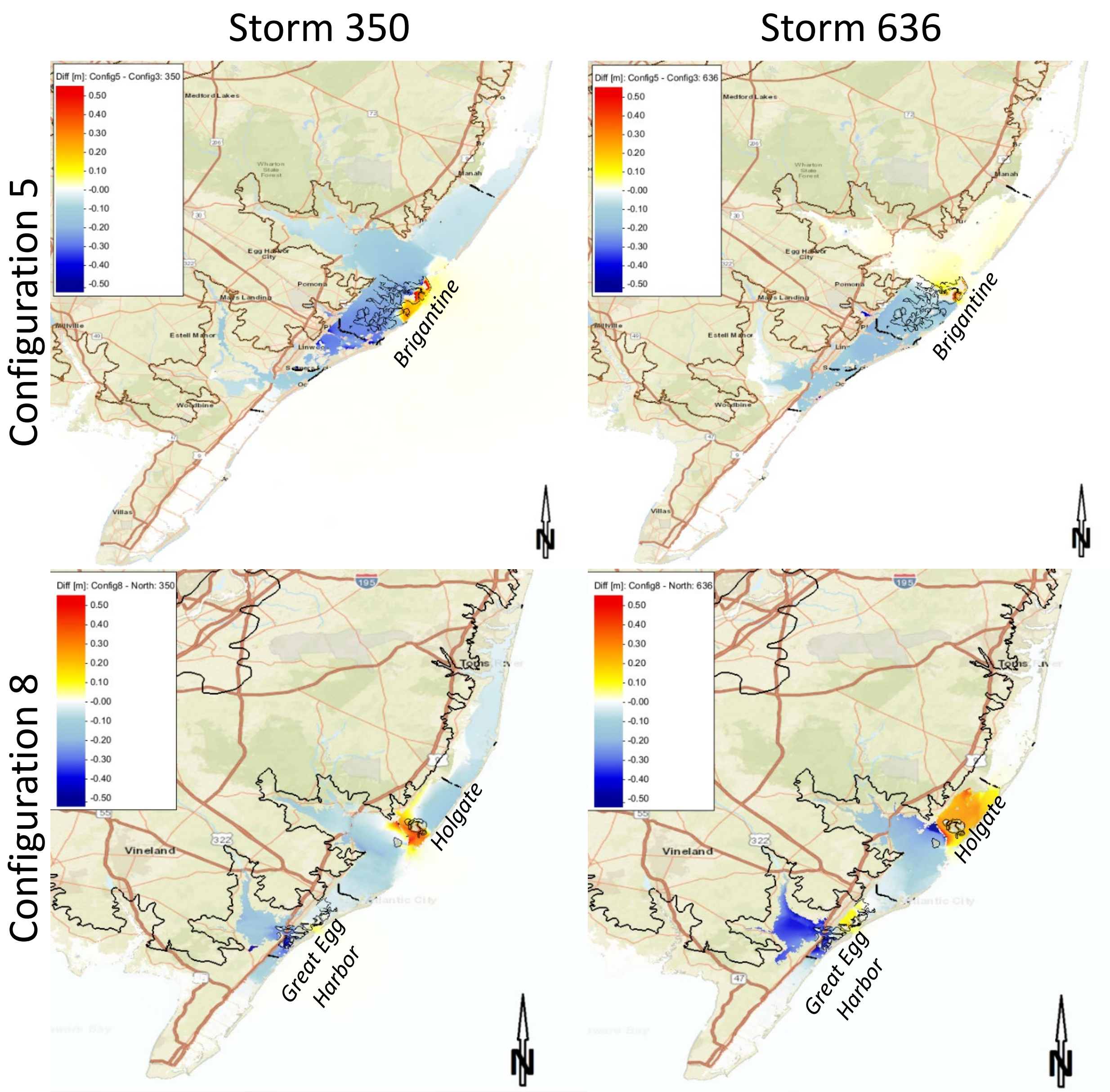


Figure 17 Difference in maximum water level elevation for storms 350 and 636 under modeling configuration 5 (Brigantine NNBF) and configuration 8 (Holgate and Great Egg Harbor NNBF) compared to the non-NNBF (structural protection only) configurations

In this report, the effects of the NNBF on back-bay water levels during storm events were compared to the water levels with only structural measures in place, to see if the NNBF could be used in combination with structural measures to improve outcomes (i.e., reduce back bay water levels and wave heights). Table 6 and Table 7 shows the peak water levels for selected save points for structural only configurations (indicated as ST) and structural and NNBF configurations (indicated as ST+NNBF). While the data in Table 2 are not directly comparable to the data is Tables 6 and 7 due to changes in the existing conditions modeled in CHS (Melby and Green, 2015) as well as the exclusion of wave influence in Table 6, the results indicate the majority of simulated water level reduction is attributable to the structural measures. The addition of NNBFs to the structural measures provides some further reductions or increases, depending on the pattern of water level response but those changes are lesser in magnitude than those induced by the structural measures. However, even in cases where NNBF may increase water levels relative to the structural-measure-only configuration, there is generally an improvement over the “do nothing” condition.

Table 6 Peak water level elevations due to surge for selected save points with structural measures only (ST, "North") and structural and NNBF (ST+NNBF, "Configuration 8") meshes.

AREA			**HOLGATE**						**GREAT EGG HARBOR**					
SAVE POINT ID			61		73		33		49		117		111	
CONFIG			ST	ST+ NNBF	ST	ST+ NNBF	ST	ST+ NNBF	ST	ST+ NNBF	ST	ST+ NNBF	ST	ST+ NNBF
STORM ID	99	**WL elev. MSL (m)**	1.85	1.69	2.48	2.40	2.34	2.32	3.11	3.15	2.73	2.85	2.72	2.32
	349		1.51	1.31	1.71	1.47	2.20	2.27	1.96	1.93	2.12	2.18	1.75	1.56
	350		1.51	1.39	1.97	2.03	2.30	2.34	2.23	2.19	1.93	2.02	2.16	1.72
	357		1.13	1.11	1.11	1.08	1.40	1.40	1.15	1.15	1.11	1.11	1.29	1.11
	433		1.75	1.76	1.99	1.79	3.69	3.89	2.21	2.21	3.12	3.48	2.41	2.03
	434		1.59	1.60	1.77	1.93	2.17	2.17	2.15	2.16	2.09	2.19	2.22	1.87
	469		1.35	1.45	1.48	1.67	2.02	2.06	1.67	1.68	2.03	2.14	2.12	1.75
	524		1.02	0.83	1.37	1.30	1.39	1.40	1.88	1.88	1.77	1.82	1.46	1.53
	636		1.05	1.26	1.49	1.73	1.63	1.60	1.43	1.43	1.70	1.78	2.04	1.68
	646		0.99	1.08	0.94	1.04	1.41	1.43	1.12	1.07	1.61	1.69	1.82	1.43

Table 7 Peak water level elevations due to surge and waves for selected save points with structural measures only (ST, "Configuration 3") and structural and NNBF (ST+NNBF, "Configuration 5") meshes.

AREA			BRIGANTINE			
SAVE POINT ID			59		50	
CONFIG			ST	ST+ NNBF	ST	ST+ NNBF
STORM ID	99	WL elev. MSL (m)	2.72	2.75	3.70	3.50
	349		2.23	2.59	2.13	1.89
	350		2.38	2.49	2.89	2.62
	357		1.70	1.62	1.67	1.54
	433		3.46	4.11	2.23	1.81
	434		2.66	2.54	3.08	2.84
	469		2.15	2.20	2.23	2.01
	524		0.94	1.02	1.28	1.14
	636		2.38	2.22	2.66	2.48
	646		1.72	1.72	1.51	1.36

Configuration 8 did not include the effects of the NNBF on waves. However, based on the STWAVE results from Configuration 5, the reduction or amplification of wave heights associated with the NNBF may significantly affect water level response and should be accounted for to capture the full effect of the NNBF.

3.2.1 Holgate

At the Holgate restored marsh location, storms, such as 99, 350, and 433 showed peak water level reductions north and south of the horizontal levees and islands and increased water levels in the vicinity of the island complex (Figure 18, top panel). However, storms 636, 646, 434, and 469 exhibited strong north to south winds; the horizontal levee and created islands blocked flow from exiting Little Egg Harbor resulting in an extensive area of increased maximum water levels north of the restored marsh (Figure 18, bottom panel). This pattern persisted for storms with north to south winds regardless of the magnitude of the water level responses.

For all storms including storm 636, the gates across the tidal creeks along the horizontal levee remained closed. However, the increases in water levels associated with the north to south wind direction may be moderated by leaving the horizontal levee gates open. The extent to which the gates can be used to affect water levels north of the Holgate NNBF is not clear. Further analysis would be required to balance water level response reductions in one area with increases in others. For instance storm 350 produced widespread reductions in water levels south of the levee in Great Bay and in parts of Little Egg Harbor and Manahawkin Bay north of Beach Haven while increasing water levels along Tuckerton Beach, the fringing wetlands along the landward shoreline of Little Egg Harbor and Manahawkin Bay, and in areas around Mystic Island. Additionally, several of the islands remain emergent at high water levels indicating that island elevations could potentially be lowered while still reducing storm water levels for storms that produced lower water level responses under storm conditions similar to storm 350, potentially moderating some of the adverse effects on water level response under some storm conditions.

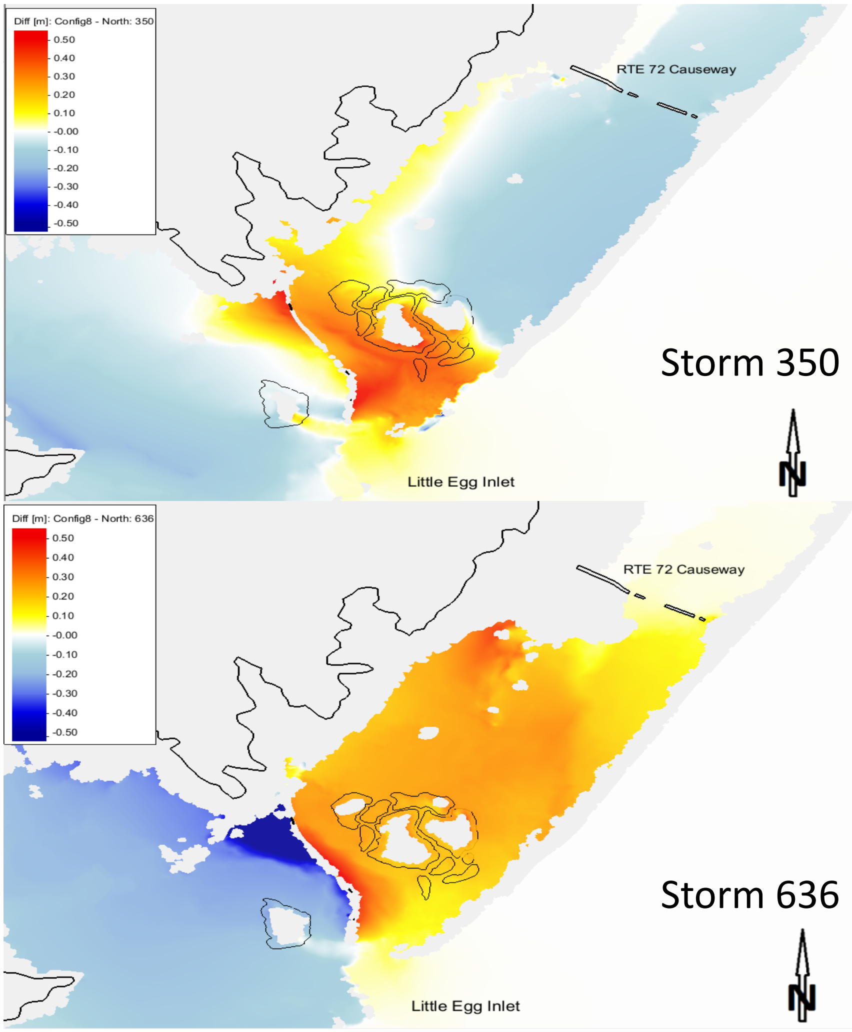


Figure 18 Peak water level differences due to Holgate Island and horizontal levee NNBF for storms 350 and 636

Like peak water levels, the effects of the NNBF on individual storm hydrographs was variable. Figure 19 shows the location of the three save points used in the Holgate region to show the effect of NNBFs on storm hydrograph characteristics such as duration and peak timing. Save point 33 was "in front of" the NNBF while points 61 and 73 were "behind" the NNBF, assuming Little Egg Inlet was the primary conduit for surge into Little Egg Harbor and Manahawkin Bay. For reference, the base condition peak water levels reported at points 61 and 73 in the Coastal Hazards System for these save points were 2.29 and 3.04 m, respectively, which indicates that the surge barriers further north at Manasquan and Barnegat Inlets already reduce water levels at these locations to 1.50 and 1.98 m, respectively. For this storm, the NNBF has a negligible effect on the water level hydrograph at point 33, there is a slight increase in water level and phase lead (more rapid increase in water level) at point 73 to 2.04 m, and decreased water level to 1.35 m that leads in phase at point 61.

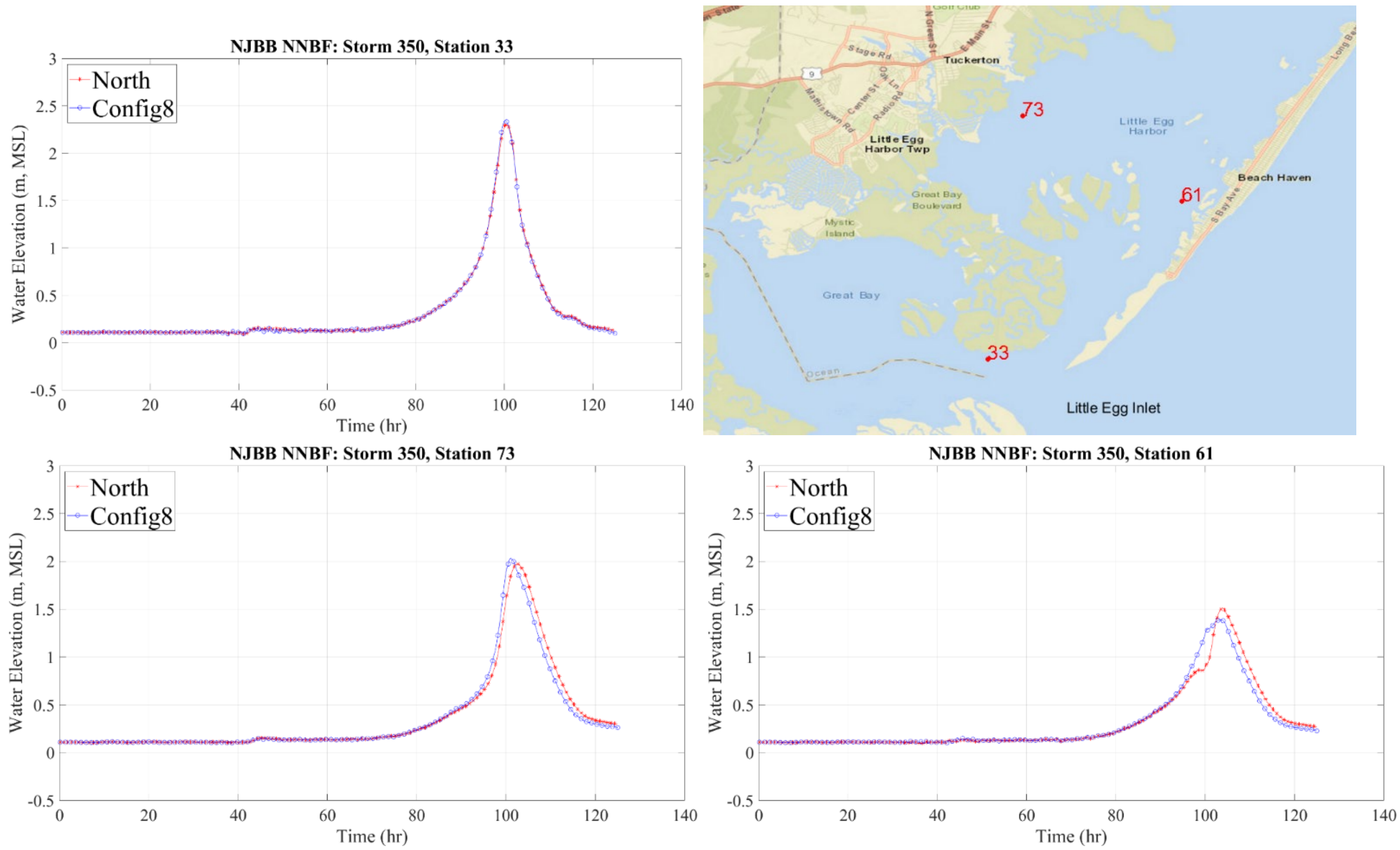
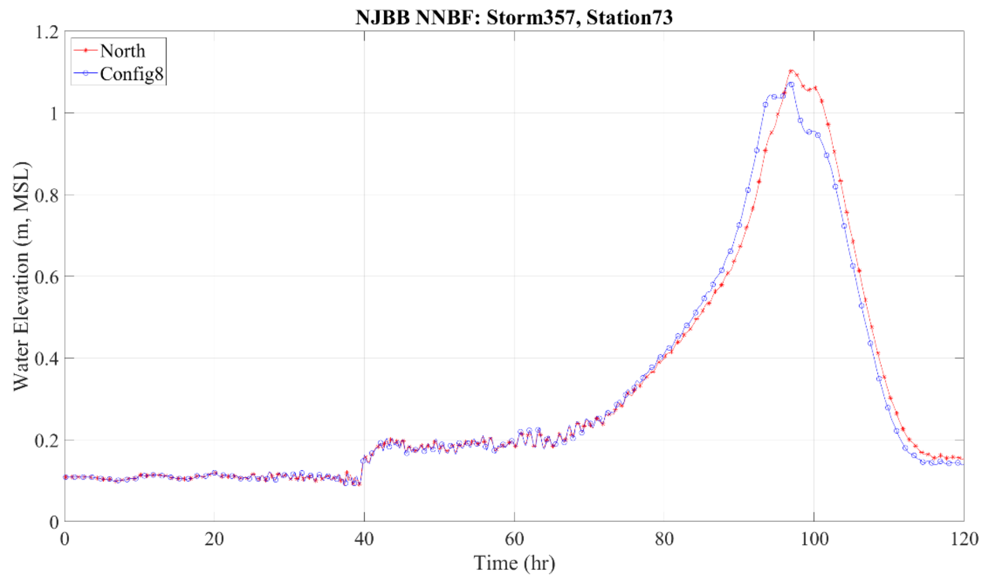


Figure 19 Holgate save points and examples of storm hydrograph effects for storm 350. The blue hydrograph represents the configuration with NNBF and structural measures and the red hydrograph represents the configuration with structural measures only

For storms 357 and 524, which of all simulated storms produced the lowest water level responses in this area with no CSRM measures in place, the effect of the NNBF on the hydrograph shape was inconsistent. In the case of storm 357, water levels increased more rapidly and initially fell more quickly with only a few centimeters reduction in peak water level elevation at station 73. However, for storm 524, water levels increased at about the same rate but water levels fell more quickly with the NNBF in place, decreasing the duration of potential flooding.



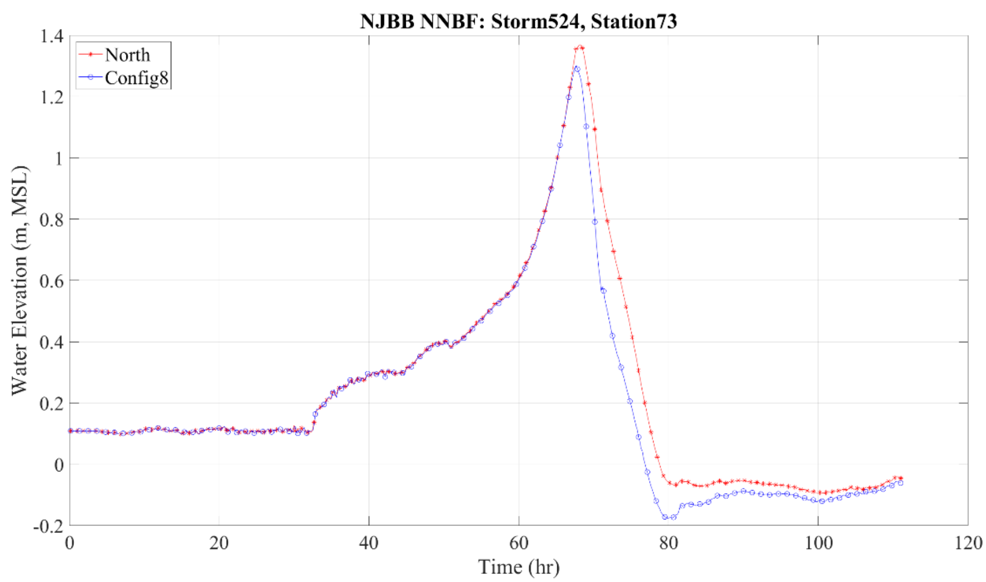


Figure 20 Holgate NNBF effects on hydrographs at save point 73 for two high annual exceedance probability storms. The blue hydrograph represents the configuration with NNBF and structural measures and the red hydrograph represents the configuration with structural measures only

3.2.2 Brigantine

The maximum water level envelope comparisons show that the Absecon Bay marshes provide an added reduction in water level due to surge and waves in Absecon Bay and Reed Bay on the order of 10 to 30 cm, depending on the characteristics of the simulated storm (Figure 15, Figure 21). The NNBFs serve to suppress flow into these bays with a corresponding slight increase in water level in Great Bay for storms with stronger winds from the north and fairly significant increased water levels (10-40 cm) near the low barrier island section/ocean fronting edge of the marsh when winds are from the east. The spatial extent of the reduced water levels extends beyond the marsh restoration area for a surprising great distance. Maximum water levels are reduced with the marshes restored as far north as Little Egg Harbor and southward into Lake Bay, Scull Bay, Great Egg Harbor Bay, and Peck Bay.

Of the ten storms that were simulated, six show partial to complete bay reductions of 10-30 cm in the southern bays, showing that the NNBF serve to suppress flow from the north and thus mitigates surge from entering the southern bays through the navigation channel opening at the Absecon Blvd causeway. Storm 350 shows a typical response of reduction in maximum water level in Absecon and Reed Bay extending northward into Great Bay and Little Egg Harbor and southward into Lake Bay, Scull Bay, Great Egg Harbor Bay, and Peck Bay and increased maximum water levels near the ocean fronting edge of the restored marsh region.

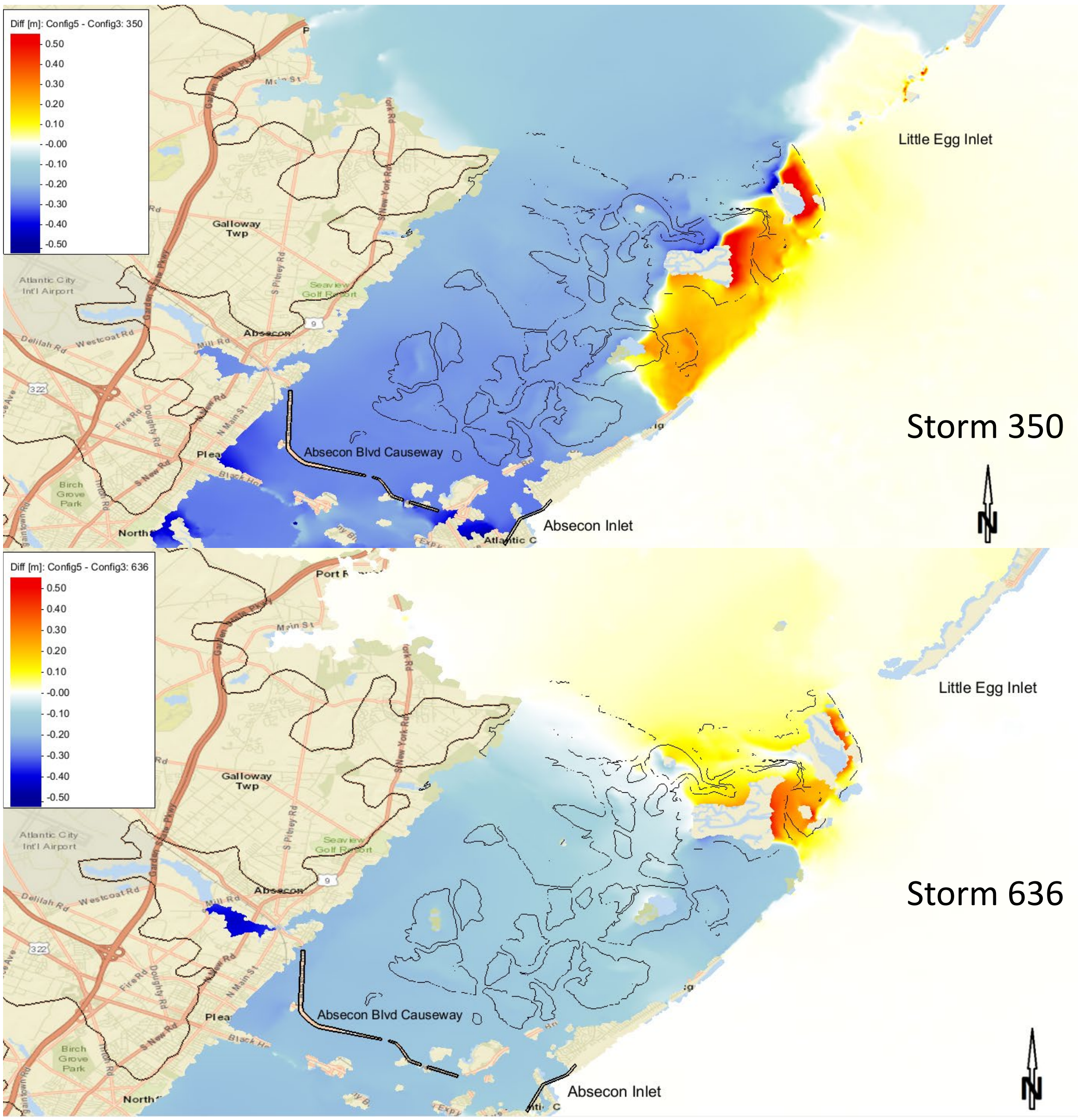


Figure 21 Peak water level differences due to Brigantine area NNBF for storms 350 and 636

The second typical response is demonstrated by the response to Storm 636 forcing, which results in increased water levels north of the restored marsh region and reductions extending from Reed Bay southward to Peck Bay, due to the predominant north to south wind direction and the suppression of flow to the south afforded by the restored marshes.

The NNBF typically reduced the duration of elevated water levels in Absecon Bay at save point 50 (Figure 22). The duration of water level above 2.6 m was reduced on the order of 10 hours for storm 350, which could reduce potential flooding in some surrounding areas, especially in cases where elevated water levels cause overtopping of existing or proposed floodwalls or levees.

The addition of the NNBFs reduced water levels in Absecon Bay at save point 50 during all storm conditions when compared with structural measures alone. The area of water level reduction for Storms 350 and 636 also extended south into Lake Bay to save point 49 on the other side of Absecon Boulevard causeway.

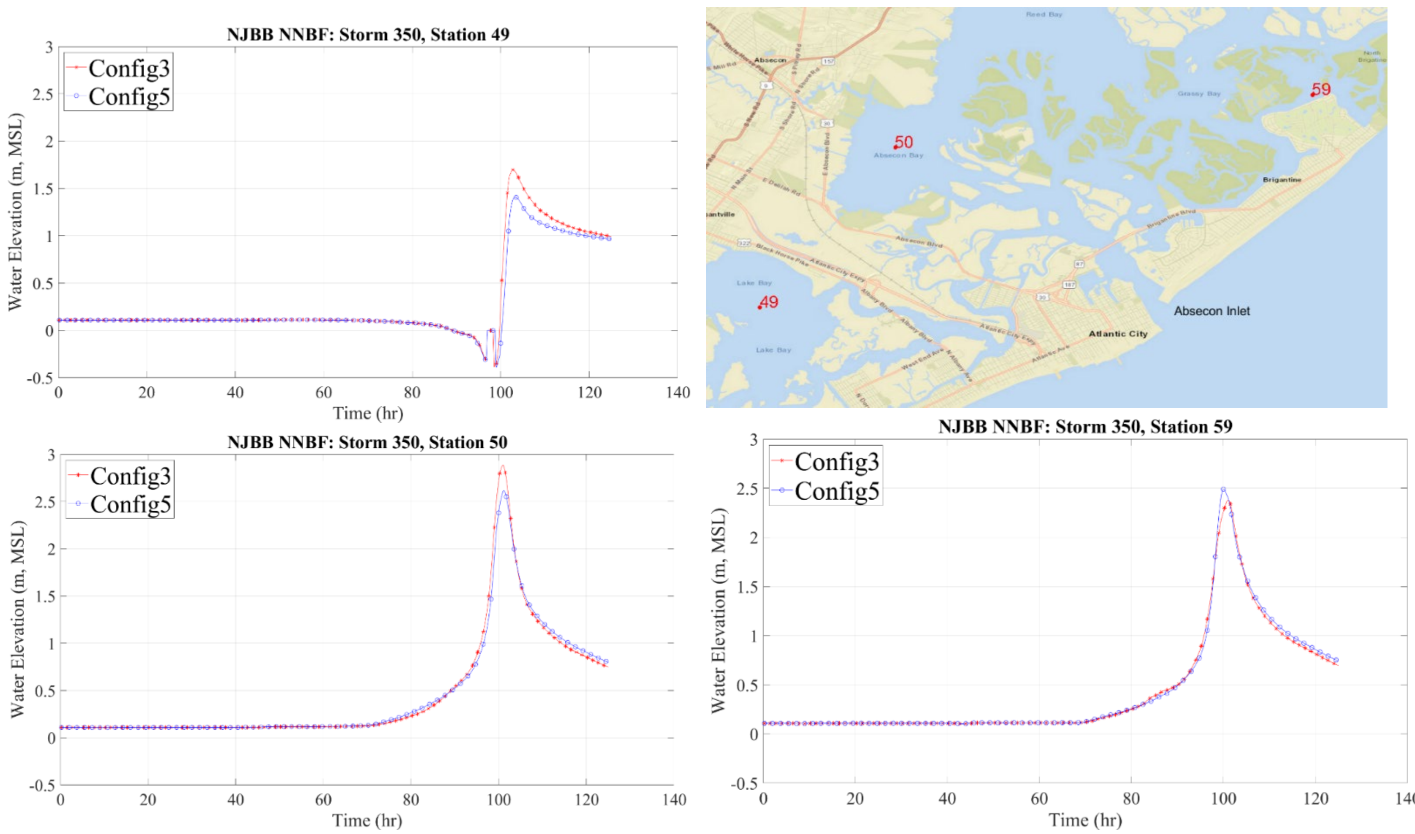


Figure 22 Brigantine save points and examples of storm hydrograph effects for storm 350. The blue hydrograph represents the configuration with NNBF and structural measures and the red hydrograph represents the configuration with structural measures only

3.2.3 Great Egg Harbor Inlet

The Great Egg Harbor Inlet response was significantly different in the areas north and south of the inlet (Figure 23). Generally the magnitude of water level reduction was the greatest for the areas south of the inlet and more modest for areas to the north. However, this was expected as the extent of existing wetland in the back bay limited the degree to which additional NNBFs could be expanded and the Longport-Somers Point causeway already serves to reduce storm surge propagating northward from Great Egg Harbor Inlet into the back bay.

With Great Egg Harbor Inlet open to surge propagation and the addition of fairly extensive (relative to the size of the bay) NNBFs in close proximity to the inlet entrance, maximum water levels actually increase in the Great Egg Harbor Inlet/restored marsh region and maximum water levels are in most cases reduced in Great Egg Harbor Bay "behind" the NNBF regions. This response is similar to closing Great Egg Harbor Inlet with a surge barrier, except that with the inlet open and NNBFs in place, maximum water levels increase in the portion of the bay closest to the inlet opening and adjacent to the barrier islands. Storms 99, 433, 434, 469, and 636 show this typical response in the Great Egg Harbor region.

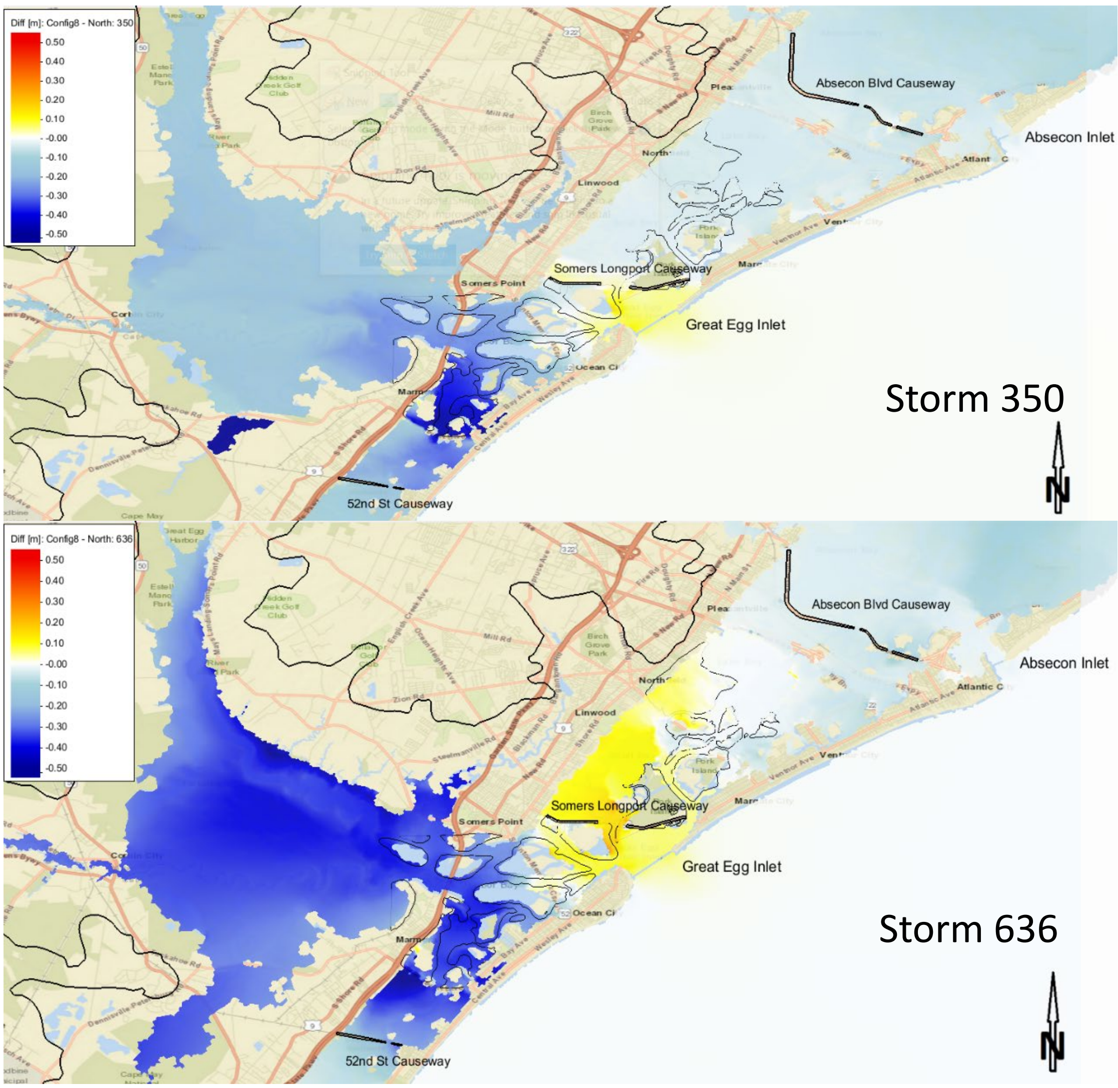


Figure 23 Peak water level differences due to Great Egg Harbor area NNBF for storms 350 and 636

Storm 636 also shows increases in water levels north of the inlet due to the blocking effect of the islands adjacent to the inlet, similar to the island blocking effect observed at Holgate. However, Figure 21 indicates the Brigantine area NNBF can also reduce water levels in Lake Bay and

Scull Bay during storm 636. Since Configuration 8 was run independently of Configuration 5, it is unclear what the combined effect of the proposed NNBF in the Brigantine and Great Egg Harbor areas would be and if the Brigantine NNBF could potentially reduce the adverse effects on water levels in the back bay areas north of Great Egg Harbor Inlet.

In the Great Egg Harbor area, storm hydrograph responses were fairly consistent for most storms regardless of the overall water level. Negligible differences in the water level hydrographs were observed at save point 49 with and without the NNBFs. Elevated water levels were consistently observed at save point 117 near the inlet with more significant water level increases occurring during storms with greater forward speed. The greatest water level decreases occurred to the south of the inlet at save point 111. Generally, peak water levels were reduced but the trailing end of the hydrograph was slightly prolonged since the islands decreased the rate at which water could leave the back bay.

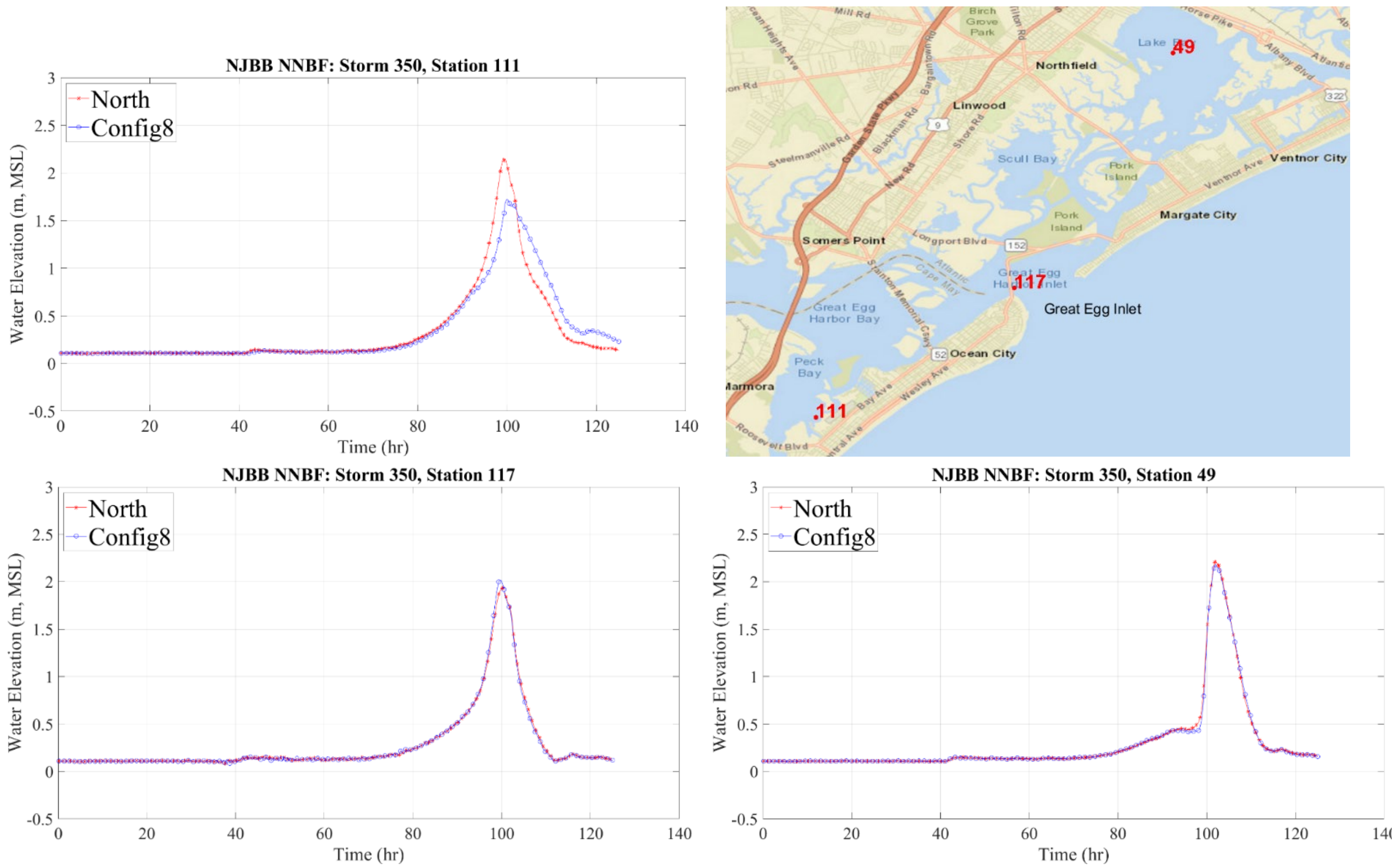


Figure 24 Great Egg Harbor save points and examples of storm hydrograph effects for storm 350. The blue hydrograph represents the configuration with NNBF and structural measures and the red hydrograph represents the configuration with structural measures only

NNBF options in the Great Egg Harbor area may have some dependency on the NNBF proposed in the Brigantine area and the effects should be investigated together. Additional modeling should consider the potential effects of the NNBF in the southern portion of the Great Egg

Harbor area on flows from Great Egg Harbor River to ensure that the NNBFs do not exacerbate potential riverine flooding upstream.

3.3 STWAVE results

From the results of the child domain, plots of the maximum significant wave height for each simulation, as well as, time series plots from the 5 identified stations are provided in Appendix B. For discussion, the plots and results from Storms 350 and 636 will be included here.

Figure 25 and Figure 26 show a "zoomed-in" depiction of the wave heights around the project designs. Shown in Figure 25 are the maximum significant wave heights for storm 350 for Configurations 3 and 5. The maximum observed significant wave height values were greater than 20 ft., with most of the wave energy breaking along the open coastline, indicating the waves generated around the NNBF islands, which are sheltered behind the barrier islands, is due to local wind growth. Storm 636, shown in Figure 26, the maximum significant wave height values were also greater than 20 ft., and similar to what was observed in storm 350, the wave energy appears to break along the coastline, indicating local generation in the areas of the NNBF.

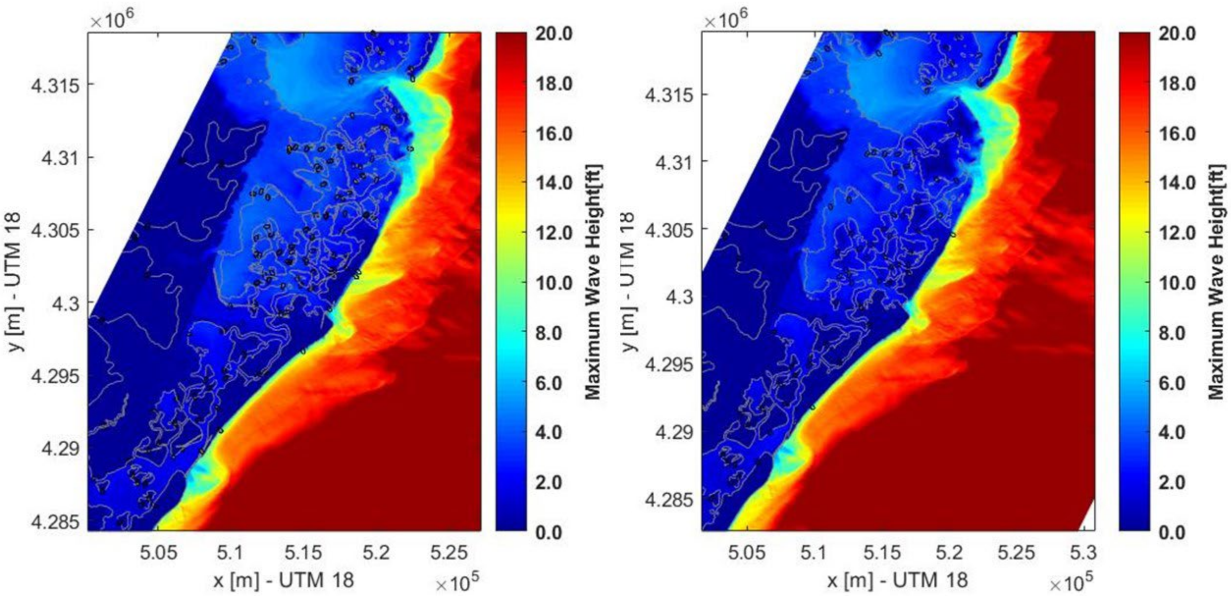


Figure 25 Max Wave Height (ft) of Storm 350 for Configuration 3 (left) and Configuration 5 (right).

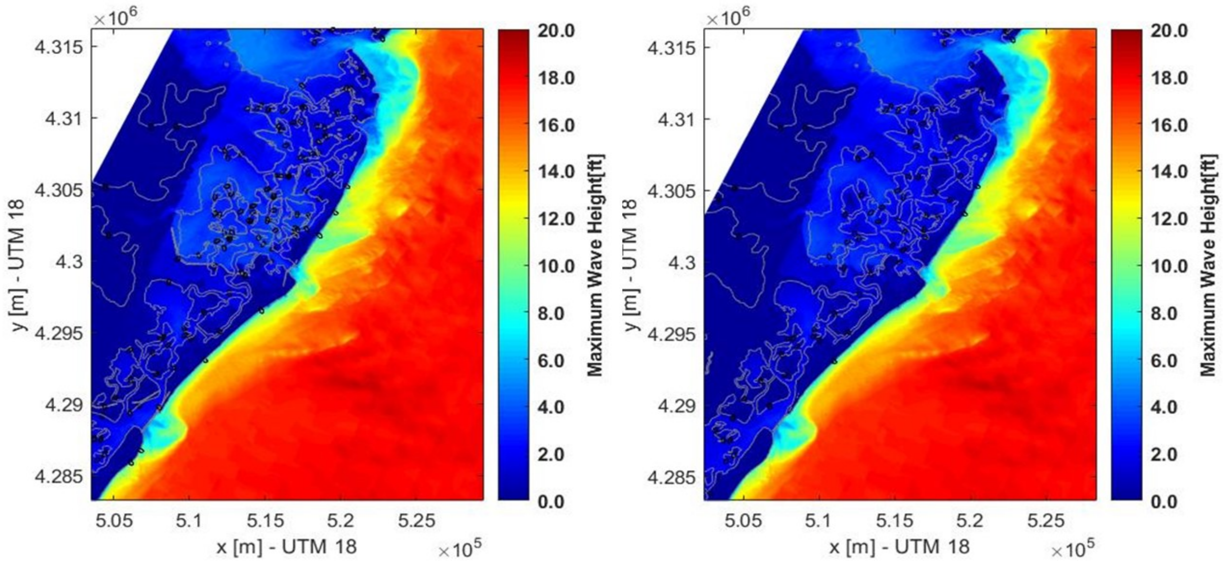


Figure 26 Max Wave Height (ft) of Storm 636 for Configuration 3 (left) and Configuration 5 (right).

Differences are observed in the maximum wave heights between Configuration 3 and 5. For storm 350, shown in Figure 27, a reduction of 3.5 ft. is shown due to the presence of the NNBF. Slight increases of ~1 ft. are observed behind the storm surge barrier at Little Egg and Brigantine Inlets, and along the perimeter of a few of the NNBF islands. For storm 636, shown in Figure 28, reductions of 2-3 feet are shown in the areas where the implemented NNBF islands are present. Some slight, 1 ft. or fewer, increases are observed around the perimeter of a few of the NNBF

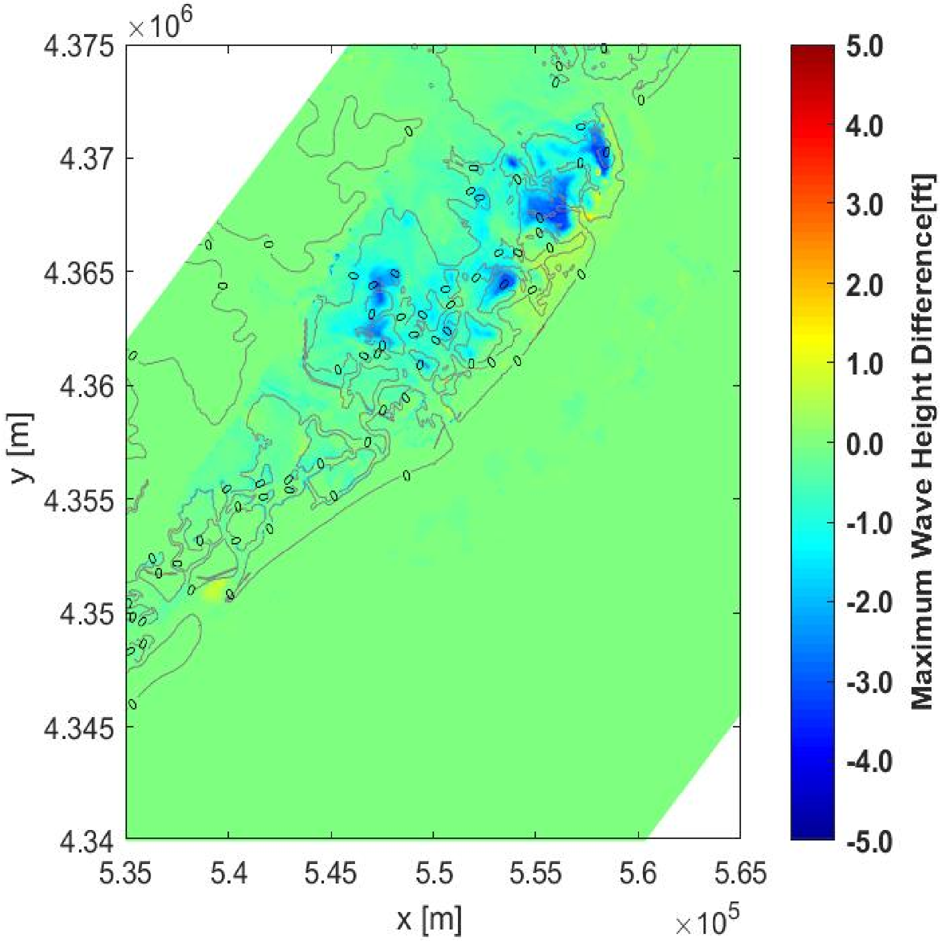


Figure 27 Maximum wave height difference for storm 350 between Configuration 3 and Configuration 5. Cool tones indicate reductions in wave height due to NNBFs and warmer tones indicate wave height increases due to NNBFs.

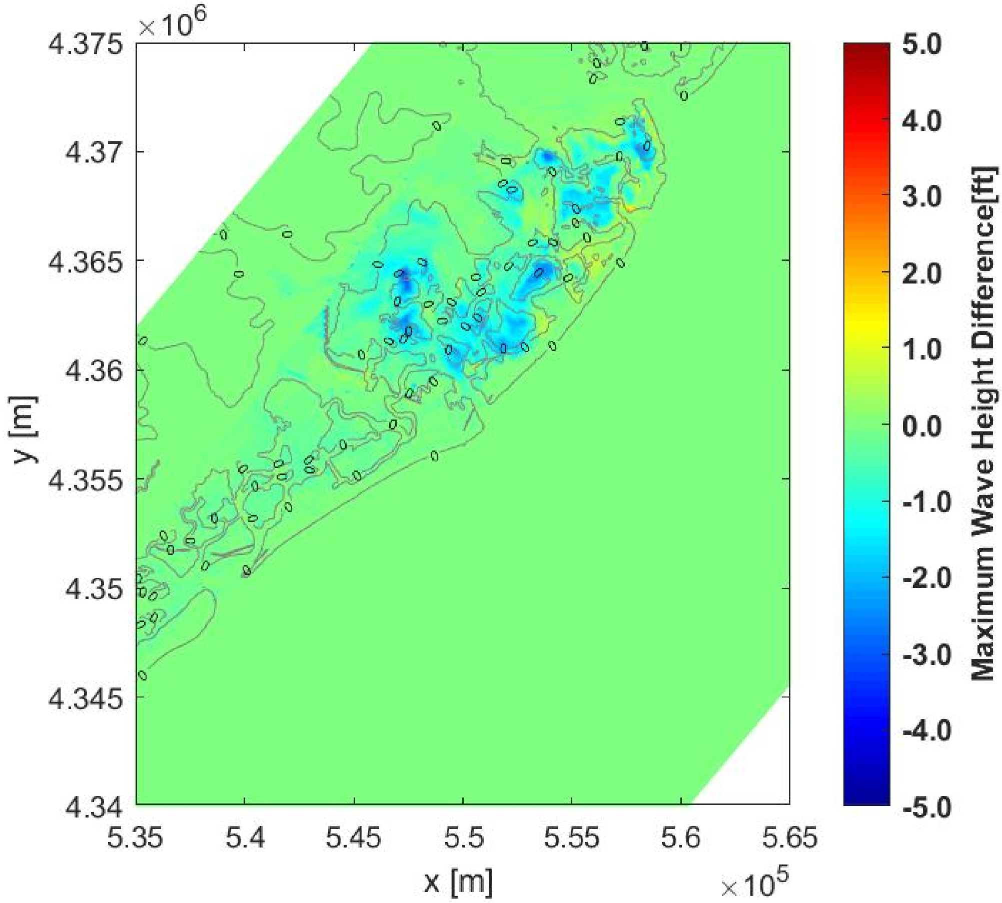


Figure 28 Maximum wave height difference for storm 636 between Configuration 3 and Configuration 5. Cool tones indicate reductions in wave height due to NNBFs and warmer tones indicate wave height increases due to NNBFs.

The time series plots show the growth and decay of wave heights through the simulated storm event, at each of the selected locations (Figure 29 and Figure 30). For storm 350, stations 49, 111, and 117 show very little difference in significant wave height between the two configurations. However, station 50 shows decreases in the significant wave height for configuration 5 of approximately 0.3m during the peak of the storm and station 59 shows a consistent decrease in significant wave height throughout the entire storm of roughly 0.05m. For storm 636, stations 49, 50 and 111 show very slight decreases in wave height during the peak of the storm between the two configurations, and station 59 shows decreases in wave height of approximately 0.3m during the peak and decay of the storm. While, station 117 shows a slight increase (~0.1m) in the wave height during the growth and peak of the storm for configuration 5.

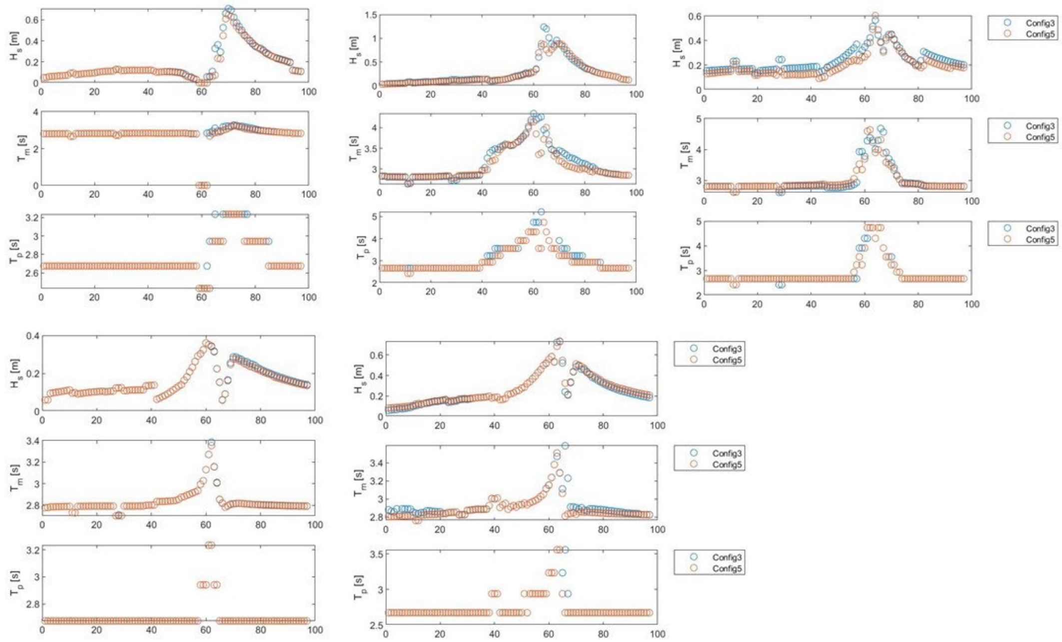


Figure 29 Time series of significant wave height, peak period, and mean period for Storm 350. Top row, from left to right is station 49, 50, 59. Bottom row, from left to right is station 111, 117. Configuration 3 is shown in blue, Configuration 5 in orange.

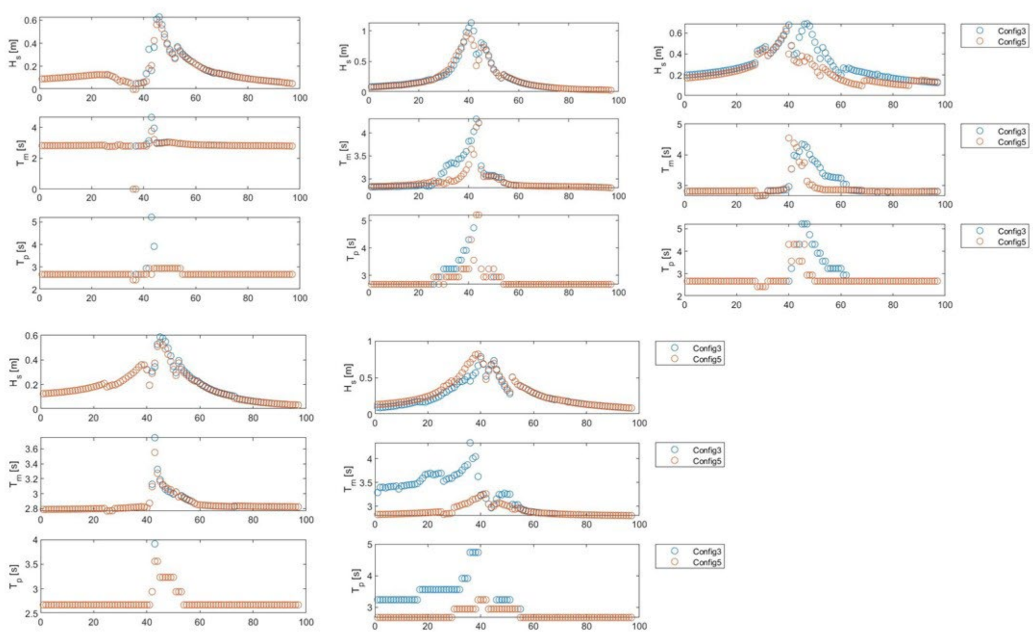


Figure 30 Time series of significant wave height, peak period, and mean period for Storm 636. Top row, from left to right is station 49, 50, 59. Bottom row, from left to right is station 111, 117. Configuration 3 is shown in blue, Configuration 5 in orange.

4 Discussion

Storm characteristics, particularly wind direction and overall storm intensity, strongly influenced how water levels responded to the implementation of the proposed NNBF. In some cases, the addition of NNBFs increased water levels relative to the configurations that included only structural measures, especially in situations that created strong north to south winds. For the storms that exhibited the greatest water level response in the NJBB area (particularly storms 0099 and 0434 with water level elevations greater than 3 m MSL without CSRM measures in place for almost all save points considered), most of the proposed NNBFs did little to affect water levels in most areas. However, even under relatively high water levels (around 3 m MSL), wave heights were reduced by approximately 0.3 m near storm peaks in the Brigantine area. The impact of the NNBF on wave heights was not assessed in the Holgate and Great Egg Harbor area since STWAVE was not run for Configuration 8 but if potential wave attenuation is factored in, the NNBFs in those areas may result in more pronounced reductions in water levels for some parts of the model domain.

For storms with less extreme water level responses, the proposed NNBFs reduced water levels from the base configurations that only included simulated structural measures in many locations. Depending on operation rules for proposed surge barriers, the proposed NNBFs could possibly provide enough reduction in water levels during higher storm response events to permit surge barriers to be left open during some less intense storms, reducing operations costs and minimizing any potential adverse environmental impacts associated with barrier closure. Additional analysis would be required to determine the storm conditions that would permit proposed barriers to be left open.

As mentioned previously, there are some areas adjacent to NNBF that could experience increases in water levels, especially during storms with north to south wind direction; these increases are relatively localized along the leading edge of the features in some areas such as Brigantine and widespread in others such as during storm 0636 where elevated water levels in Little Egg Harbor Bay and the southern portion of Manahawkin Bay are on the order of ~30 cm. Careful design can minimize these effects in some cases. For instance, the NNBF can be designed so unavoidable local regions of water level increase to fall in unpopulated and undeveloped or minimally developed areas such as wildlife refuges or golf courses. If NNBFs are designed to provide benefits for storm events with higher water levels, the elevation can be constrained to prevent extreme water level increases over large areas. For the Holgate area, the horizontal levee could be redesigned, removed, or the proposed gates blocking tidal creeks along the horizontal levee could be left open in the event of sustained north to south winds. Open gates would potentially reduce water levels north of the levee caused by flow blocking. However, the impact of any of these changes would need additional analysis to determine the magnitude of the effect during different storm conditions.

While water level change attributable to NNBF for most of the NJBB domain was relatively modest (on the order of 10-30 with some areas up to 50 cm), for many storms, the reductions in water levels occurred over a several-hour time span (~10 hours for storm 350 at save point 50 in Absecon Bay, for example). In areas protected by other structural measures such as levees or flood walls, the duration of the reduction of peak water levels can lead to reductions in flooding due to overtopping of structures as well as the load stress by shortening the duration of the highest water levels. The degree to which this water level reduction produces CSRM benefits will vary with the design of the comprehensive system of structural, NNBF, and nonstructural measures put into place. While NNBF alone may not provide the full scale of CSRM benefits, when combined with target structural and nonstructural measures, economic benefits may emerge such as reducing the required heights of structural measures such as flood walls and levees, reduced operation of surge barriers for lower magnitude storm events, improving the safety of residents not required to evacuate through reduced risk of overtopping as well as reduced risk of structural failure by reducing total loading on structural measures in the back bay environment. To quantify these potential benefits, the results provided here should be used to design additional perimeter structures and combined with economic models or simple stage-damage curves to determine how NNBF can be combined with additional structural measures to reduce economic damages and improve life safety.

5 Recommendations and next steps

The results from this initial modeling study show NNBF can provide some benefit by reducing coastal storm risk in the New Jersey back bays in some areas. The degree to which the simulated features can provide reductions in water level depends strongly on the location of concern relative to the NNBF location and the storm characteristics. While no configuration showed that the addition of the proposed NNBF measures were able to reduce water levels enough to eliminate the need for additional structural measures such as perimeter floodwalls or levees, the results do indicate that NNBF paired with some additional structural measures may show promise in reducing operation frequency of surge barriers or reducing the required height of cross-bay closures and perimeter flood walls and levees, which may be desirable from an aesthetic standpoint.

Wave modeling results in the Brigantine area show that the simulated NNBF measures were particularly effective at reducing wave heights well into the back bay region despite increasing wave heights along the fronting edge of the island features. The design of these features can be altered by changing the elevation and location of the features to minimize the wave amplification caused by these features or localize the region of amplification to undeveloped regions of the back bay.

Future work should consider reconfiguration of NNBF measures at Holgate and Great Egg Harbor to minimize adverse effects on water level during certain storm conditions. Performing coupled ADCIRC and STWAVE simulations for these areas may indicate additional benefits of the NNBFs in this region. At Holgate, the proposed horizontal levee uses gates where major tidal creeks cross Great Bay Boulevard. Additional modeling of storms such as storm 636 with strong north to south winds should be considered to determine if adverse effects on water levels north of the NNBF islands and the horizontal levee can be reduced by keeping the gates open or if the horizontal levee should be re-designed or eliminated to prevent flooding caused by the presence of the levee and islands. The widespread reductions in water levels throughout some parts of Little Egg Harbor and Manahawkin Bay during certain storm conditions show the NNBF islands and the horizontal levee are effective at reducing surge entering through Little Egg Inlet but the effect of the islands or the horizontal levee alone was not assessed. Likewise, it is unclear if the islands or the horizontal levee is the primary driver of the widespread increases in water levels associated with storm conditions that produce north to south winds. Further analysis is required to determine what types of NNBF could potentially produce CSRM benefits in that area.

At Great Egg Harbor, like Brigantine, the features as proposed cause some surge amplification near the inlet mouth. Reconfiguration and changes in the height of the features may allow this unavoidable amplification to be localized to well-protected or undeveloped areas whereas in the current configuration, the amplification occurs close to the well-developed inlet. Examination of the NNBF in association with structural measures in this region is especially critical given the density of development in the inlet area.

Final decisions on the utility of the NNBF measures implemented in this report should be informed by economic models to determine if the maximum water level reduction and duration of reduction in these regions may translate to economic benefits either directly through reduction in damages or indirectly through reduction in height of perimeter structural measures or reduced operations of surge barriers. While NNBF measures as modeled in this report are likely not cost-effective given the volume of sediment required, further work should examine the efficacy of the measures if the elevation and/or extent of the features are reduced. Given water level changes attributable to NNBFs were strongly controlled by storm characteristics rather than baseline water level alone, the effect of “medium” or “large” sized NNBFs should be examined to determine if sediment volumes required to construct the features could be reduced while still reducing water levels in critical areas under a subset of storm conditions. Since some areas like Brigantine showed water level reductions attributable to NNBFs even under conditions where the NNBFs were inundated, lower elevation NNBFs may still potentially provide CSRM benefits with significantly less required sediment. Additionally, the feasibility of utilizing navigational dredged material to construct any NNBFs as part of routine maintenance should be examined as a cost-savings measure, utilizing the Seven Mile Island Innovation Lab as a testbed to determine how to cost-effectively utilize dredged material in this manner. Likewise, additional modeling should examine the benefits of existing wetland and back bay islands, especially under future conditions that factor in the effects of sea level rise, to determine the value of preserving and restoring the existing wetlands in the system similar to the analysis conducted by The Nature Conservancy (Narayan et al., 2017). The current modeling results alone are not sufficient to exclude any type of NNBF from consideration. Further analysis with the PDT should provide additional information on the potential CSRM benefits.

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Appendix A: ADCIRC auxiliary modeling results

Mesh changes implemented in ADCIRC

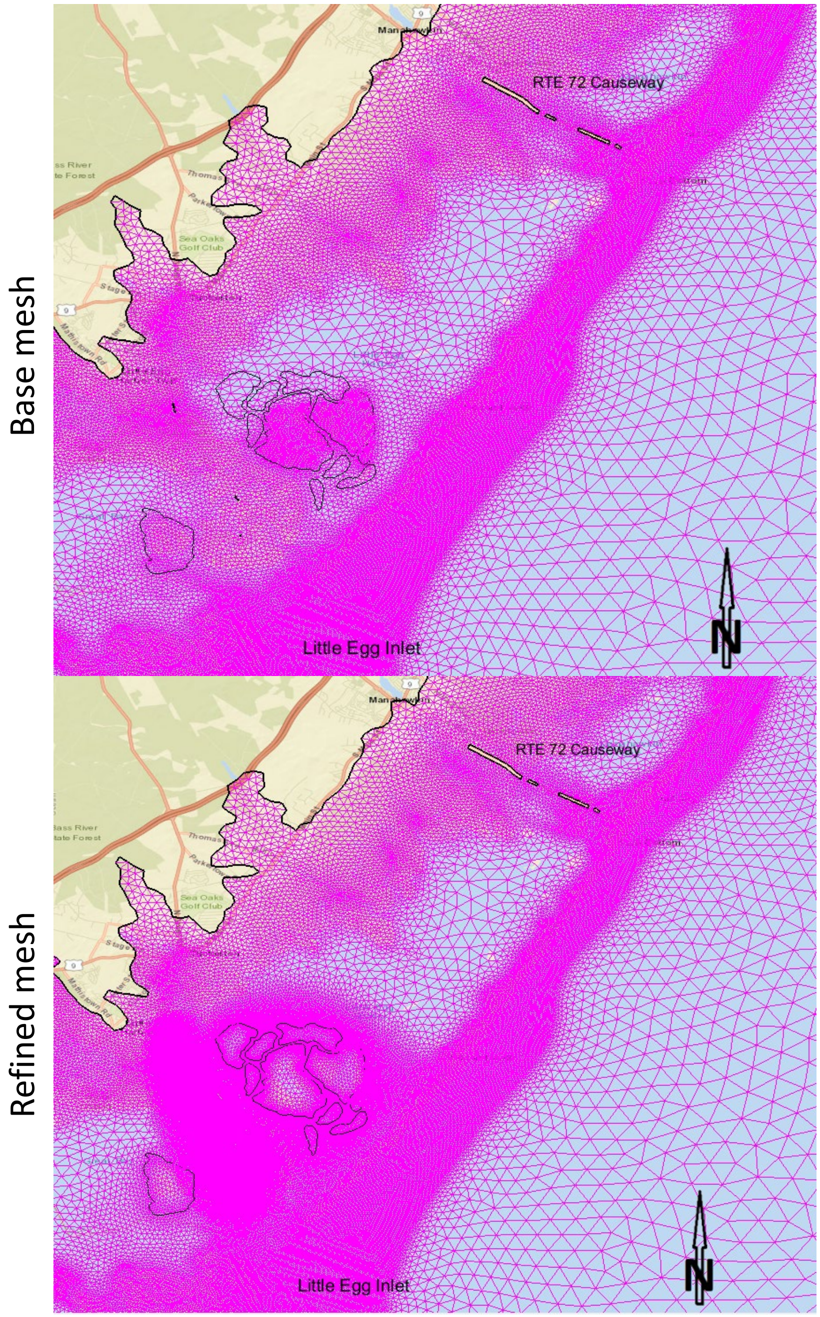

Figure 31 Change in mesh resolution in the Holgate area to accommodate the NNBF

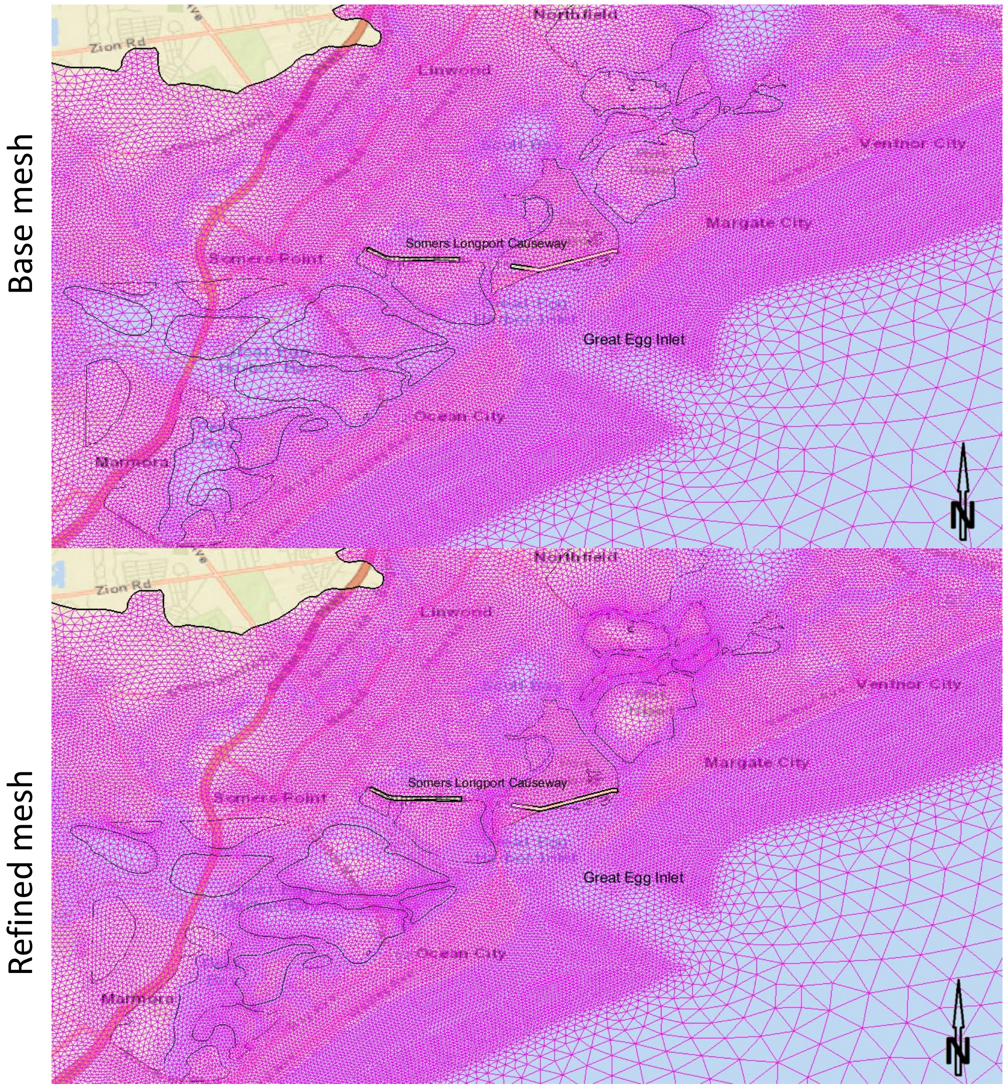

Figure 32 Change in mesh resolution in the Great Egg Harbor area to accommodate the NNBF

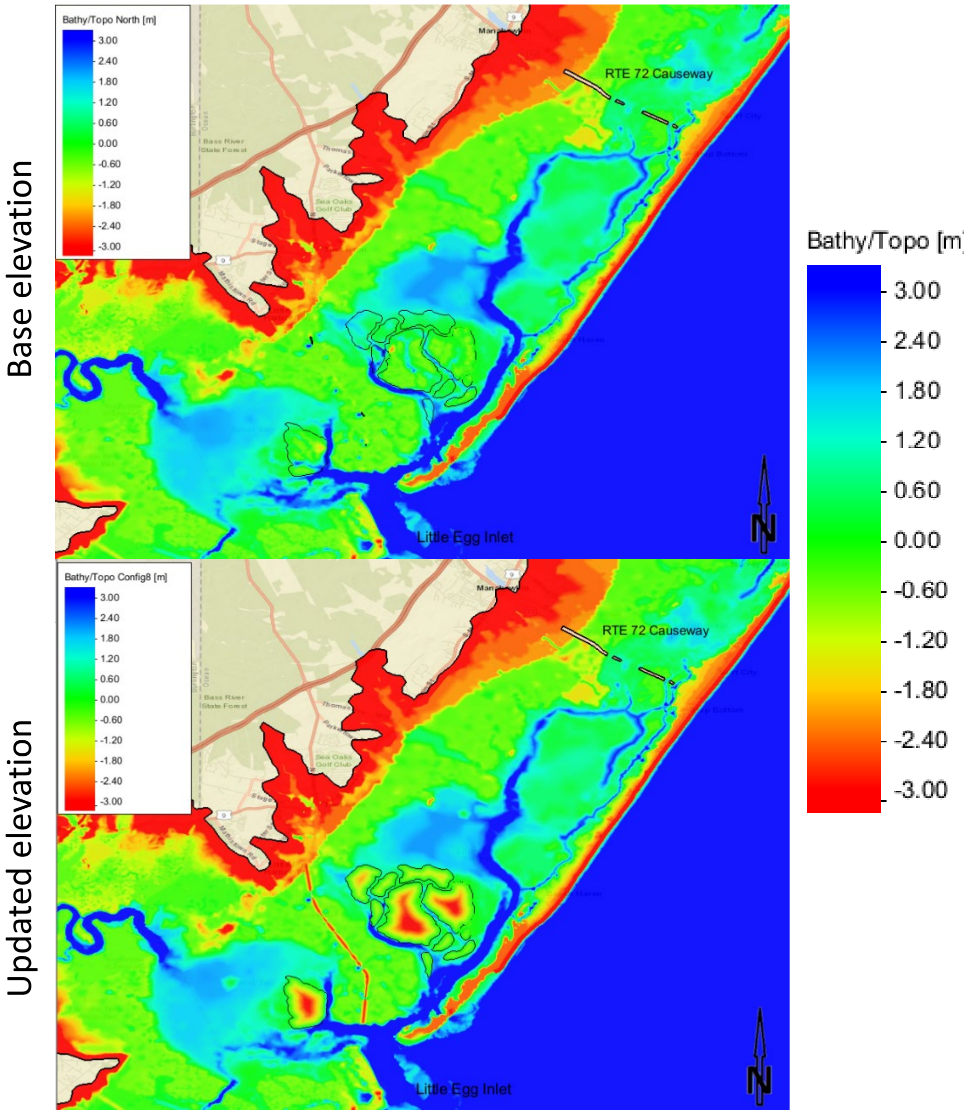

Figure 33 Updated ADCIRC elevation for Holgate area

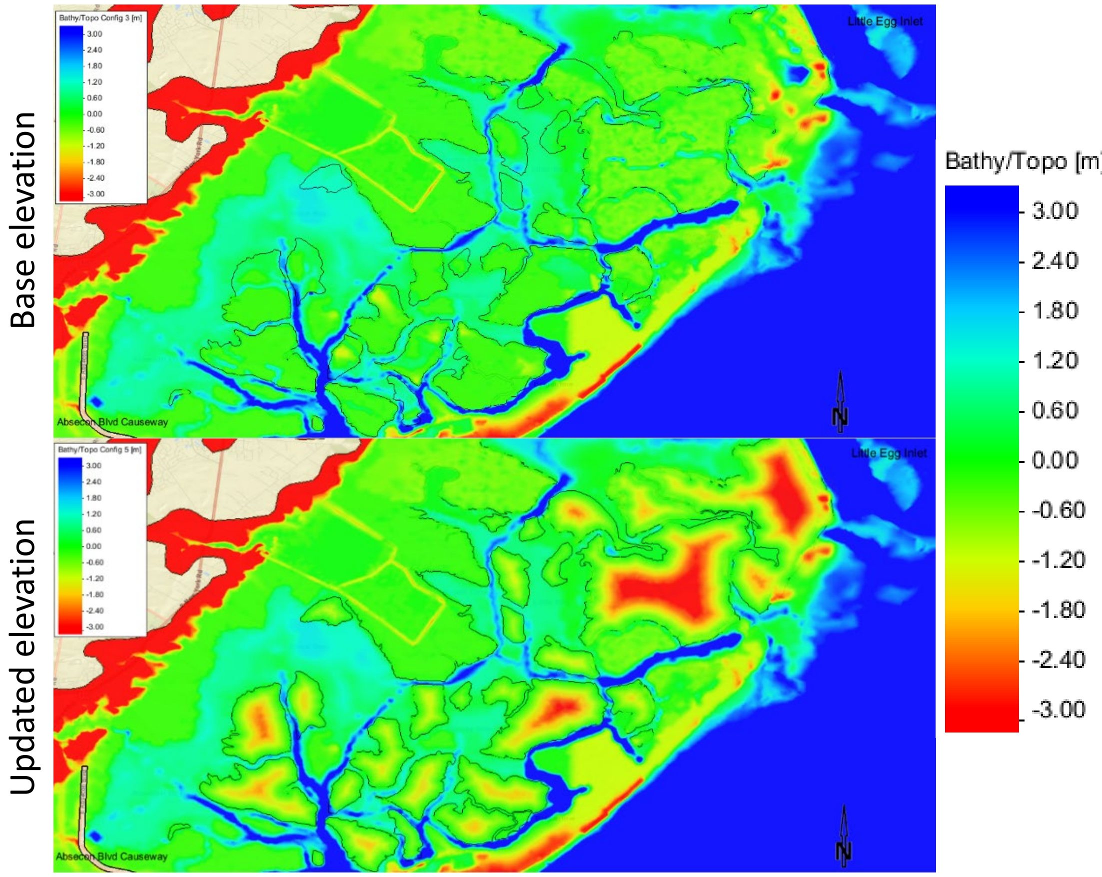

Figure 34 Updated ADCIRC elevation for Brigantine area

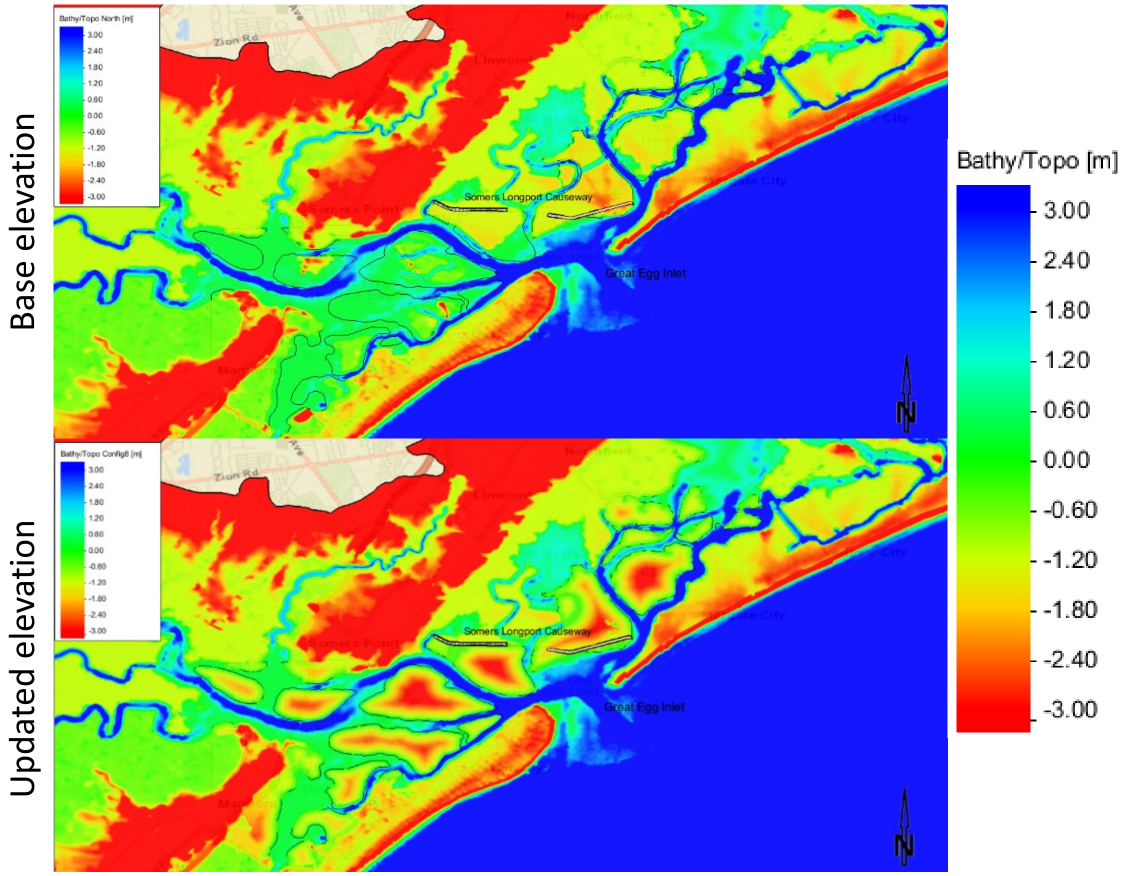

Figure 35 Updated ADCIRC elevation for Great Egg Harbor area

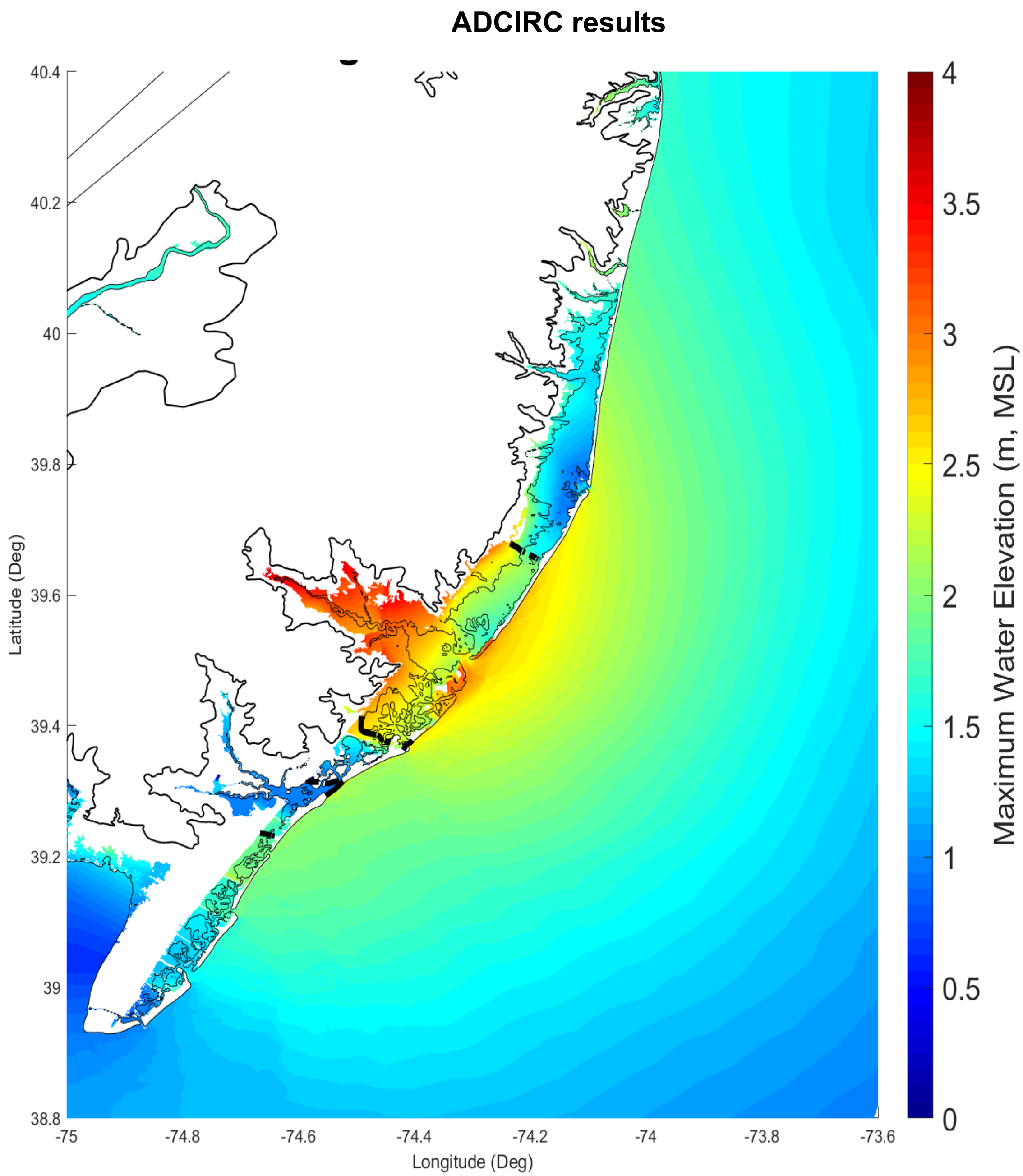

Figure 36 Maximum surge envelope for Storm 350 Configuration 5 (Brigantine area NNBF)

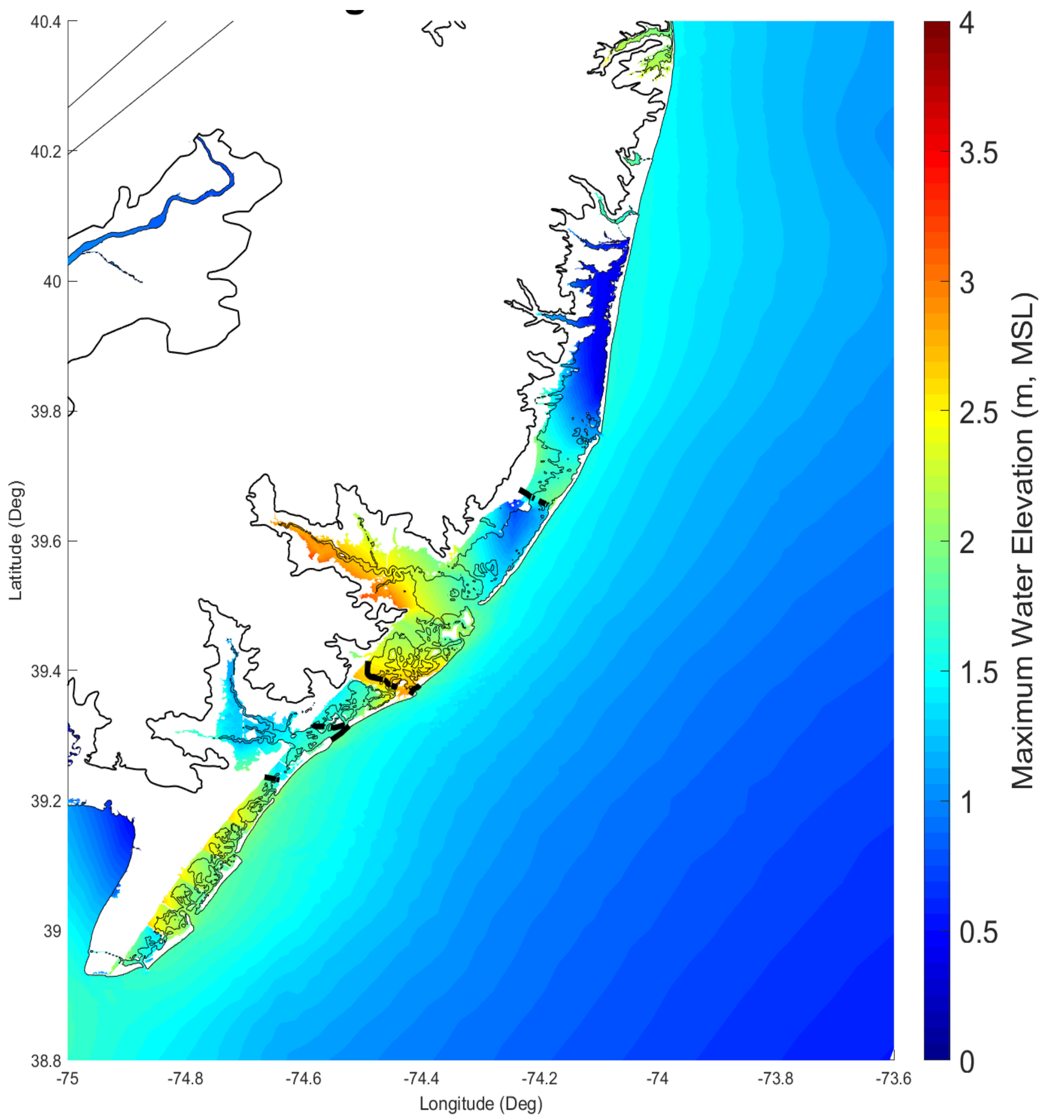

Figure 37 Maximum surge envelope for Storm 636 Configuration 5 (Brigantine area NNBF)

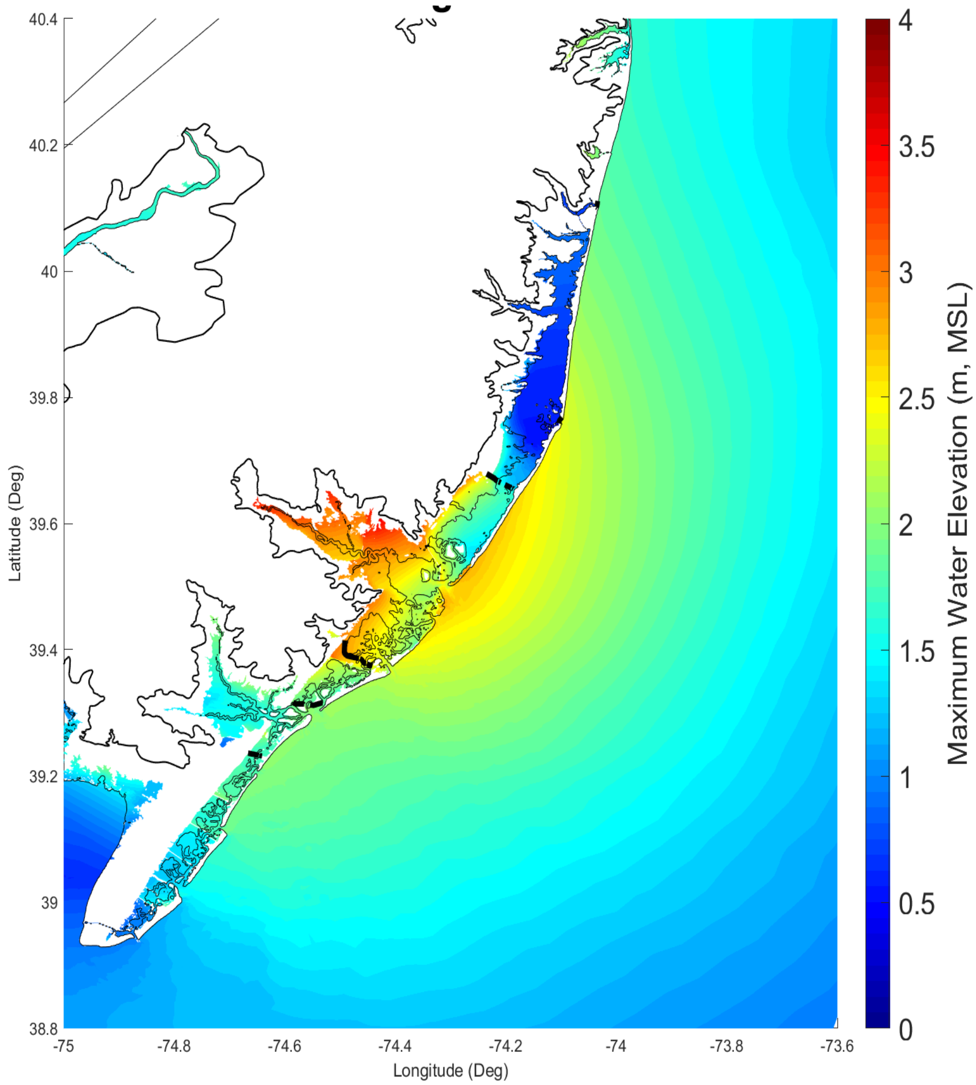

Figure 38 Maximum surge envelope for Storm 350 Configuration 8 (Holgate and Great Egg Harbor area NNBF)

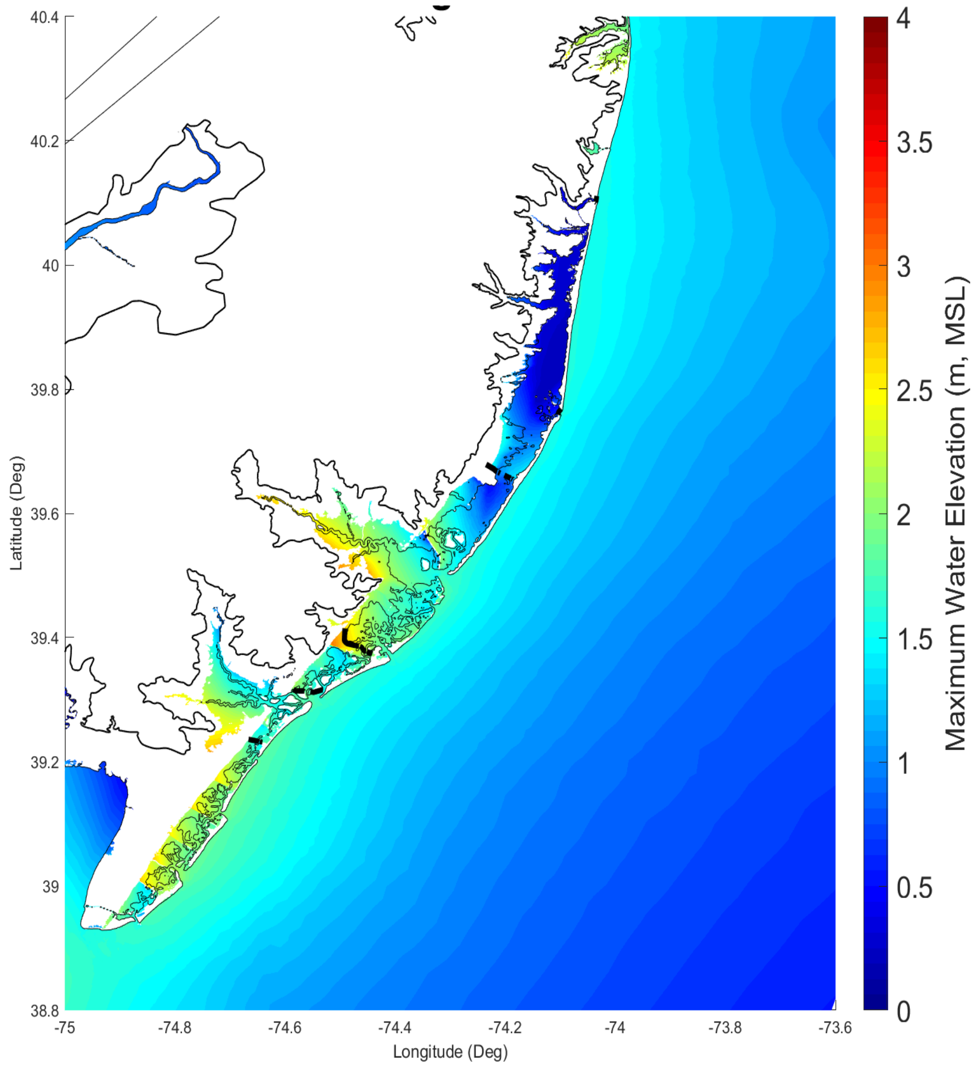

Figure 39 Maximum surge envelope for Storm 636 Configuration 8 (Holgate and Great Egg Harbor area NNBF)

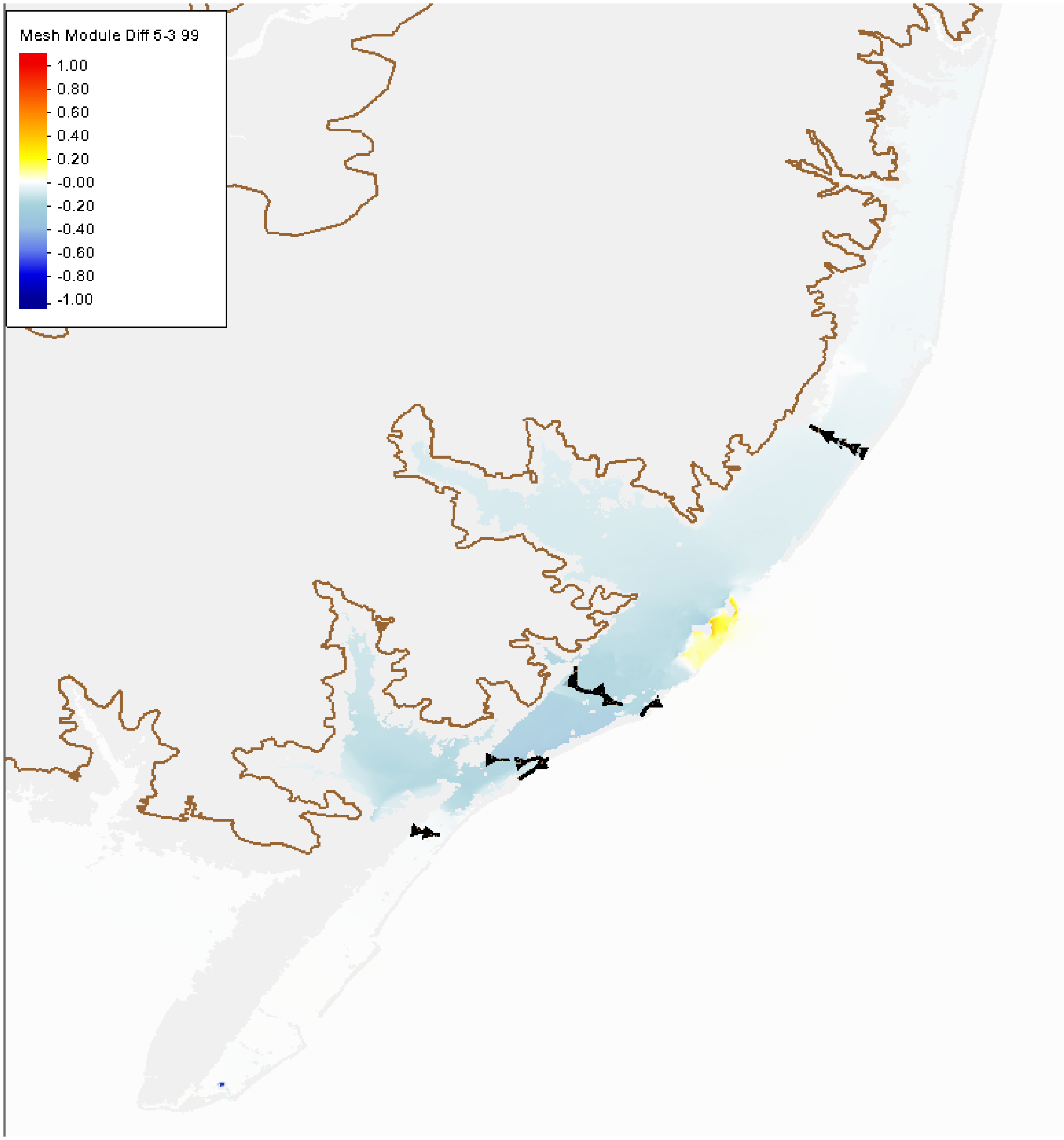

Figure 40 Peak water level differences between Configuration 5 (Brigantine area NNBF) and Configuration 3 (structural only) for storm 99

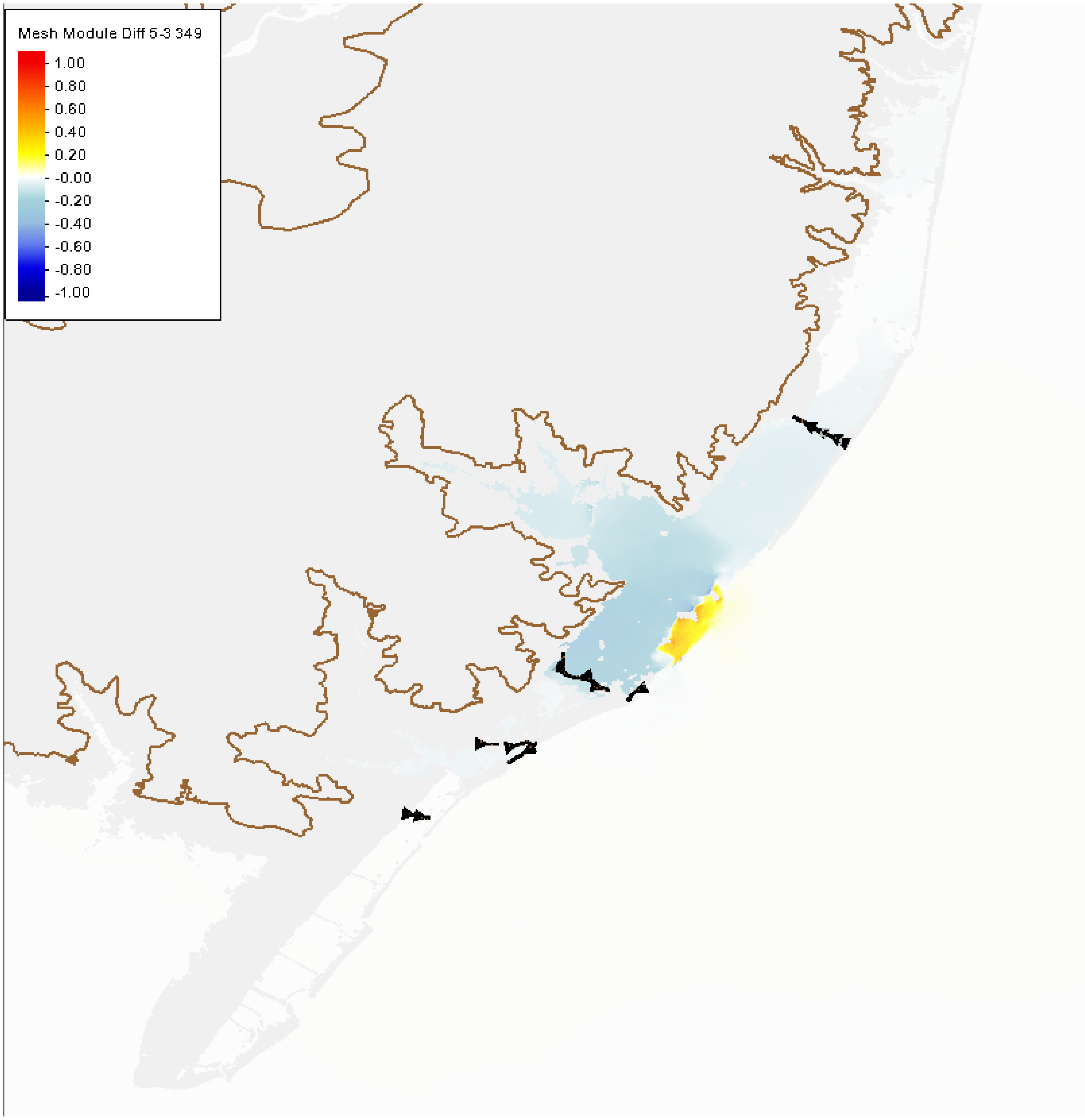

Figure 41 Peak water level differences between Configuration 5 (Brigantine area NNBF) and Configuration 3 (structural only) for storm 349

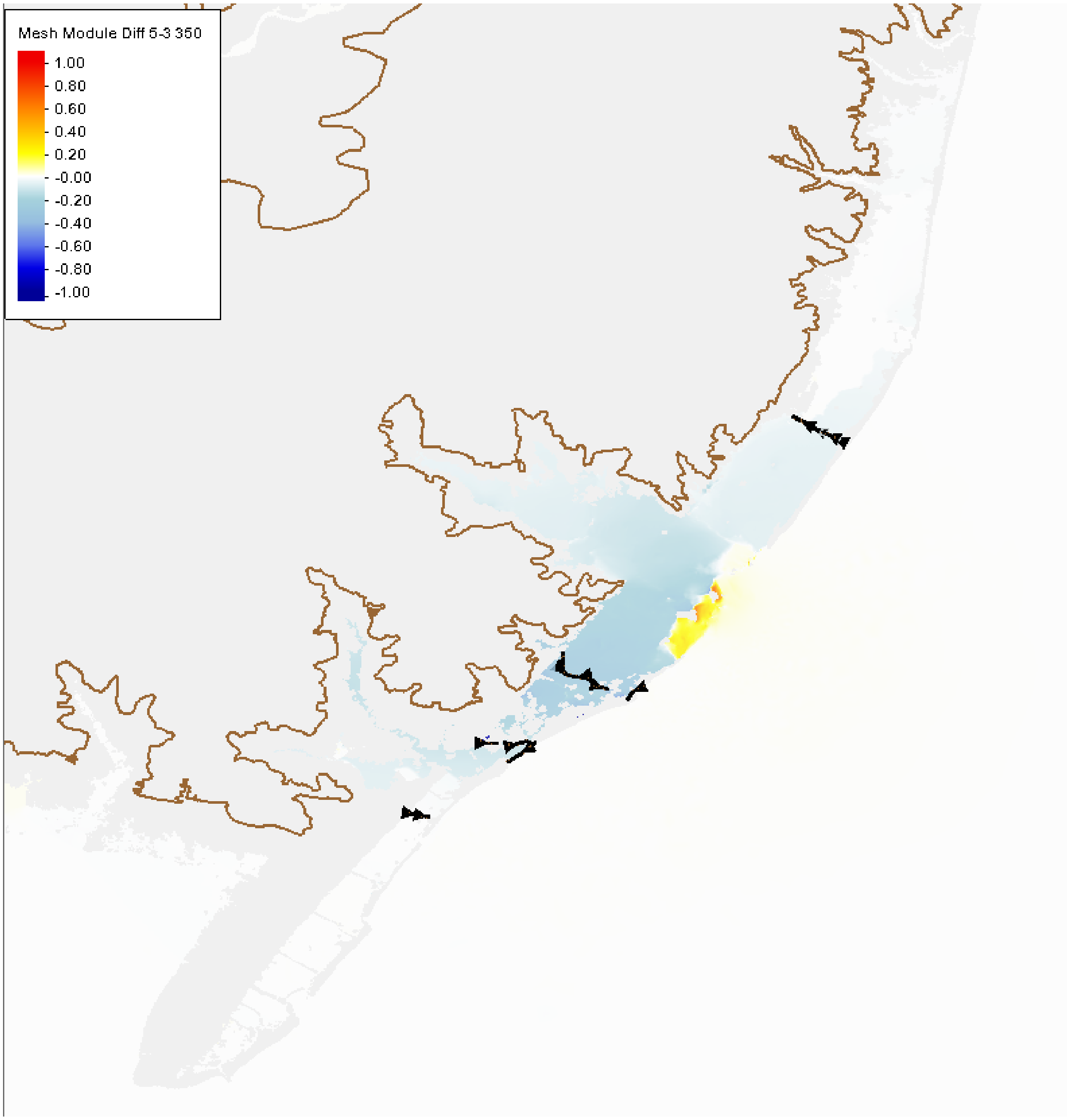

Figure 42 Peak water level differences between Configuration 5 (Brigantine area NNBF) and Configuration 3 (structural only) for storm 350

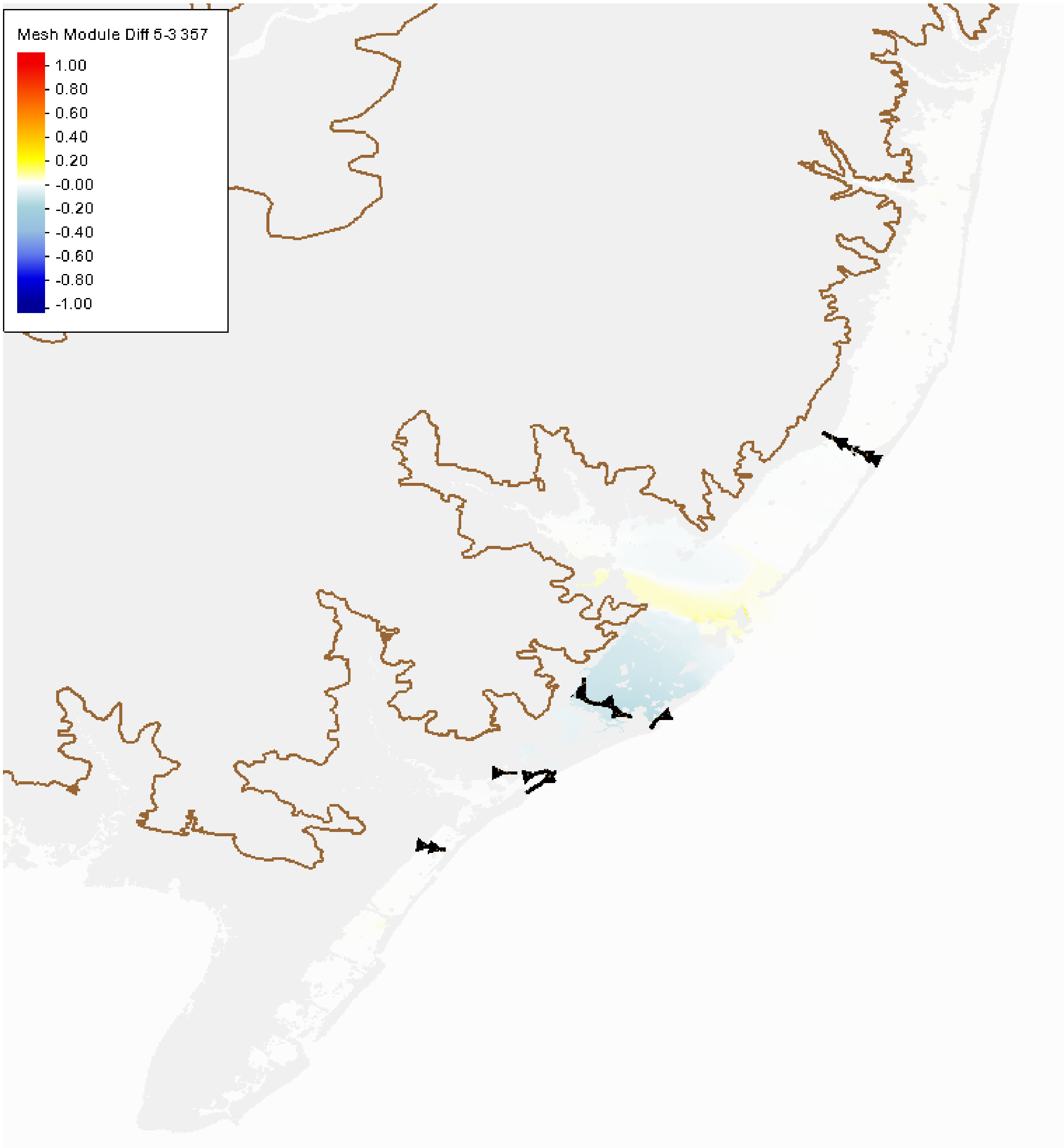

Figure 43 Peak water level differences between Configuration 5 (Brigantine area NNBF) and Configuration 3 (structural only) for storm 357

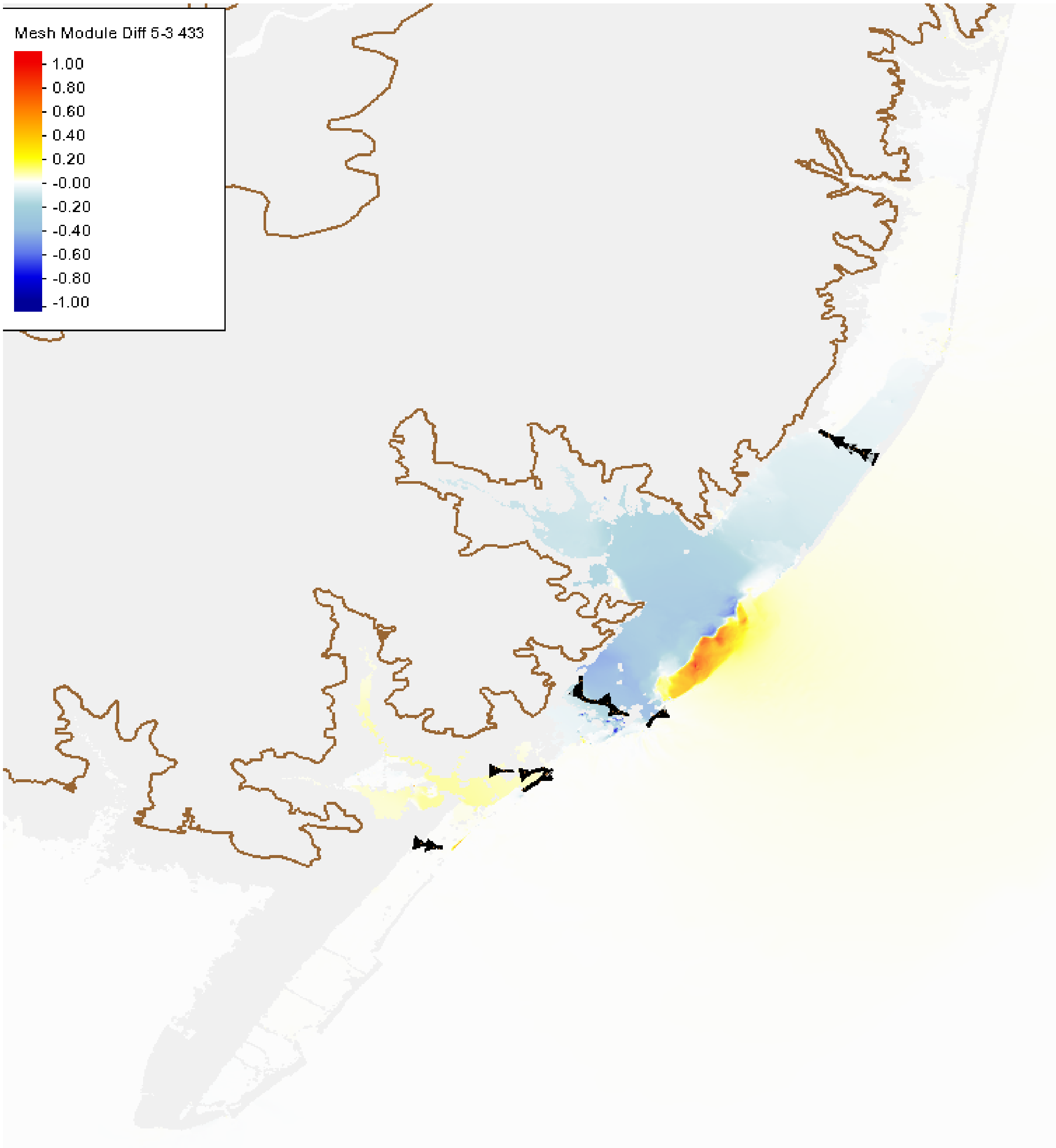

Figure 44 Peak water level differences between Configuration 5 (Brigantine area NNBF) and Configuration 3 (structural only) for storm 433

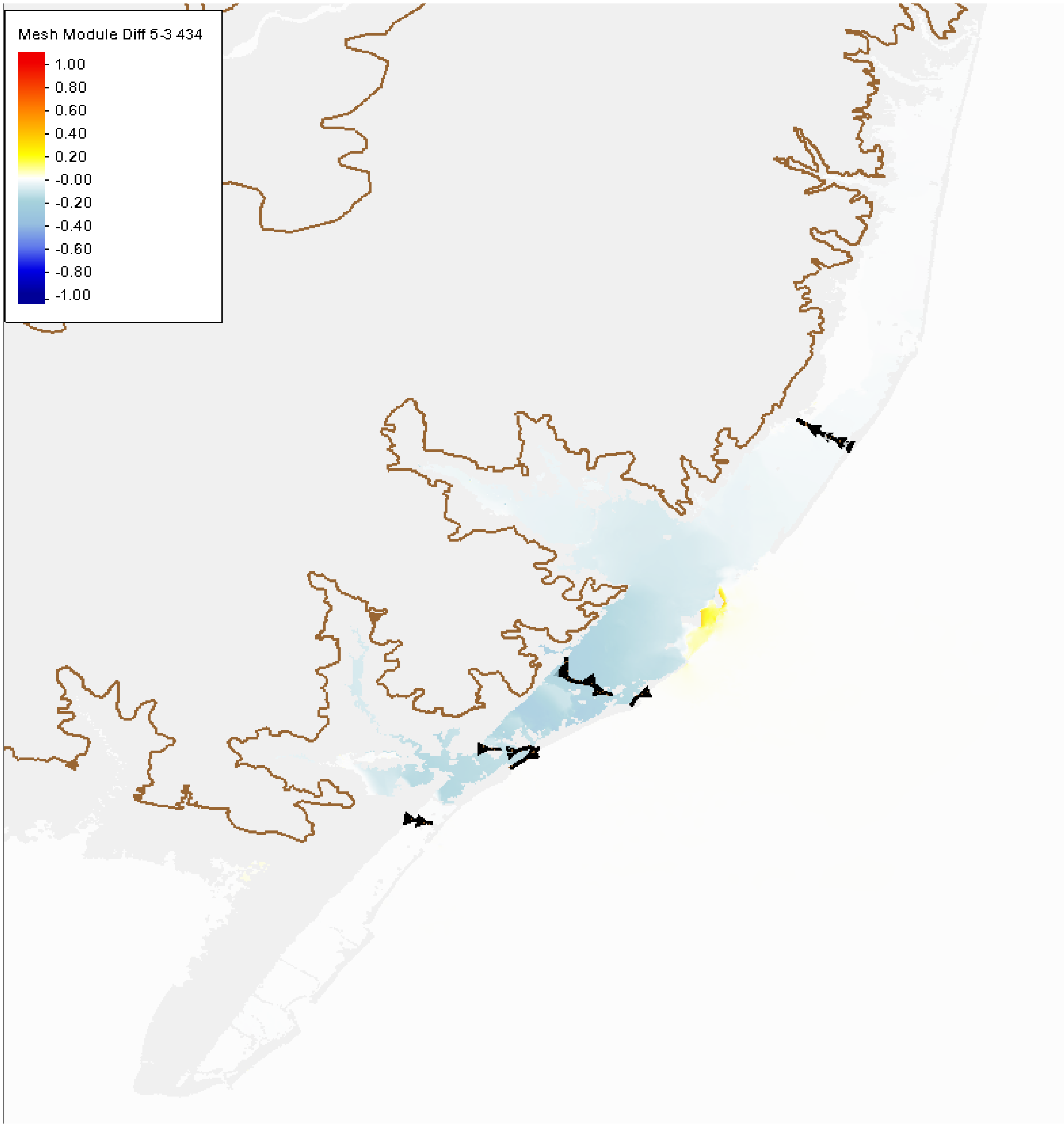

Figure 45 Peak water level differences between Configuration 5 (Brigantine area NNBF) and Configuration 3 (structural only) for storm 434

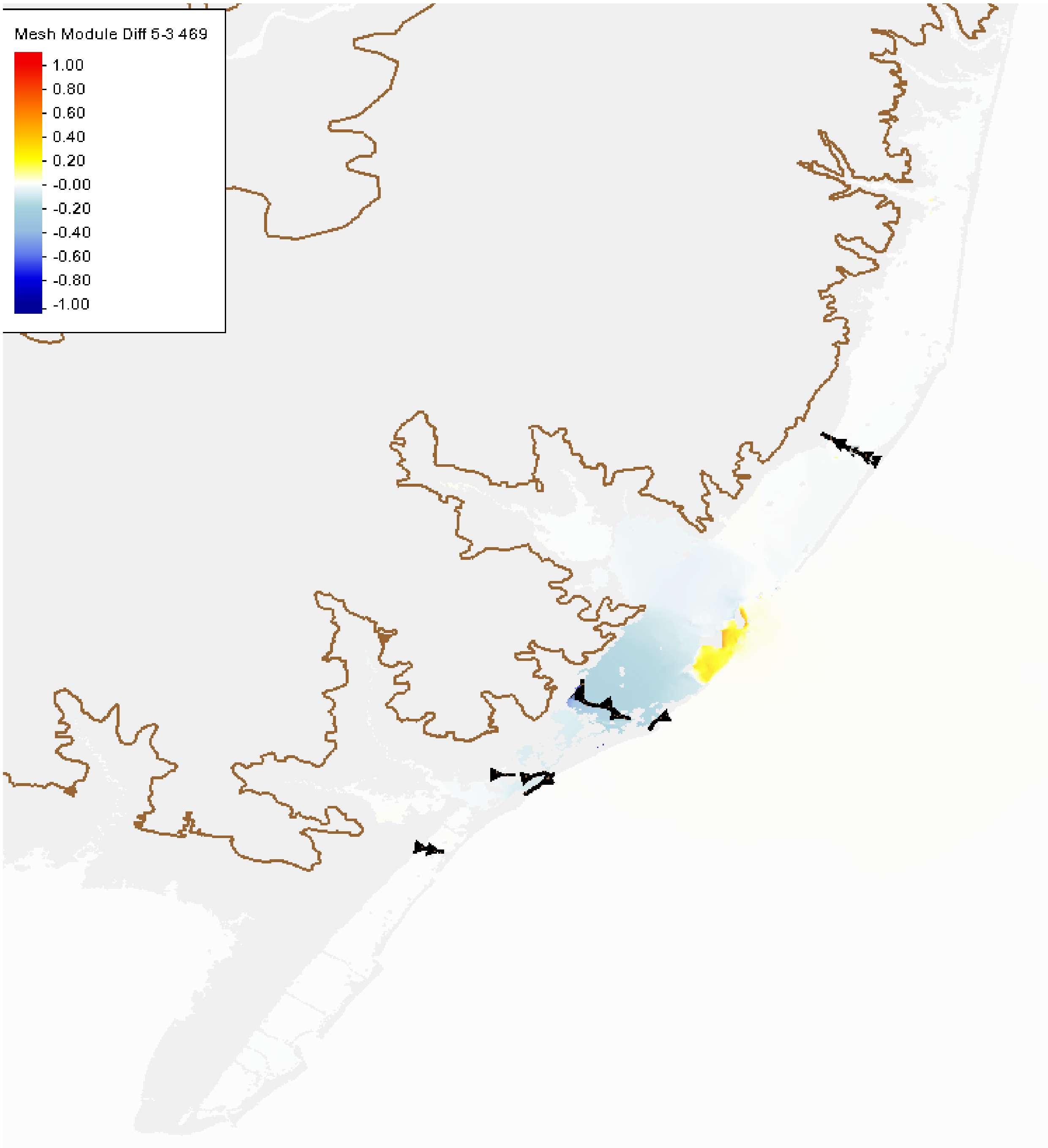

Figure 46 Peak water level differences between Configuration 5 (Brigantine area NNBF) and Configuration 3 (structural only) for storm 469

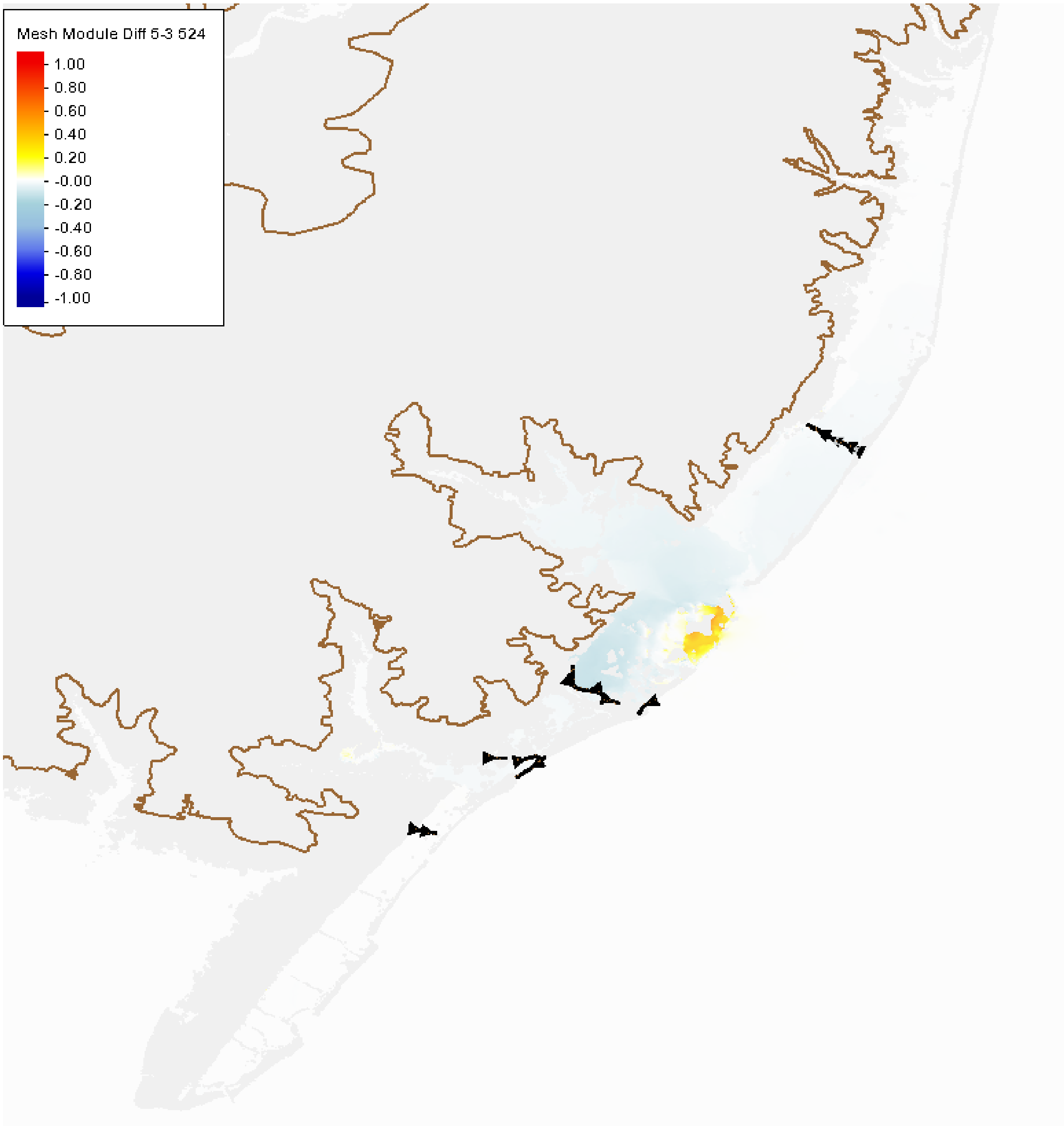

Figure 47 Peak water level differences between Configuration 5 (Brigantine area NNBF) and Configuration 3 (structural only) for storm 524

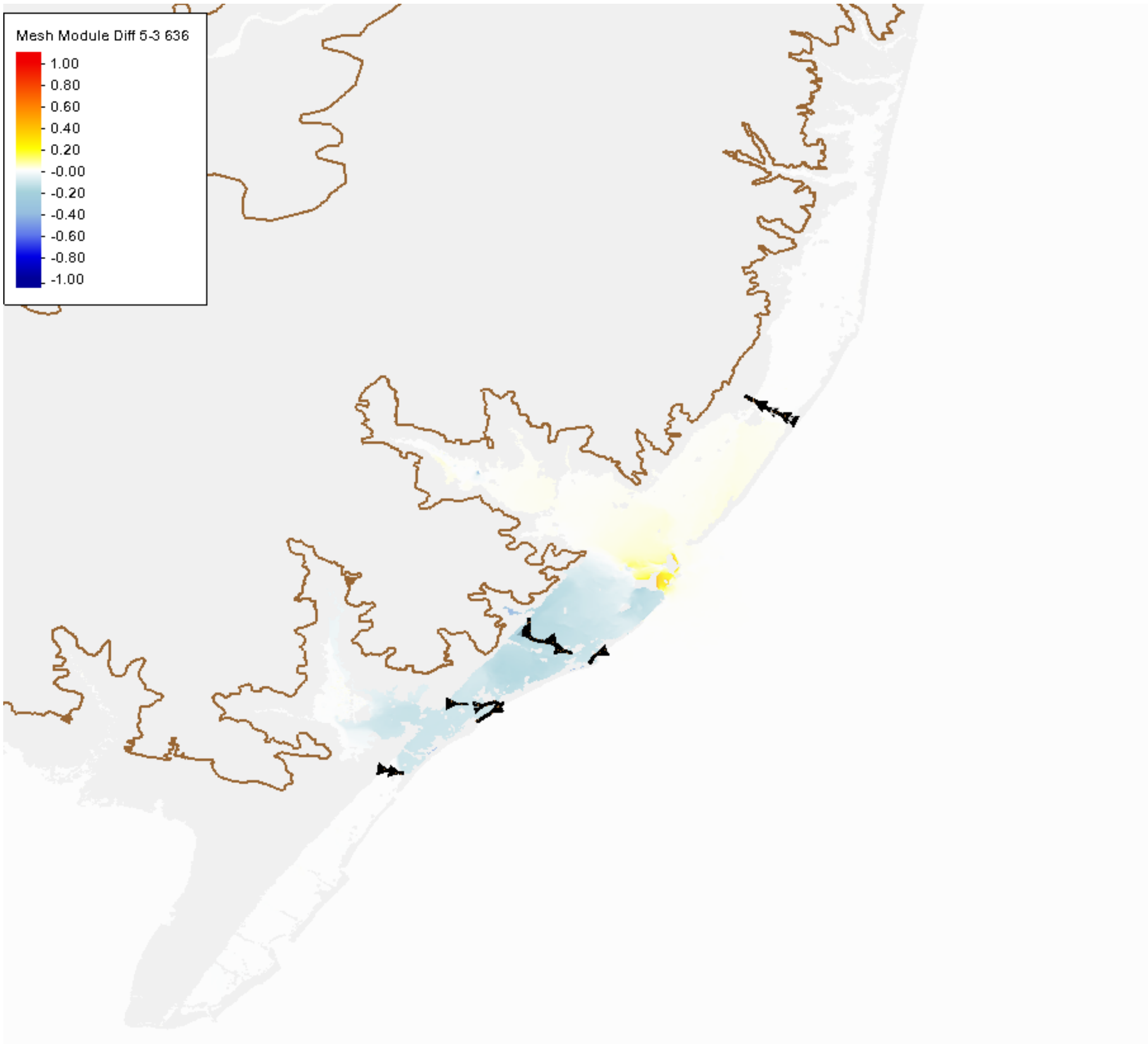

Figure 48 Peak water level differences between Configuration 5 (Brigantine area NNBF) and Configuration 3 (structural only) for storm 636

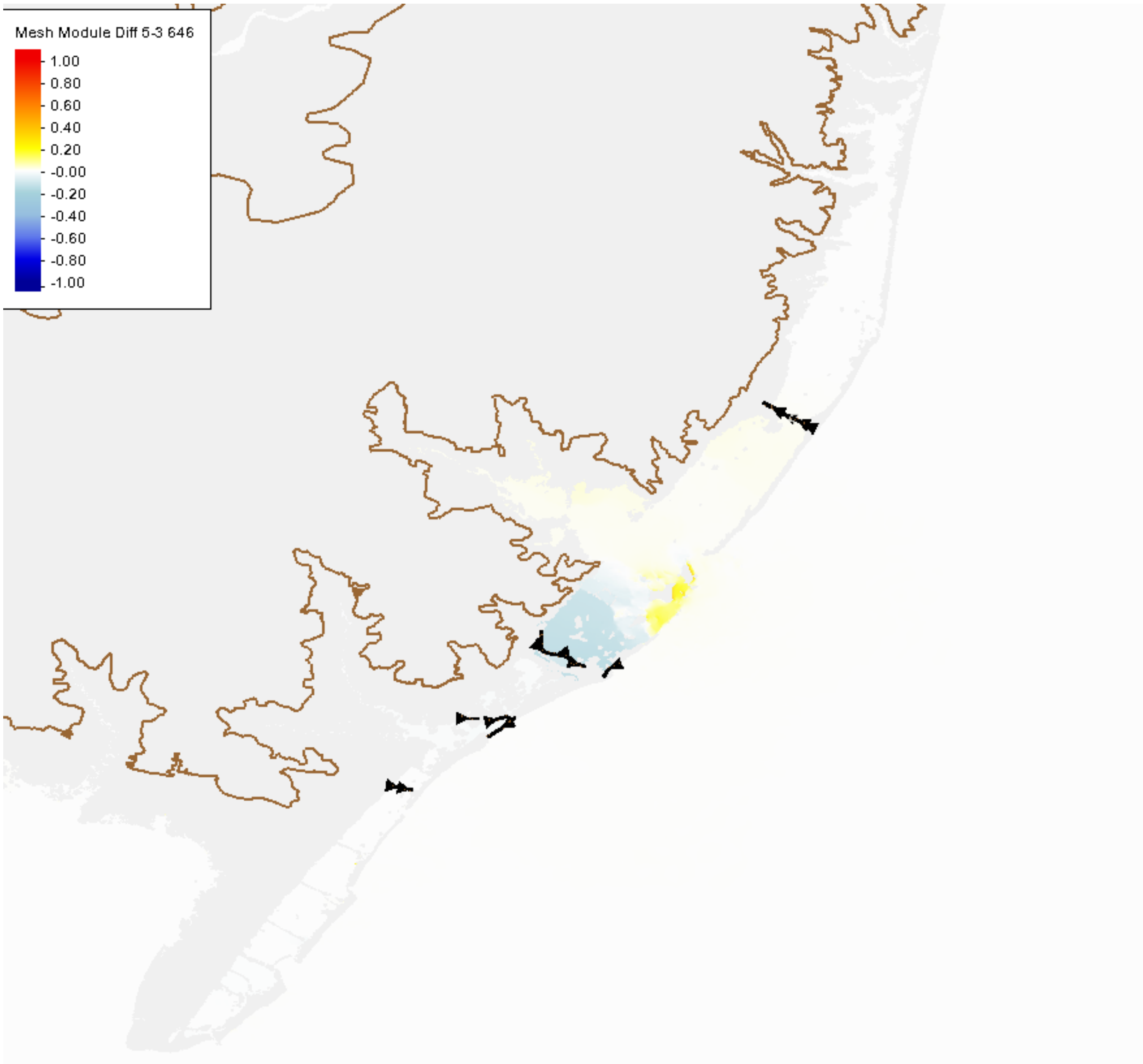

Figure 49 Peak water level differences between Configuration 5 (Brigantine area NNBF) and Configuration 3 (structural only) for storm 646

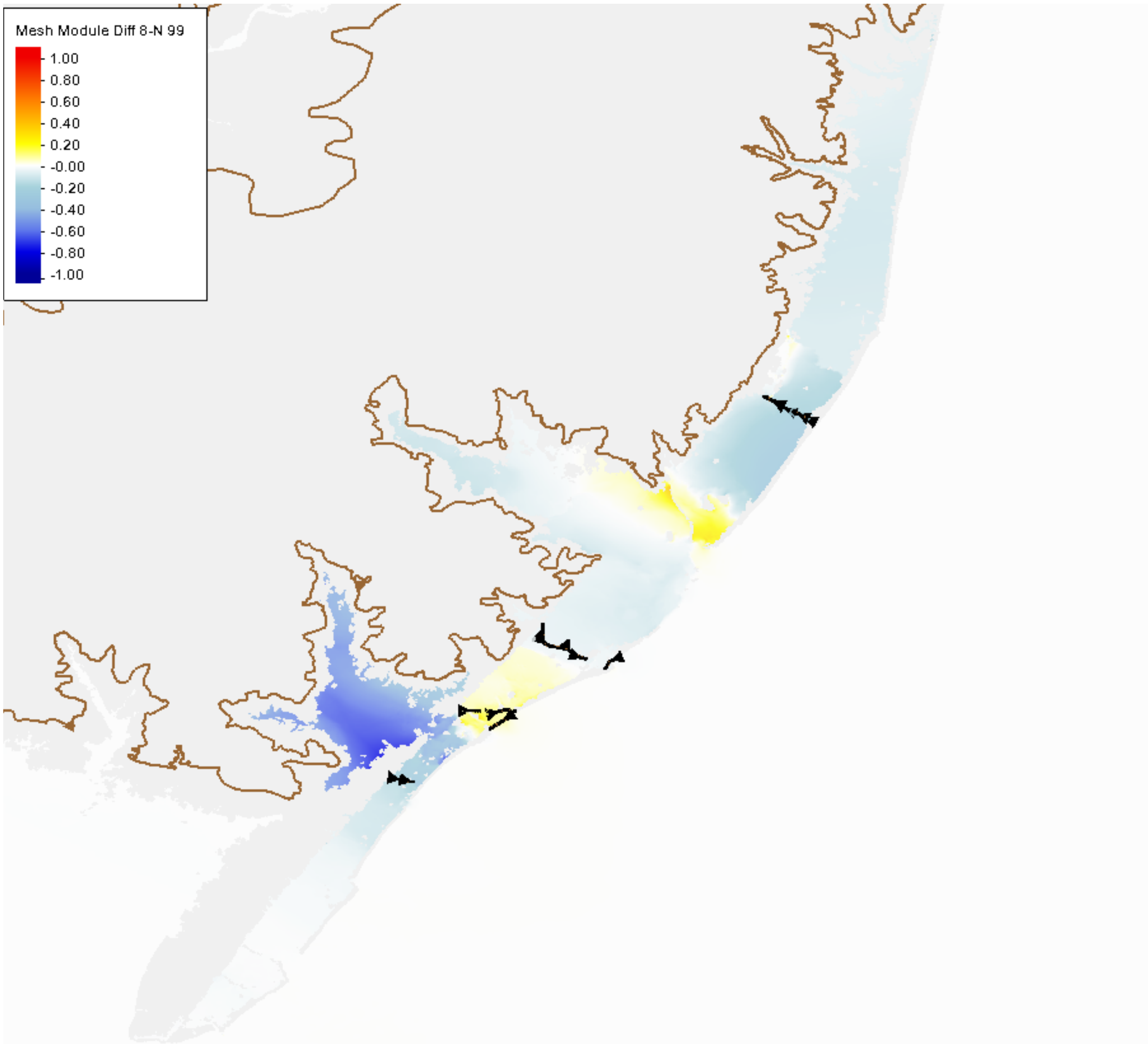

Figure 50 Peak water level differences between Configuration 8 (Holgate and Great Egg Harbor area NNBF) and North Configuration (structural only) for storm 99

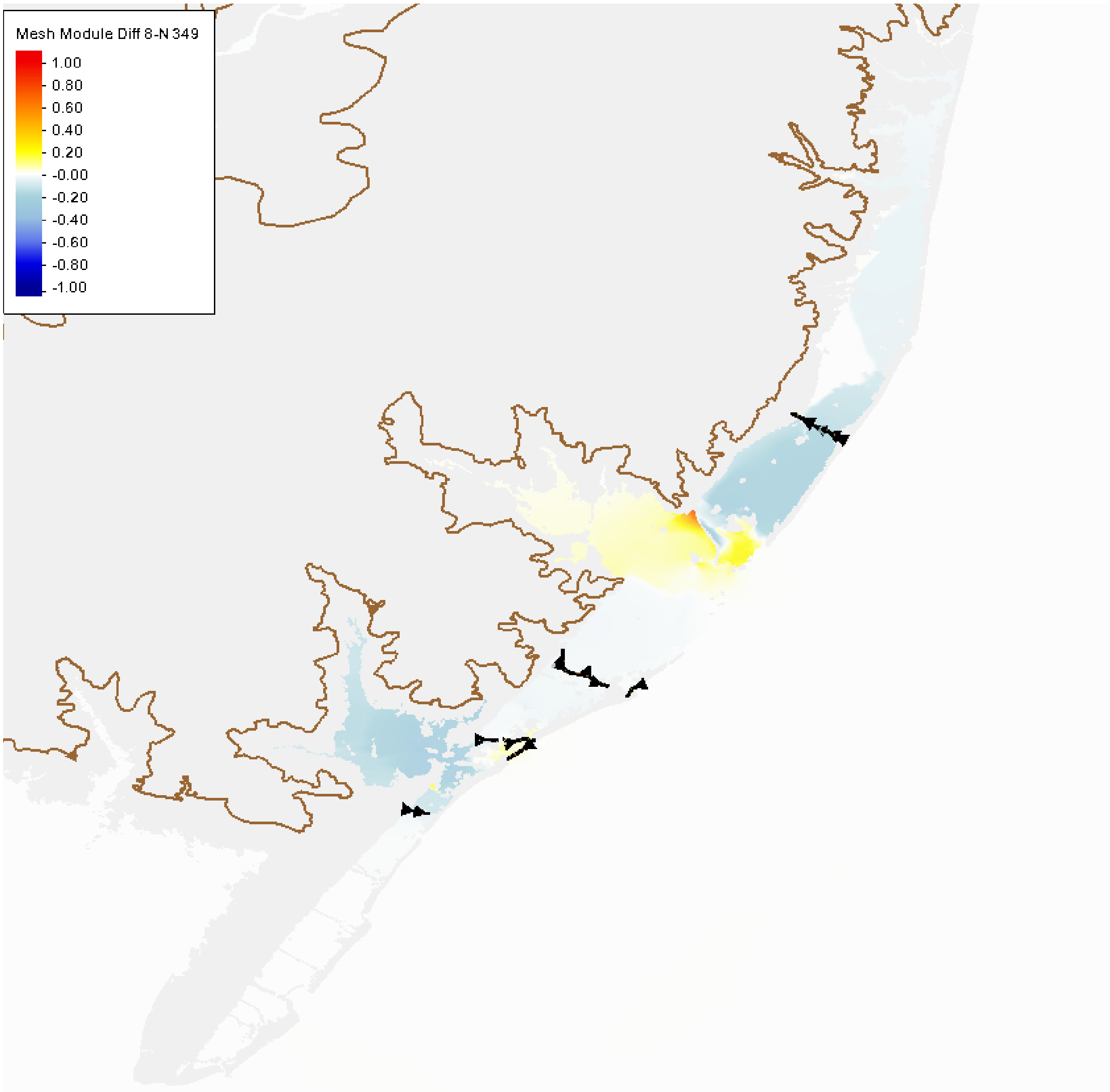

Figure 51 Peak water level differences between Configuration 8 (Holgate and Great Egg Harbor area NNBF) and North Configuration (structural only) for storm 349

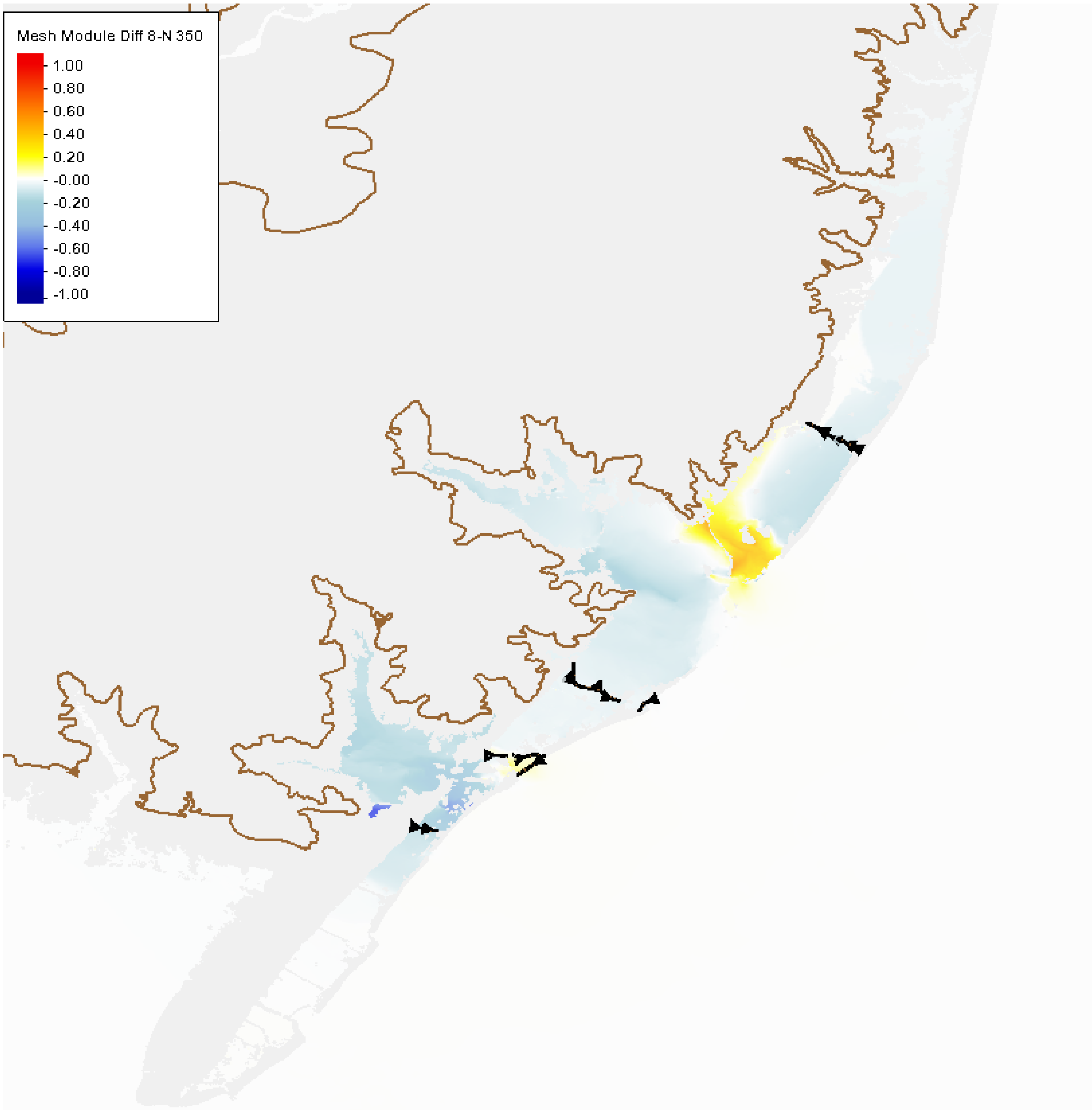

Figure 52 Peak water level differences between Configuration 8 (Holgate and Great Egg Harbor area NNBF) and North Configuration (structural only) for storm 350

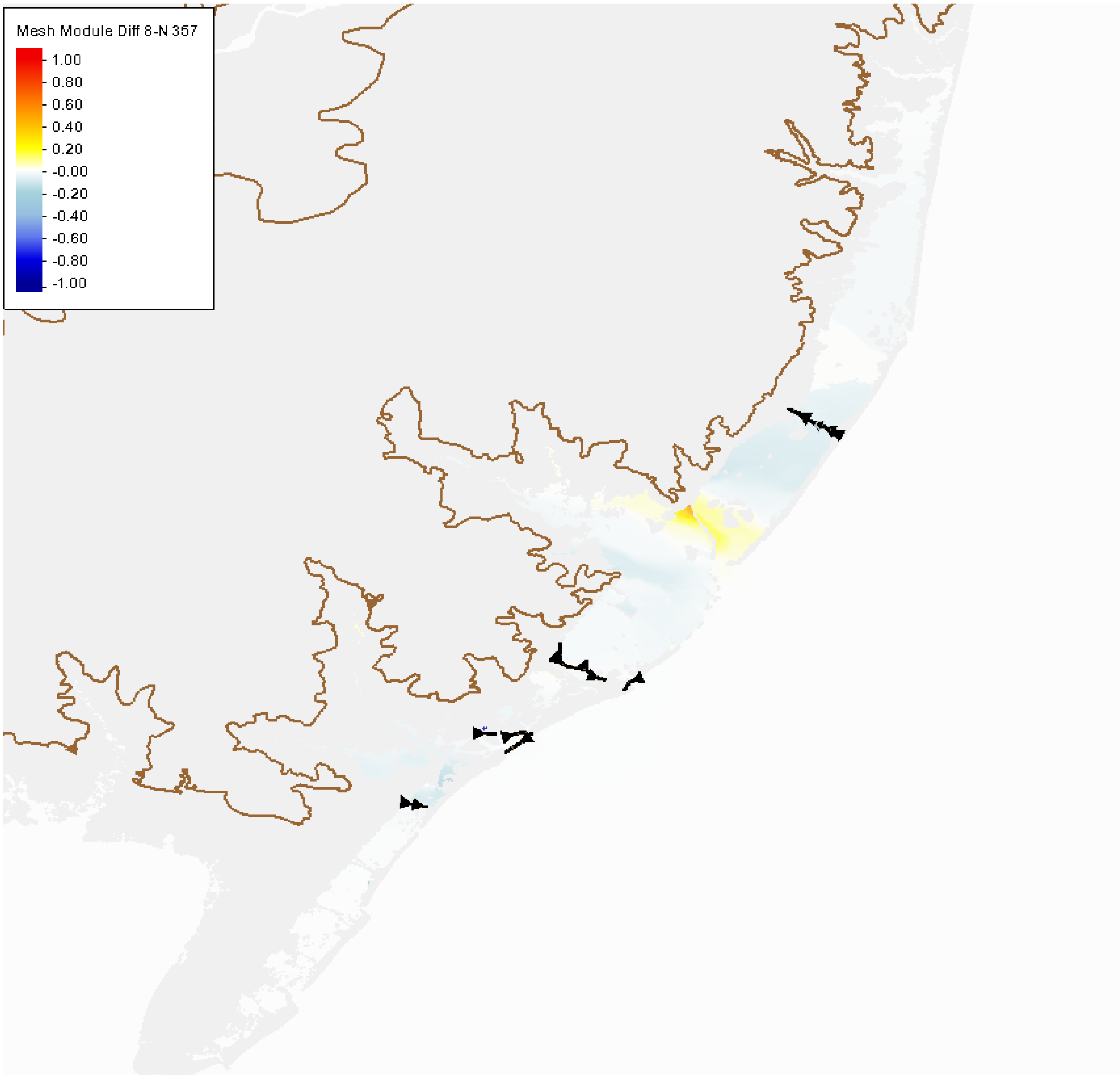

Figure 53 Peak water level differences between Configuration 8 (Holgate and Great Egg Harbor area NNBF) and North Configuration (structural only) for storm 357

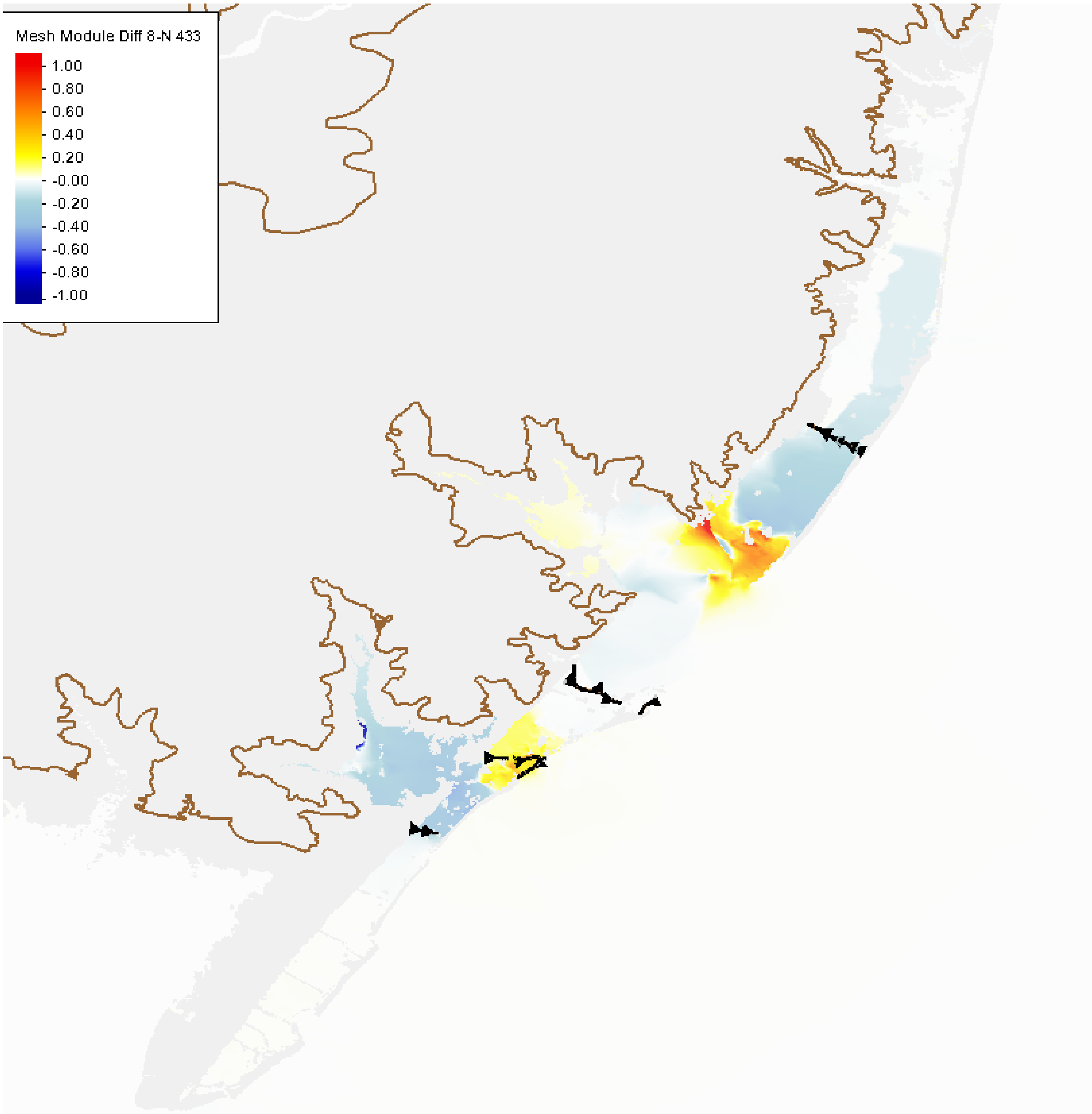

Figure 54 Peak water level differences between Configuration 8 (Holgate and Great Egg Harbor area NNBF) and North Configuration (structural only) for storm 433

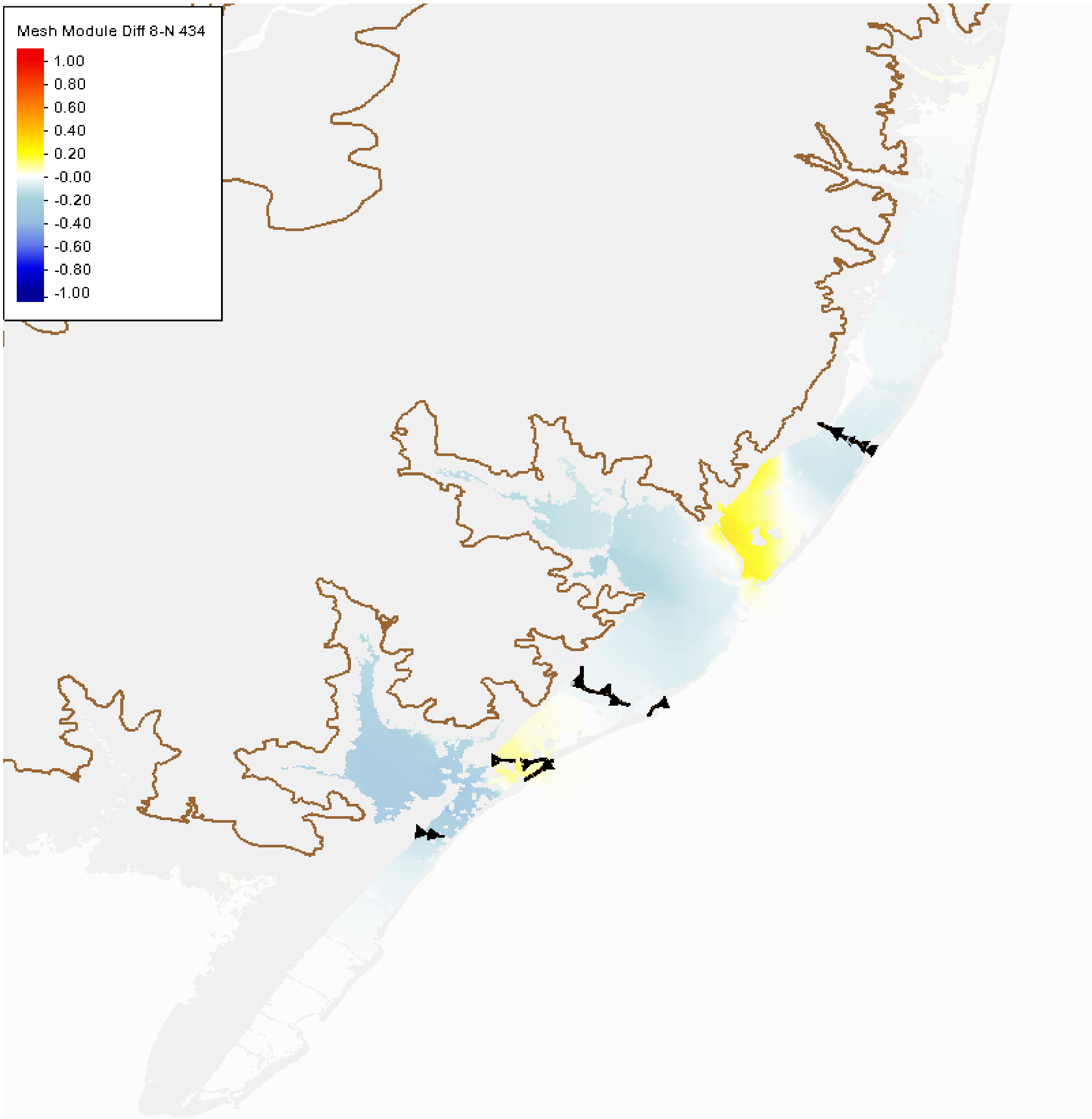

Figure 55 Peak water level differences between Configuration 8 (Holgate and Great Egg Harbor area NNBF) and North Configuration (structural only) for storm 434

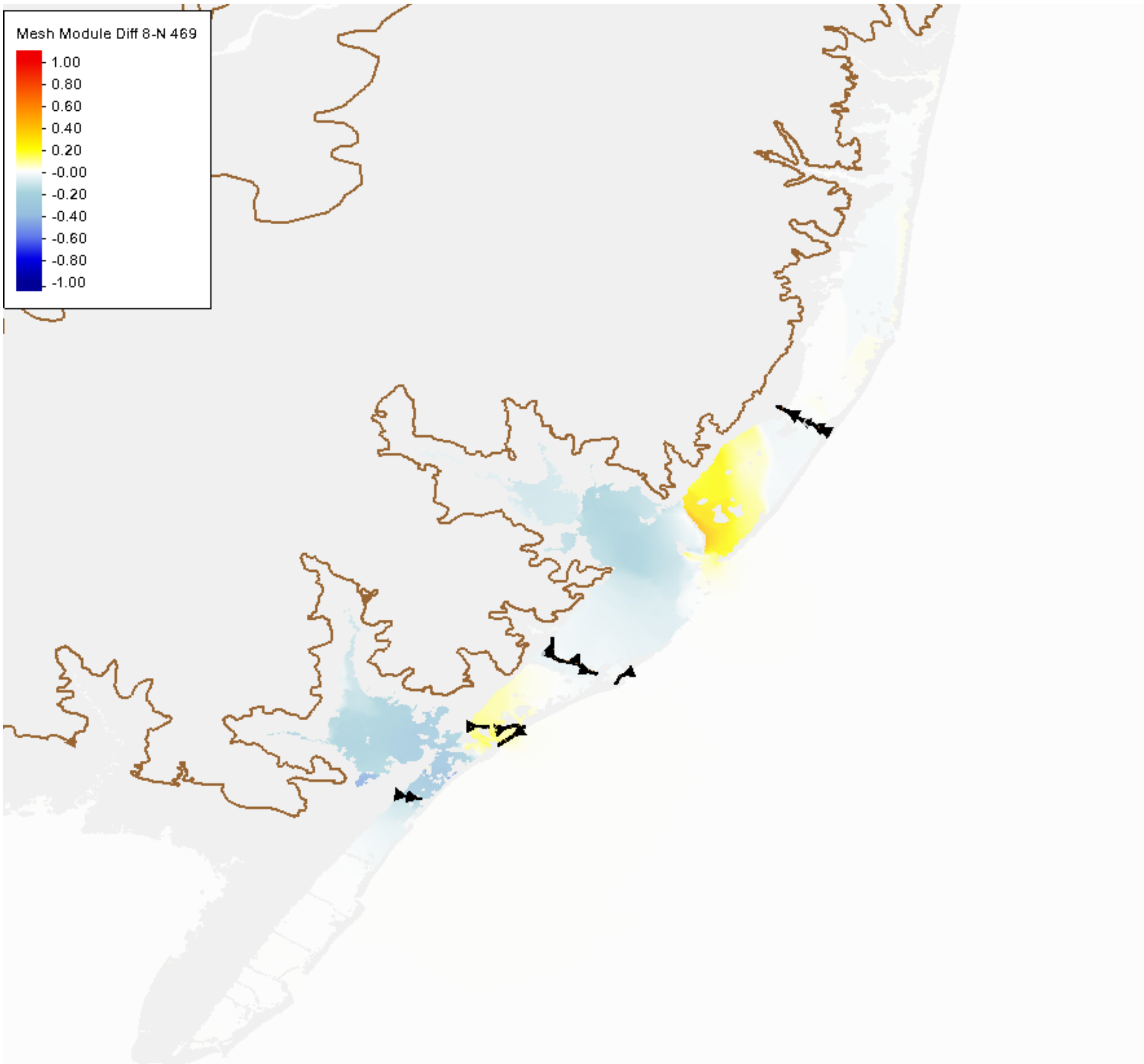

Figure 56 Peak water level differences between Configuration 8 (Holgate and Great Egg Harbor area NNBF) and North Configuration (structural only) for storm 469

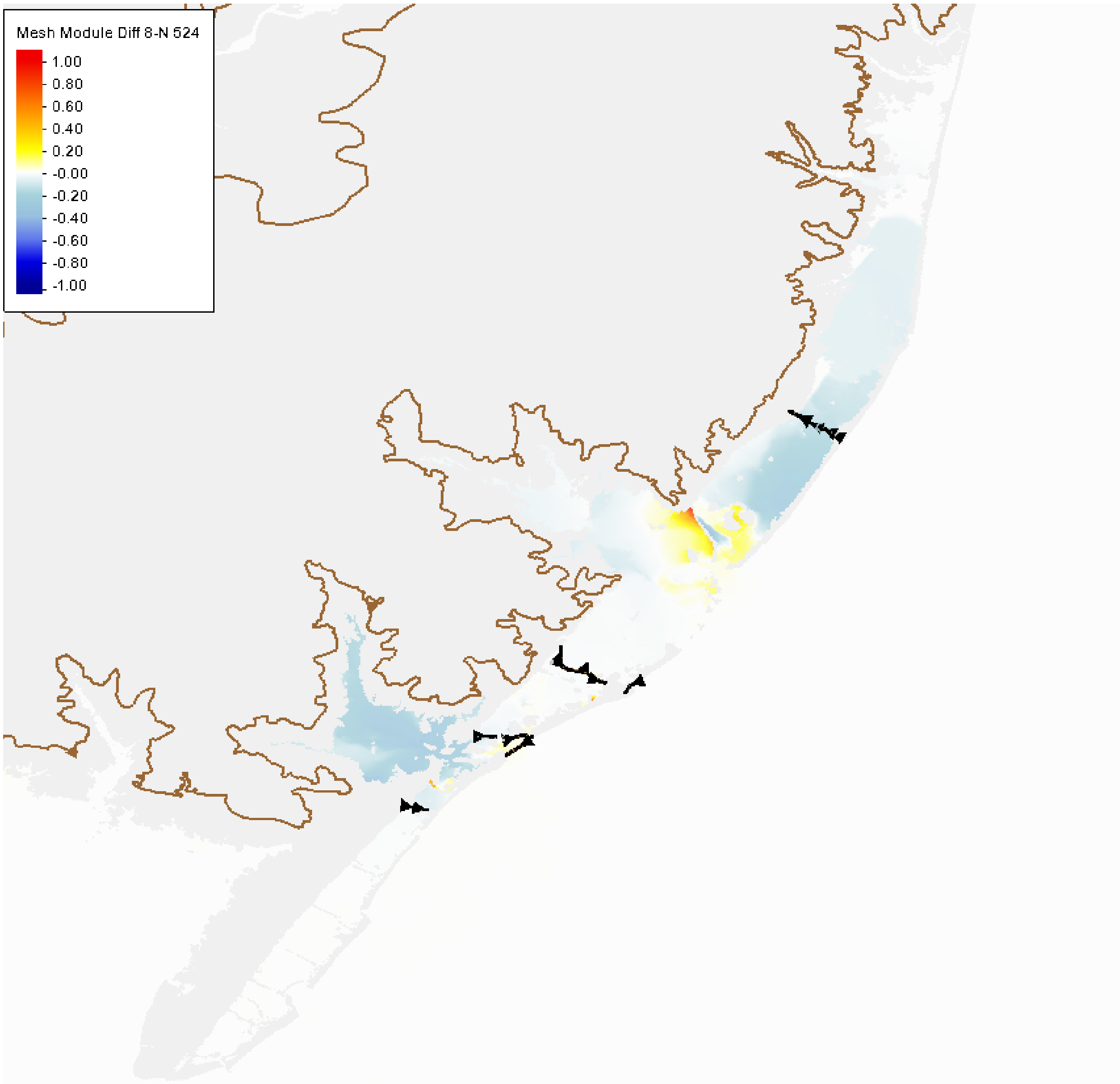

Figure 57 Peak water level differences between Configuration 8 (Holgate and Great Egg Harbor area NNBF) and North Configuration (structural only) for storm 524

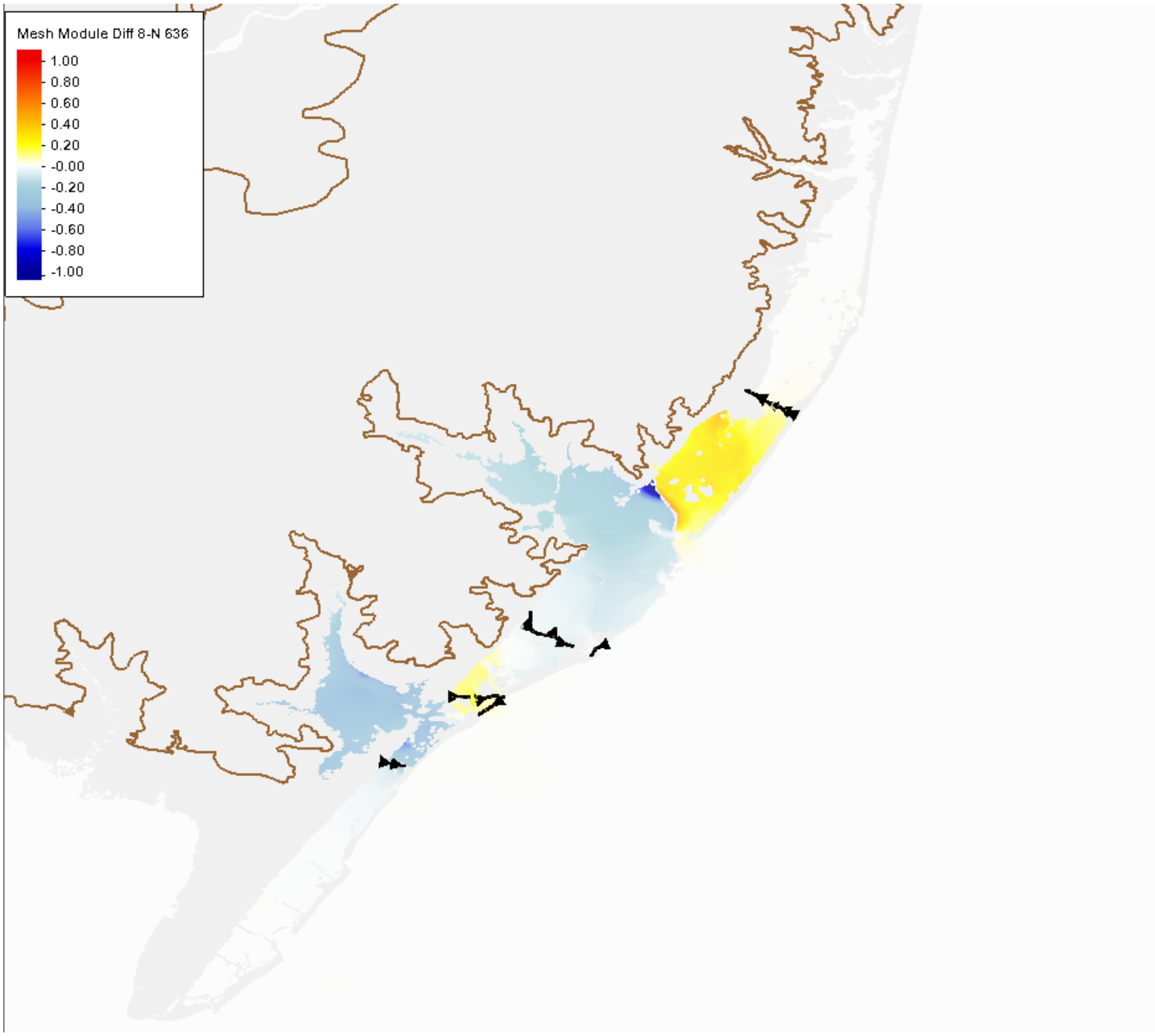

Figure 58 Peak water level differences between Configuration 8 (Holgate and Great Egg Harbor area NNBF) and North Configuration (structural only) for storm 636

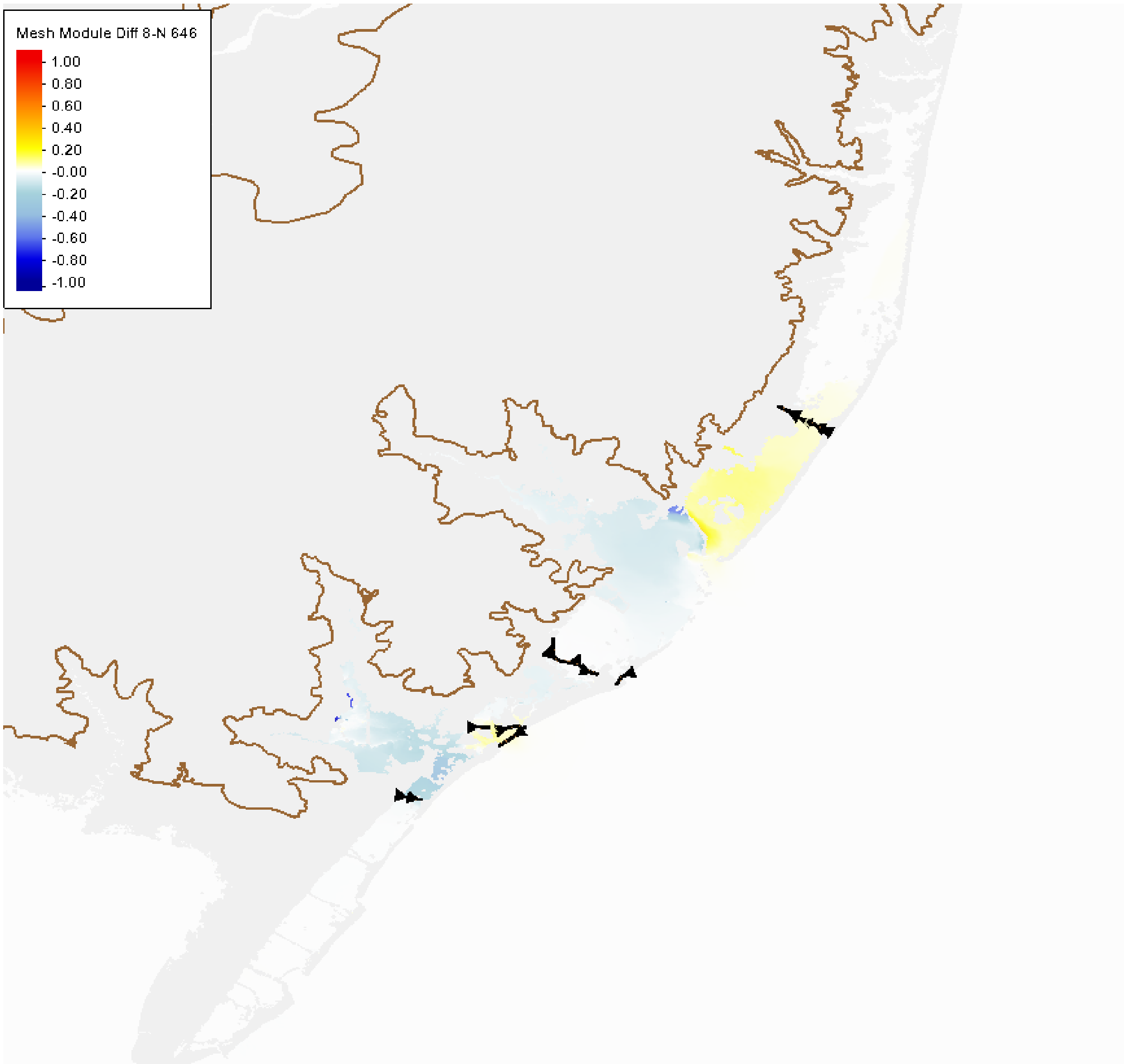

Figure 59 Peak water level differences between Configuration 8 (Holgate and Great Egg Harbor area NNBF) and North Configuration (structural only) for storm 646

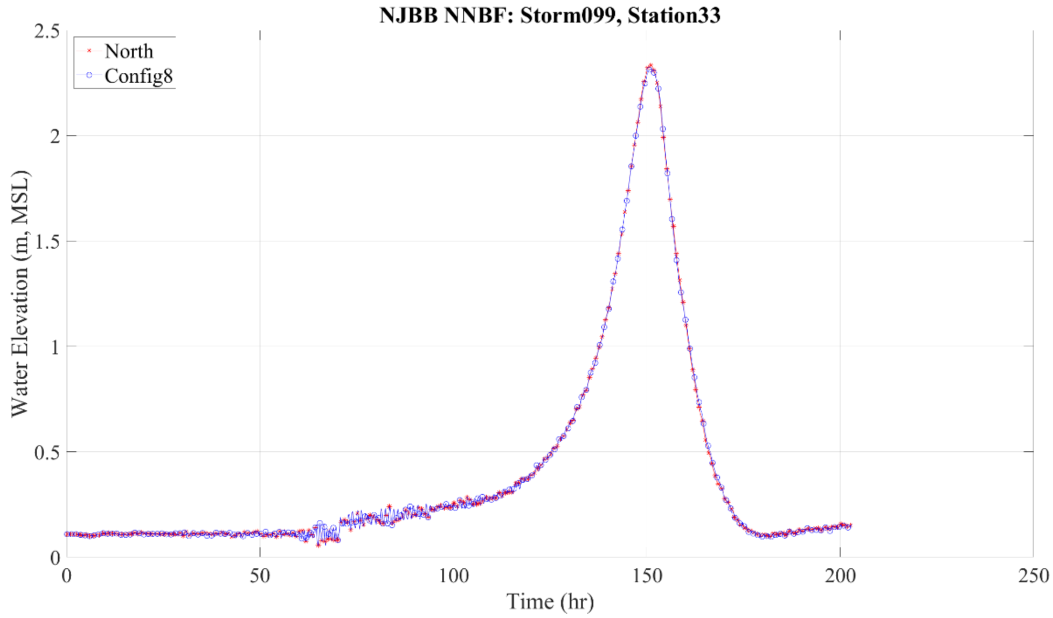

Figure 60 Storm 99 hydrograph for save point 33 "in front of" Holgate area with and without NNBF

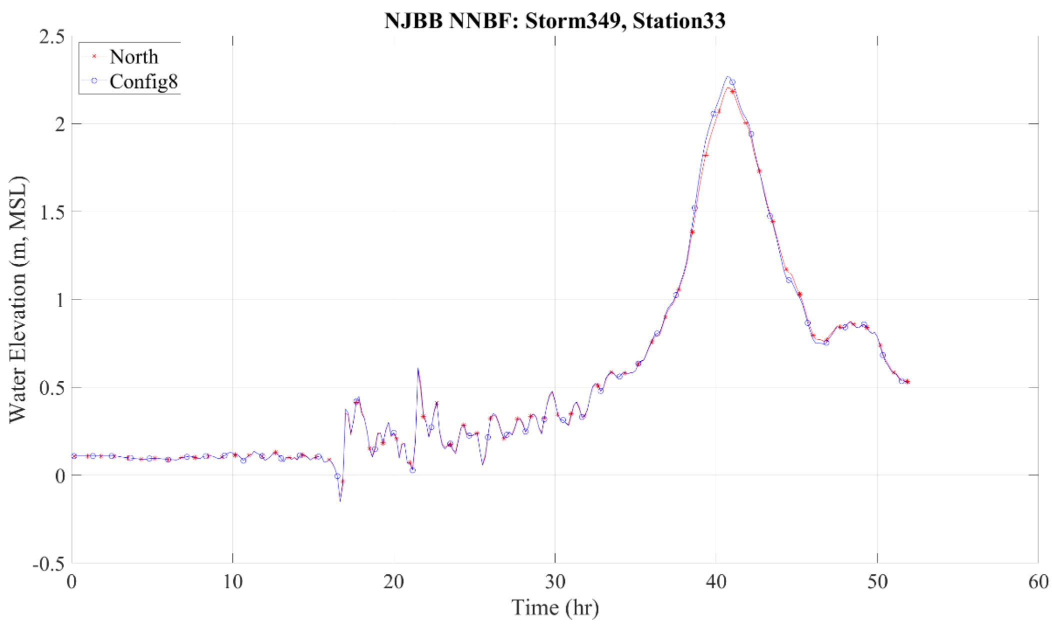

Figure 61 Storm 349 hydrograph for save point 33 "in front of" Holgate area with and without NNBF

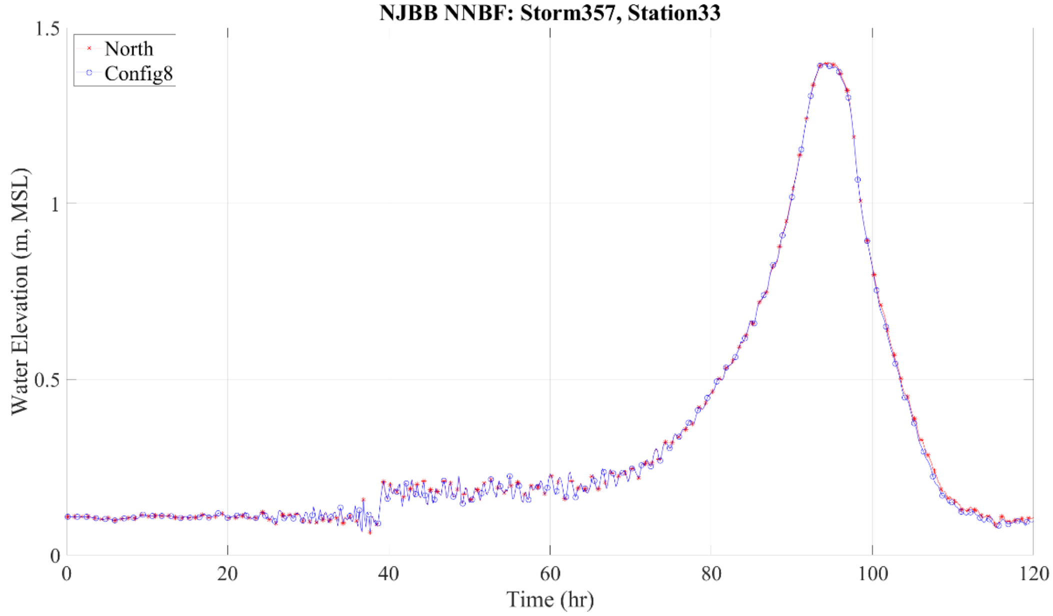

Figure 62 Storm 357 hydrograph for save point 33 "in front of" Holgate area with and without NNBF

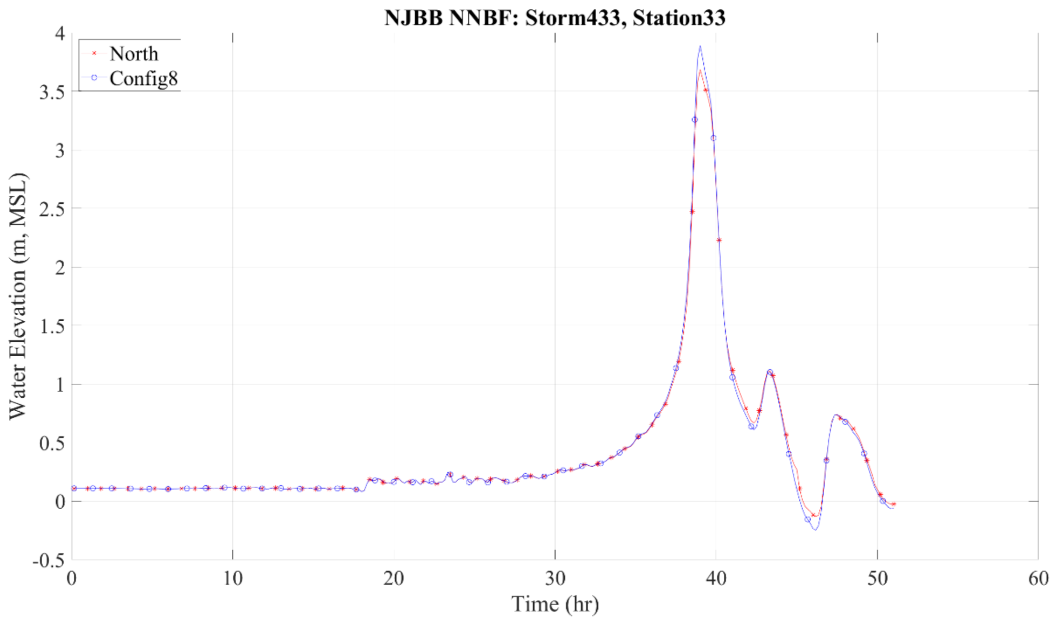

Figure 63 Storm 433 hydrograph for save point 33 "in front of" Holgate area with and without NNBF

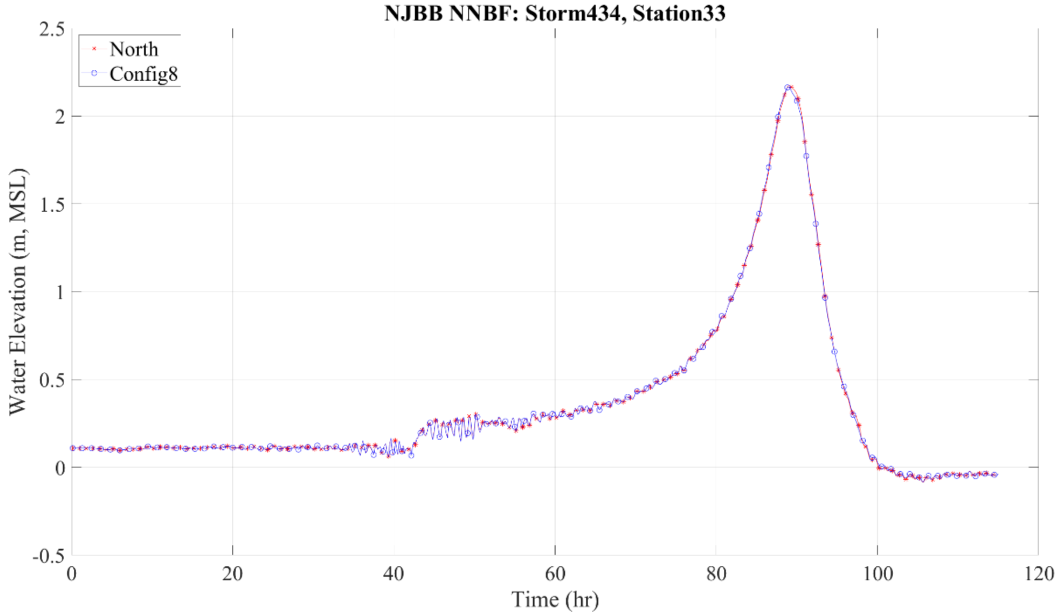

Figure 64 Storm 434 hydrograph for save point 33 "in front of" Holgate area with and without NNBF

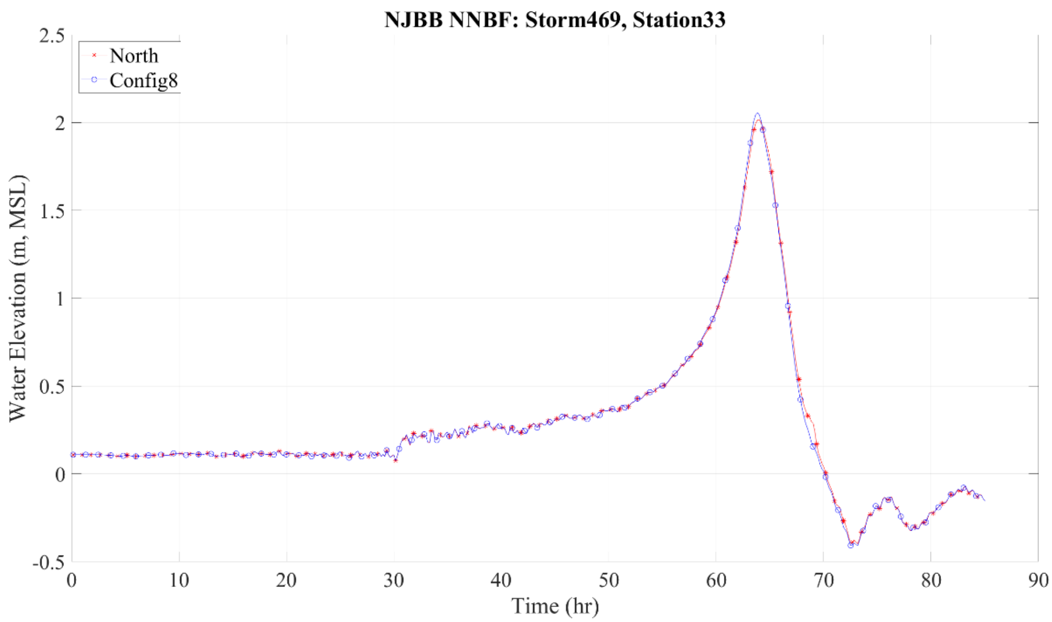

Figure 65 Storm 469 hydrograph for save point 33 "in front of" Holgate area with and without NNBF

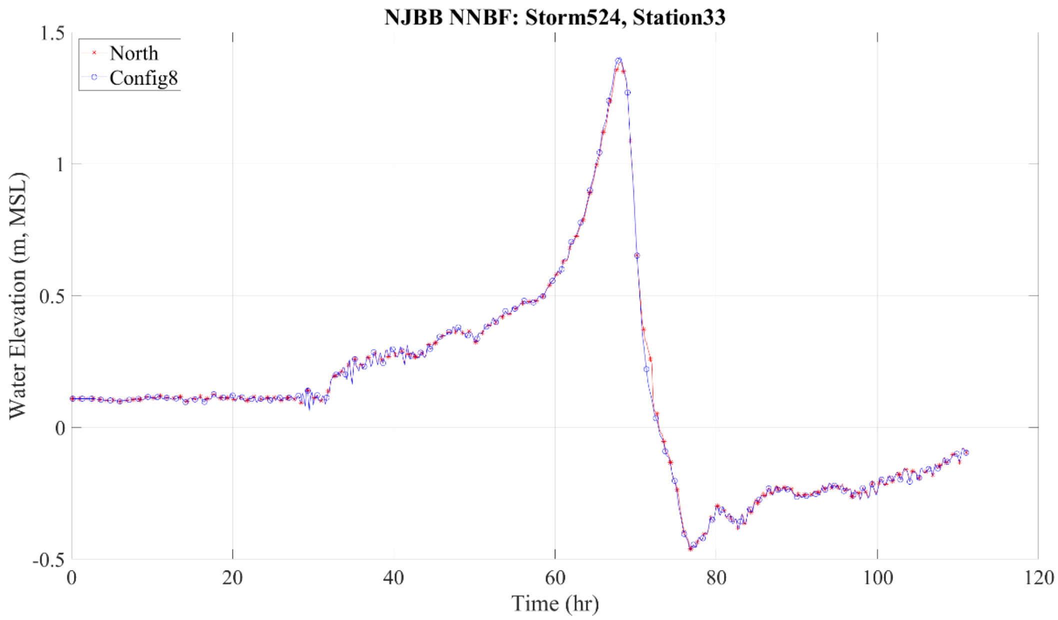

Figure 66 Storm 524 hydrograph for save point 33 "in front of" Holgate area with and without NNBF

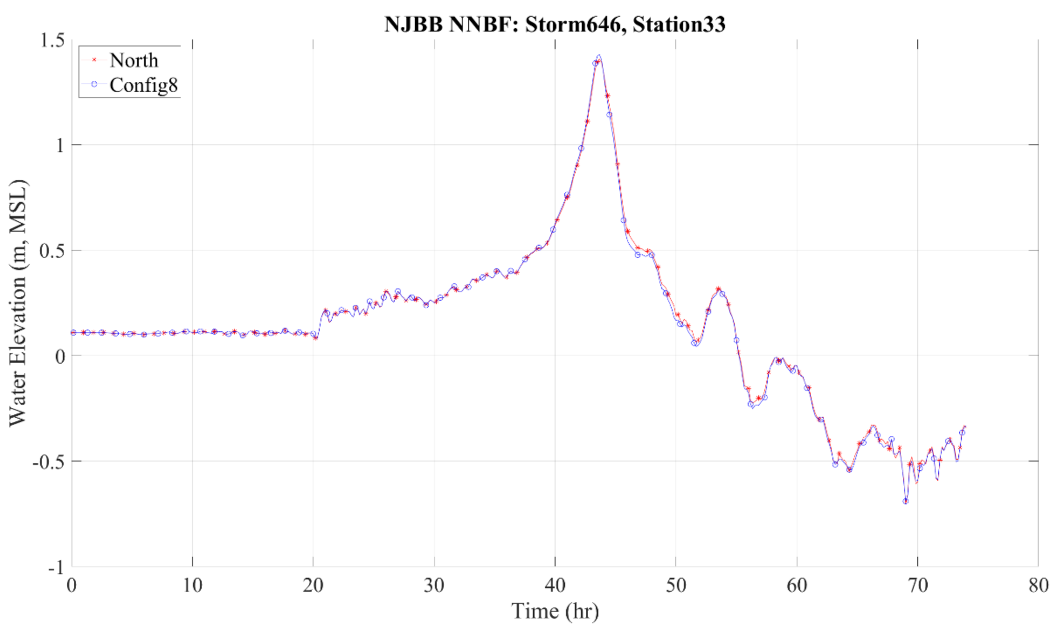

Figure 67 Storm 646 hydrograph for save point 33 "in front of" Holgate area with and without NNBF

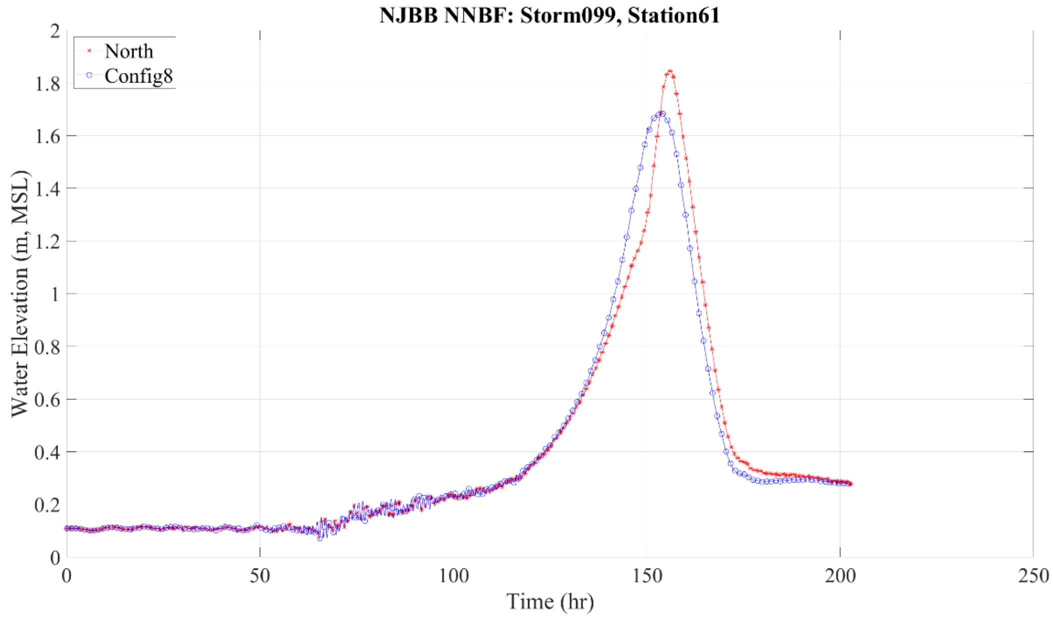

Figure 68 Storm 99 hydrograph for save point 61 "behind" Holgate area with and without NNBF

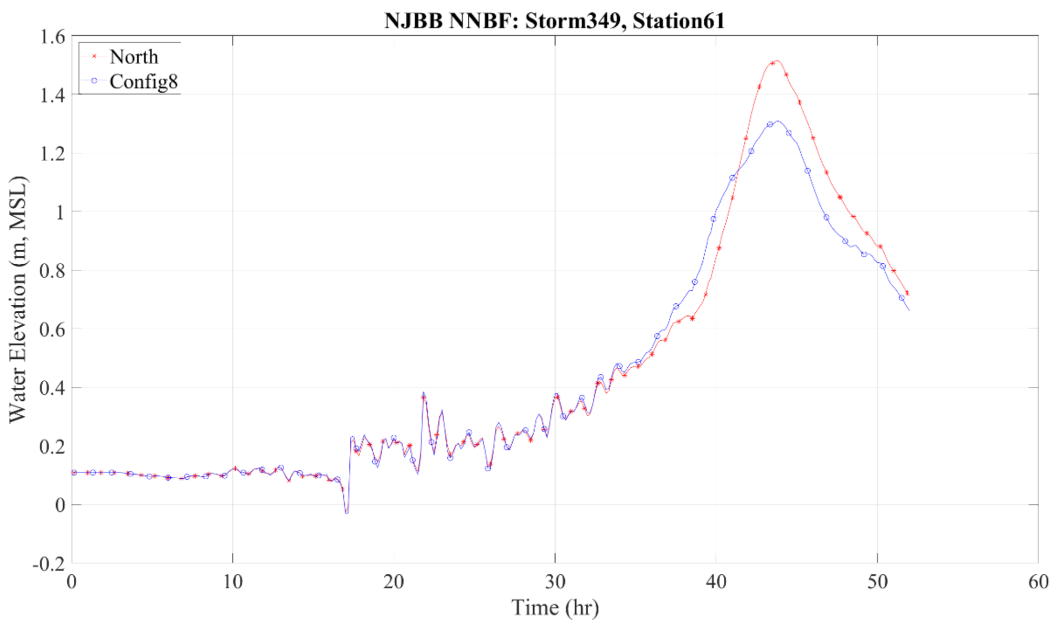

Figure 69 Storm 349 hydrograph for save point 61 "behind" Holgate area with and without NNBF

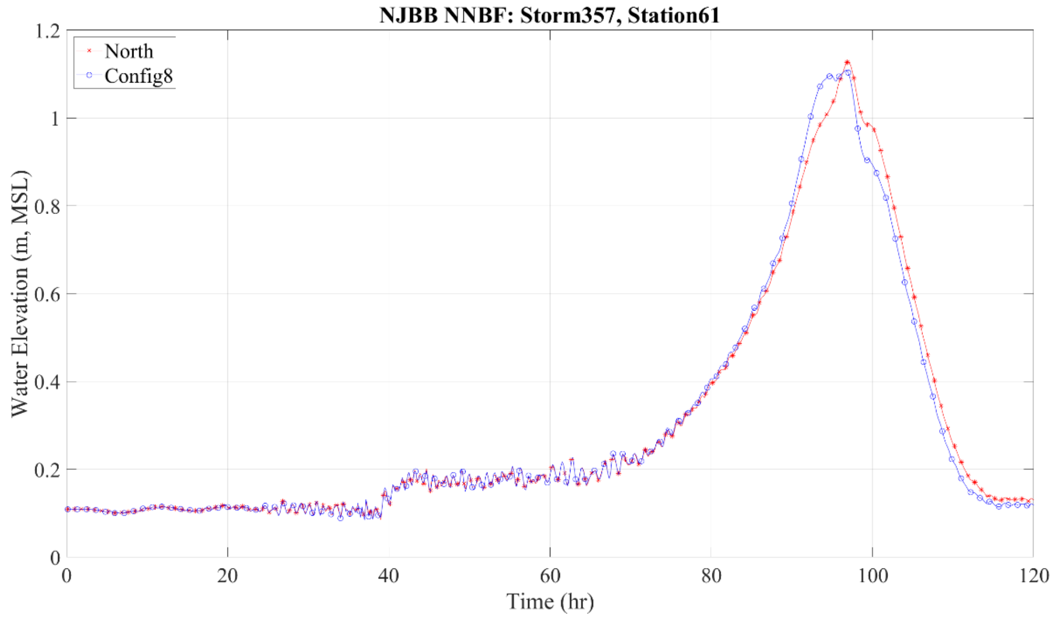

Figure 70 Storm 357 hydrograph for save point 61 "behind" Holgate area with and without NNBF

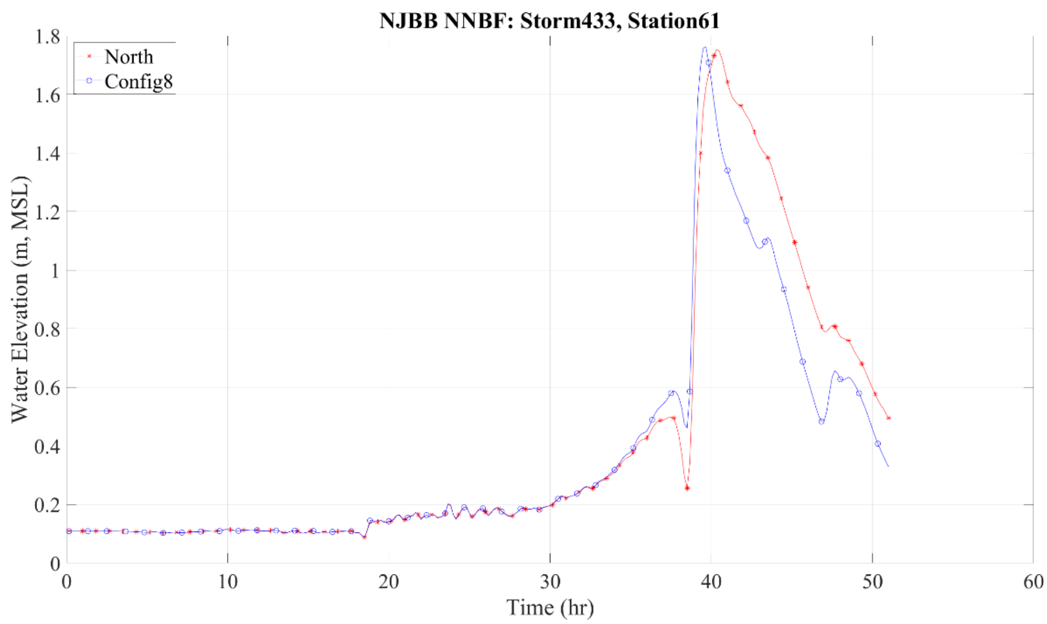

Figure 71 Storm 433 hydrograph for save point 61 "behind" Holgate area with and without NNBF

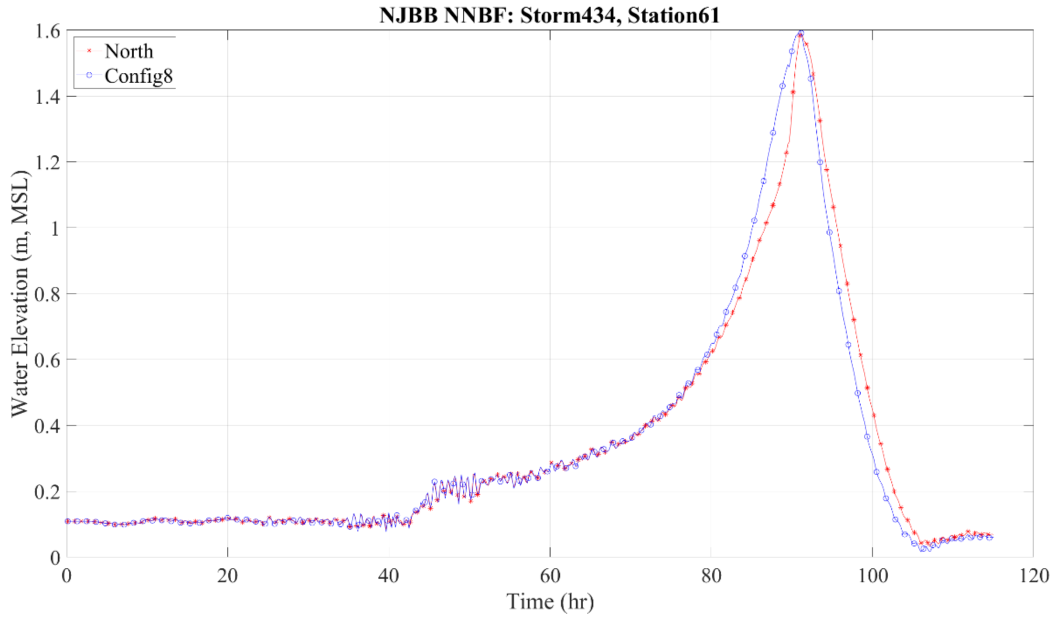

Figure 72 Storm 434 hydrograph for save point 61 "behind" Holgate area with and without NNBF

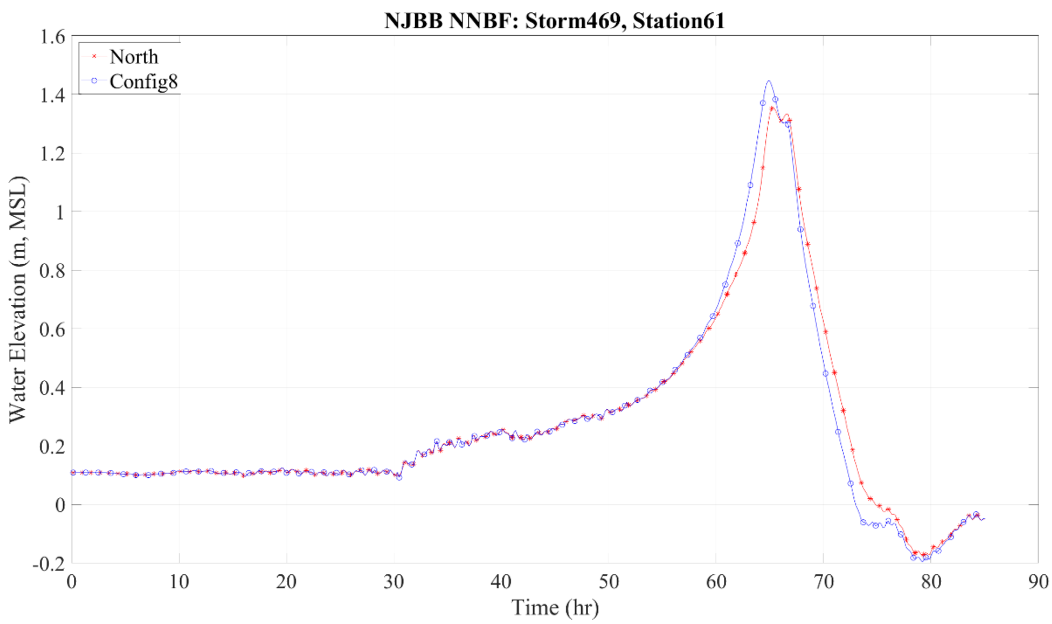

Figure 73 Storm 469 hydrograph for save point 61 "behind" Holgate area with and without NNBF

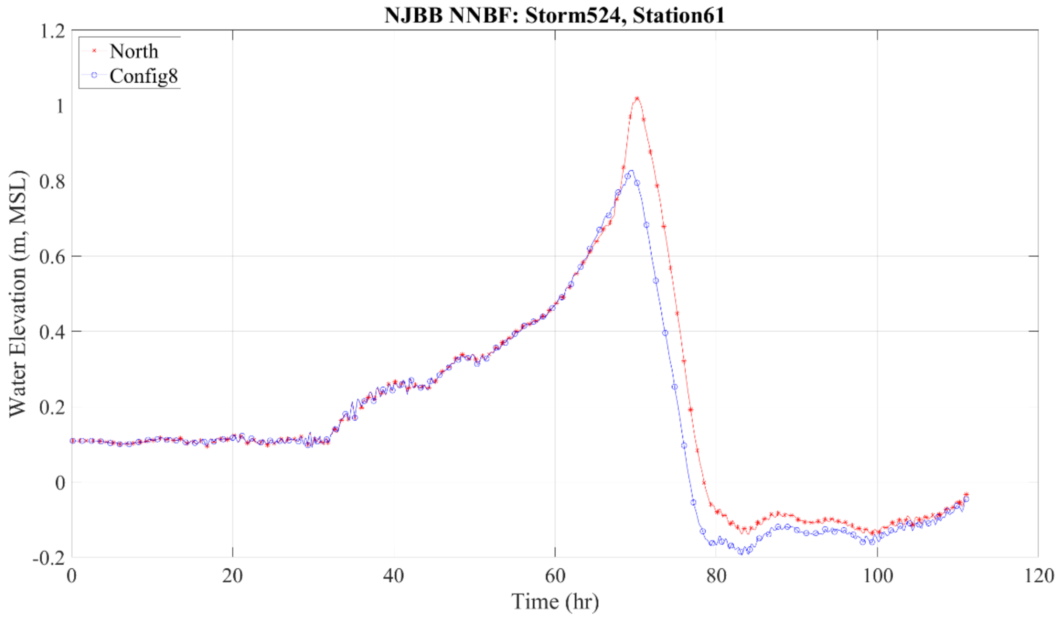

Figure 74 Storm 524 hydrograph for save point 61 "behind" Holgate area with and without NNBF

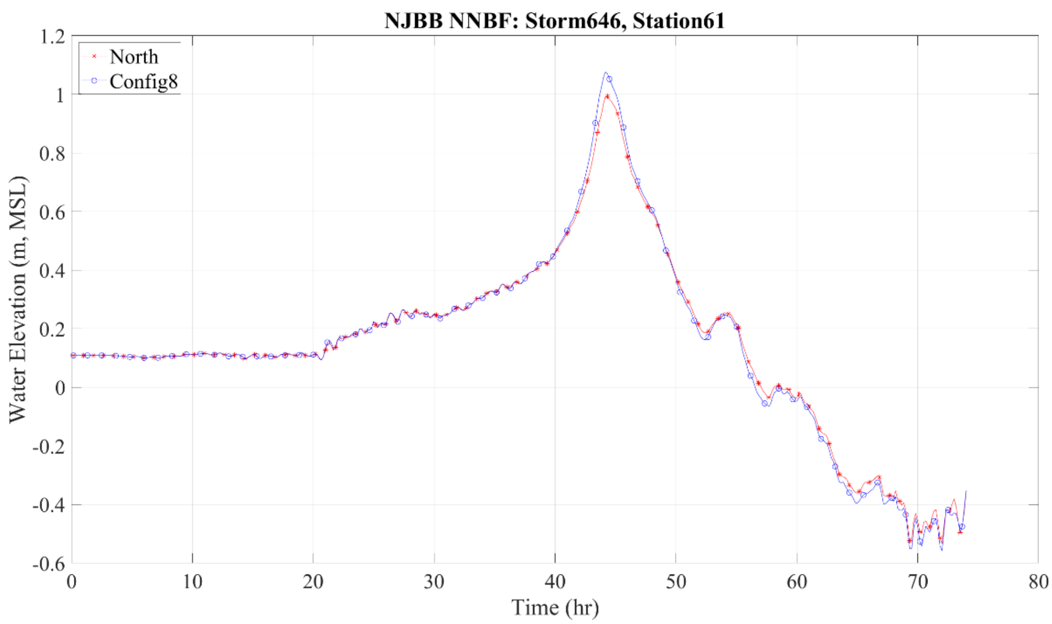

Figure 75 Storm 646 hydrograph for save point 61 "behind" Holgate area with and without NNBF

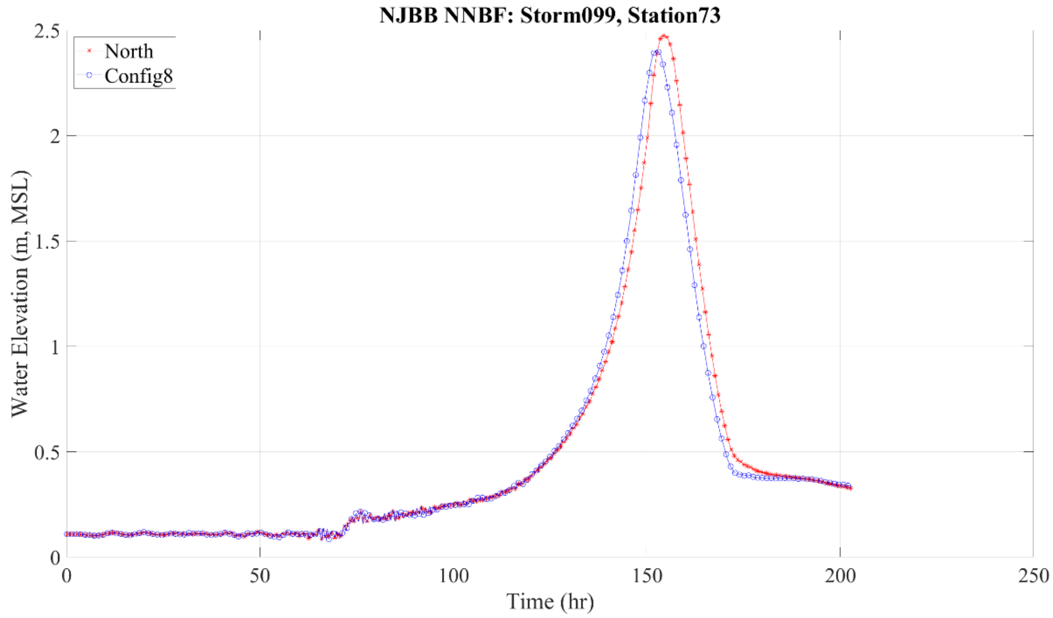

Figure 76 Storm 99 hydrograph for save point 73 "behind" Holgate area with and without NNBF

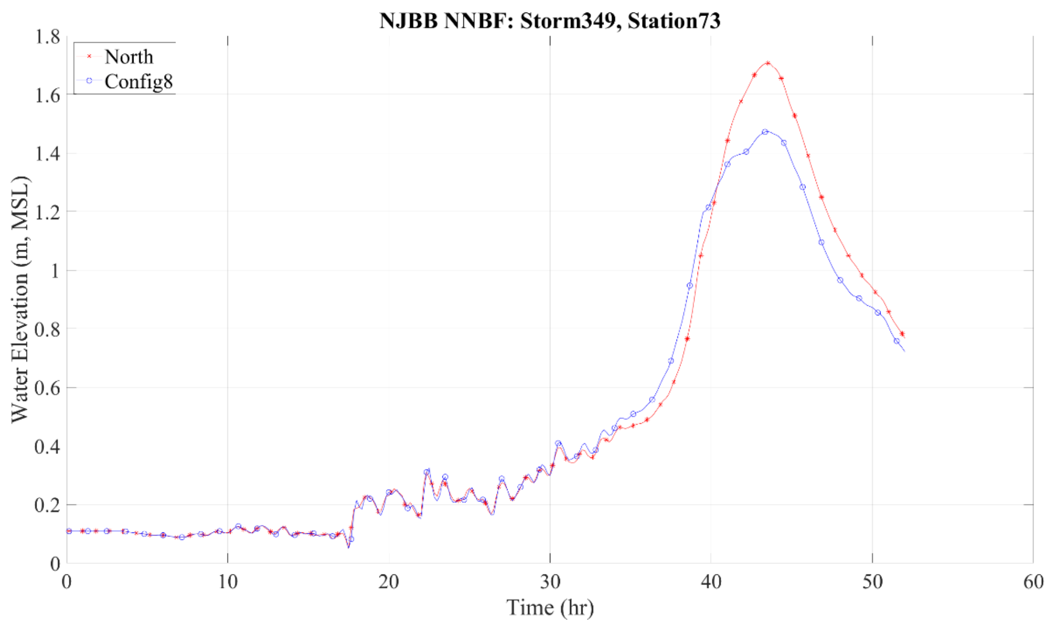

Figure 77 Storm 349 hydrograph for save point 73 "behind" Holgate area with and without NNBF

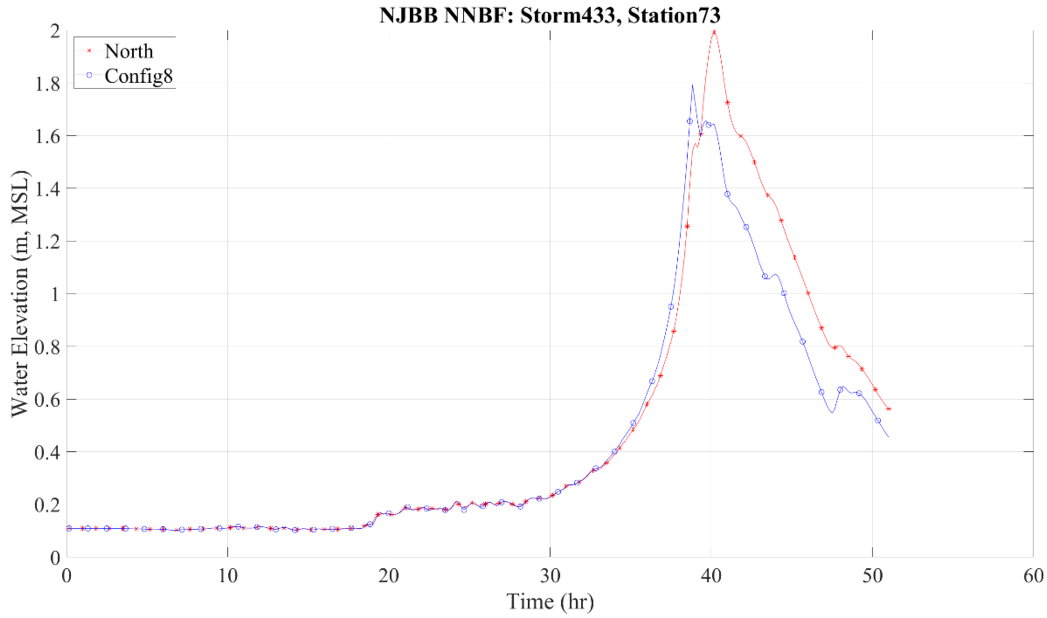

Figure 78 Storm 433 hydrograph for save point 73 "behind" Holgate area with and without NNBF

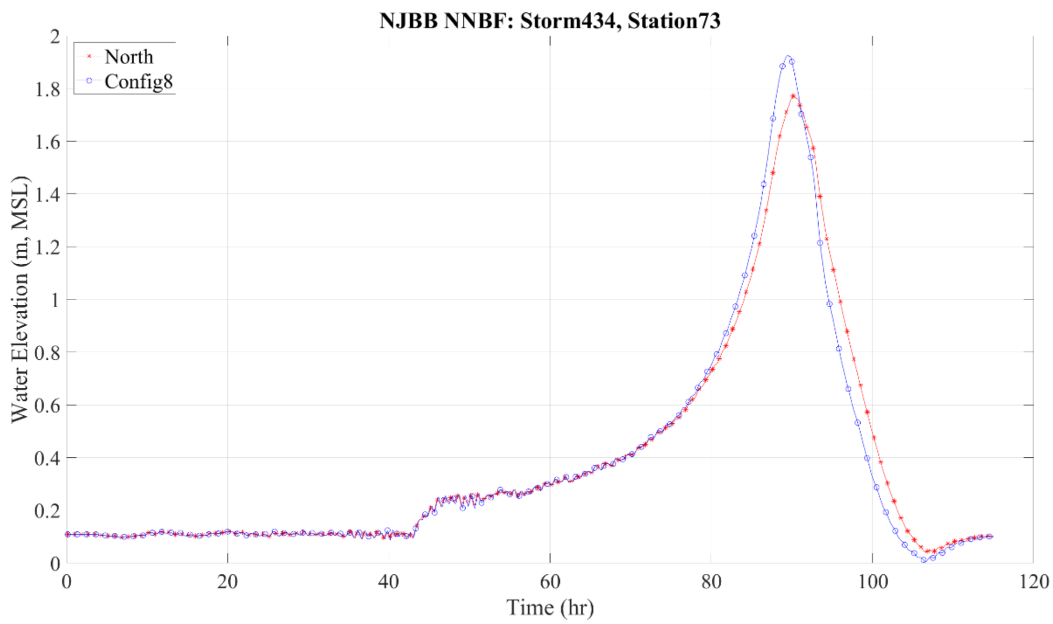

Figure 79 Storm 434 hydrograph for save point 73 "behind" Holgate area with and without NNBF

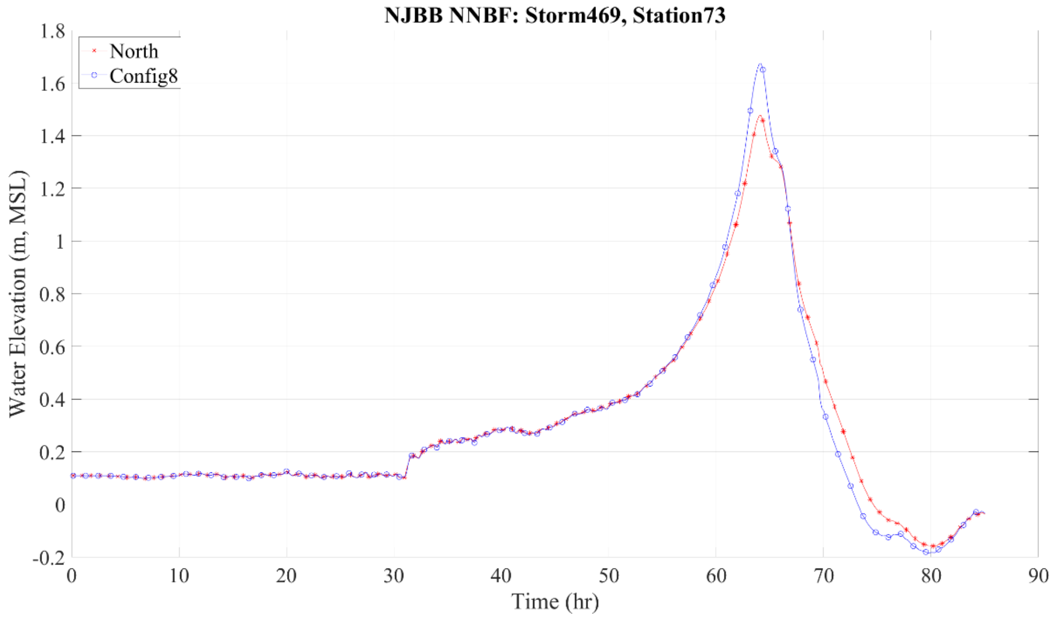

Figure 80 Storm 469 hydrograph for save point 73 "behind" Holgate area with and without NNBF

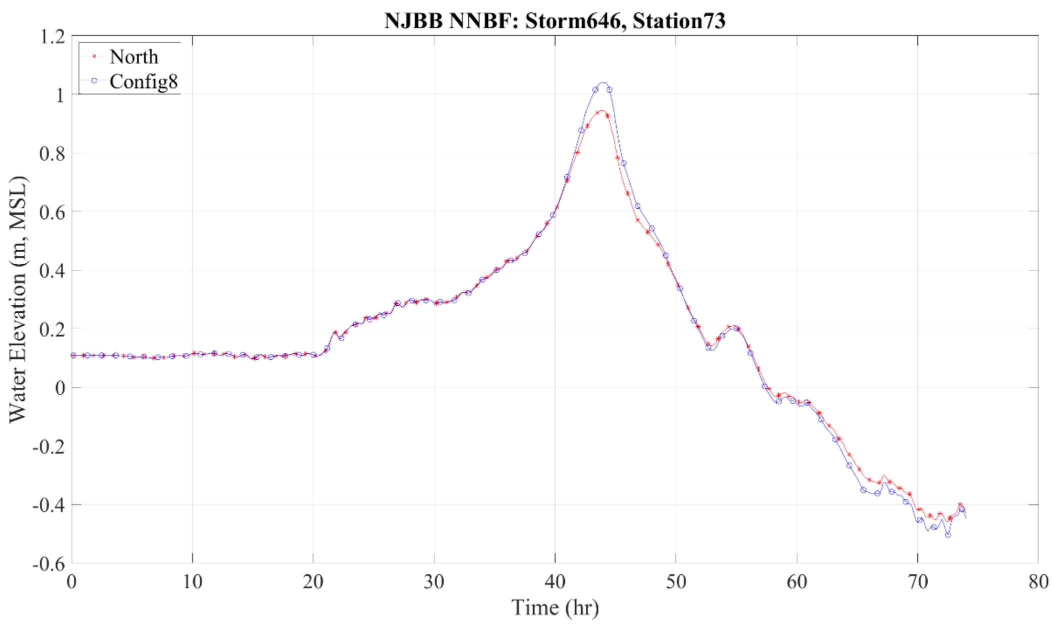

Figure 81 Storm 646 hydrograph for save point 73 "behind" Holgate area with and without NNBF

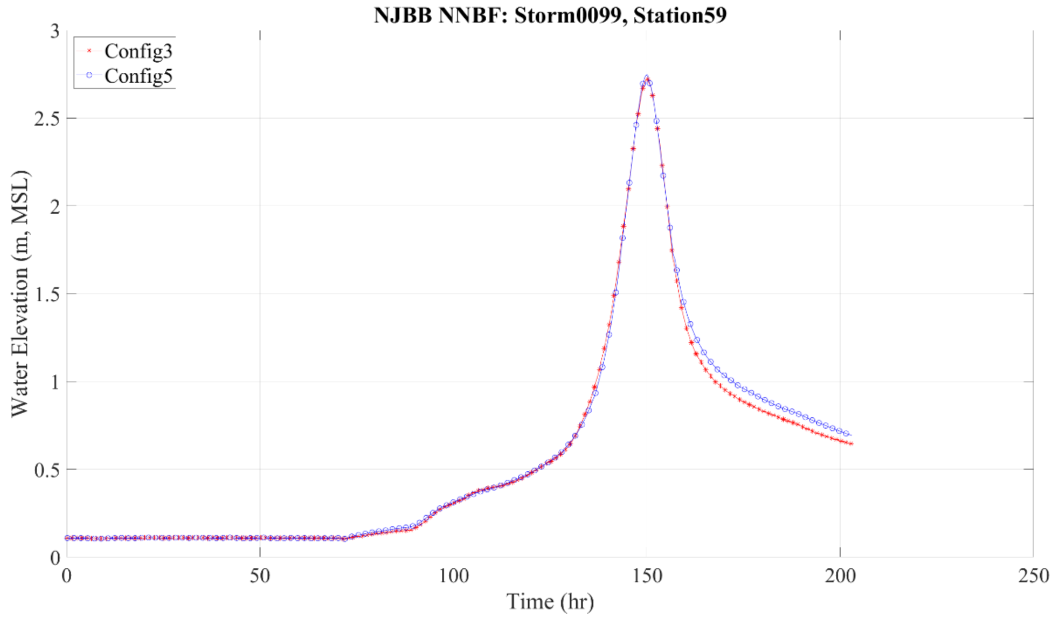

Figure 82 Storm 99 hydrograph for save point 59 "in front of" Brigantine area with and without NNBF

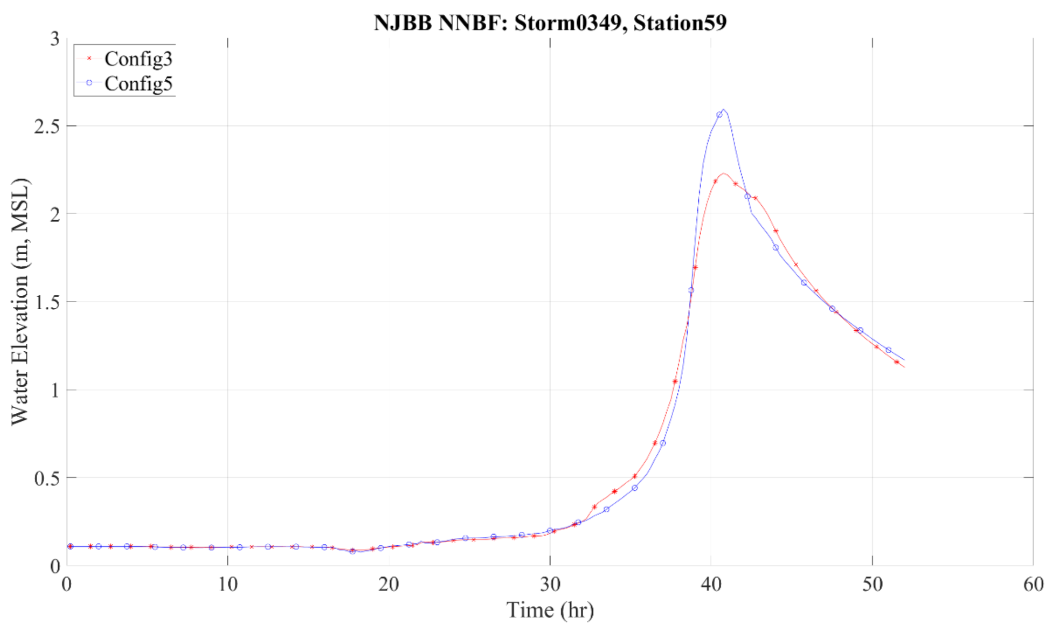

Figure 83 Storm 349 hydrograph for save point 59 "in front of" Brigantine area with and without NNBF

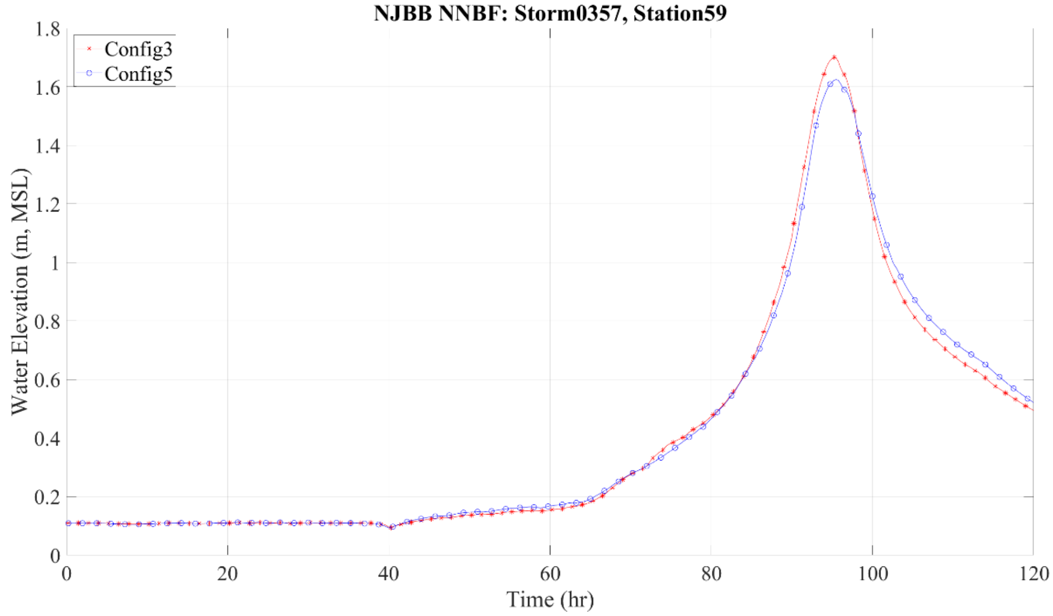

Figure 84 Storm 357 hydrograph for save point 59 "in front of" Brigantine area with and without NNBF

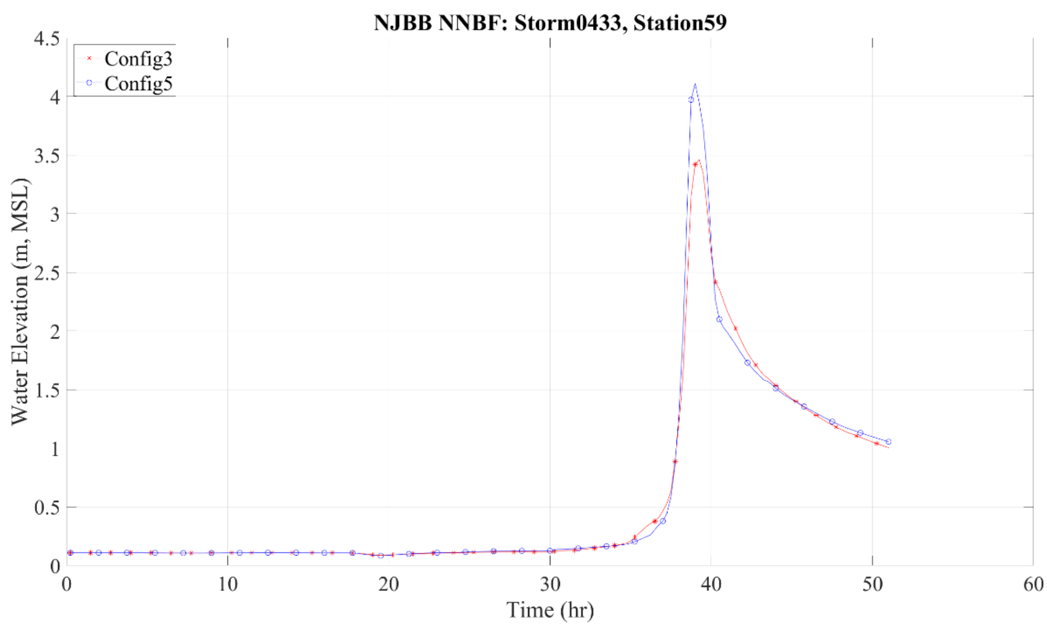

Figure 85 Storm 433 hydrograph for save point 59 "in front of" Brigantine area with and without NNBF

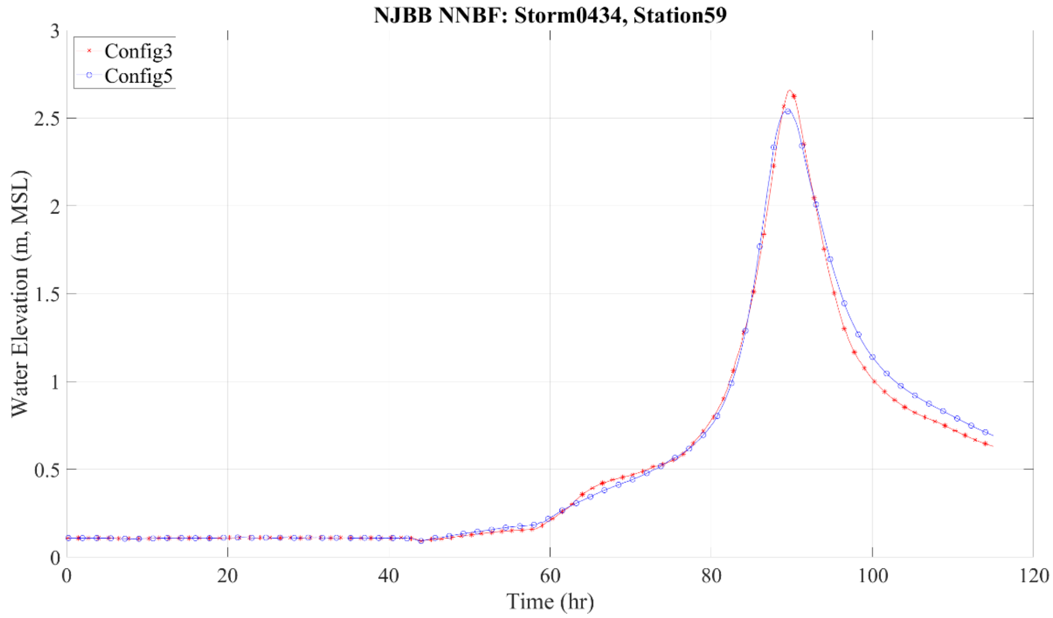

Figure 86 Storm 434 hydrograph for save point 59 "in front of" Brigantine area with and without NNBF

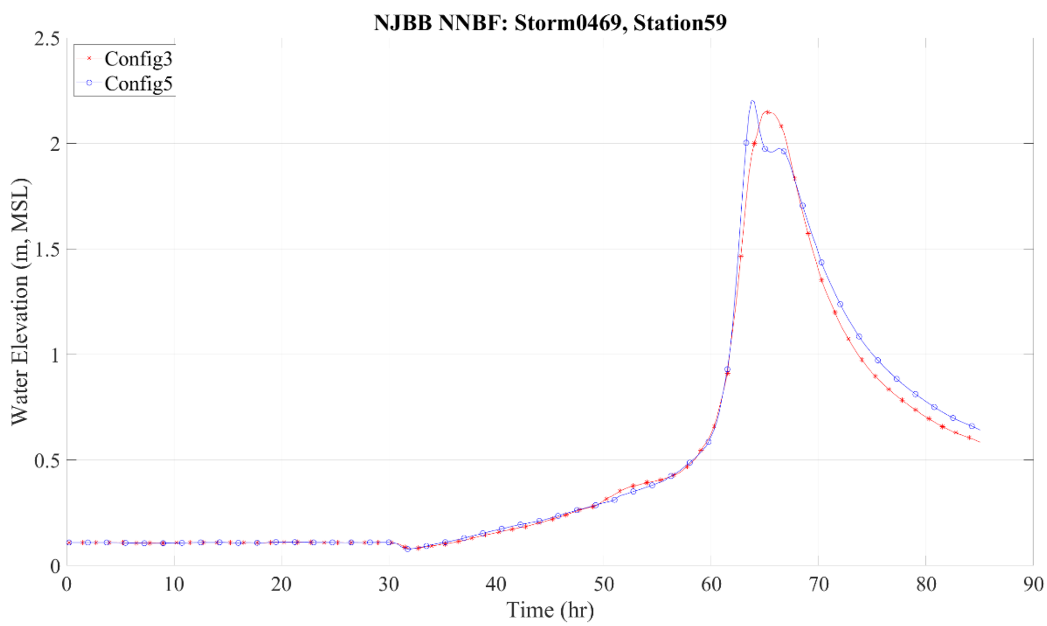

Figure 87 Storm 469 hydrograph for save point 59 "in front of" Brigantine area with and without NNBF

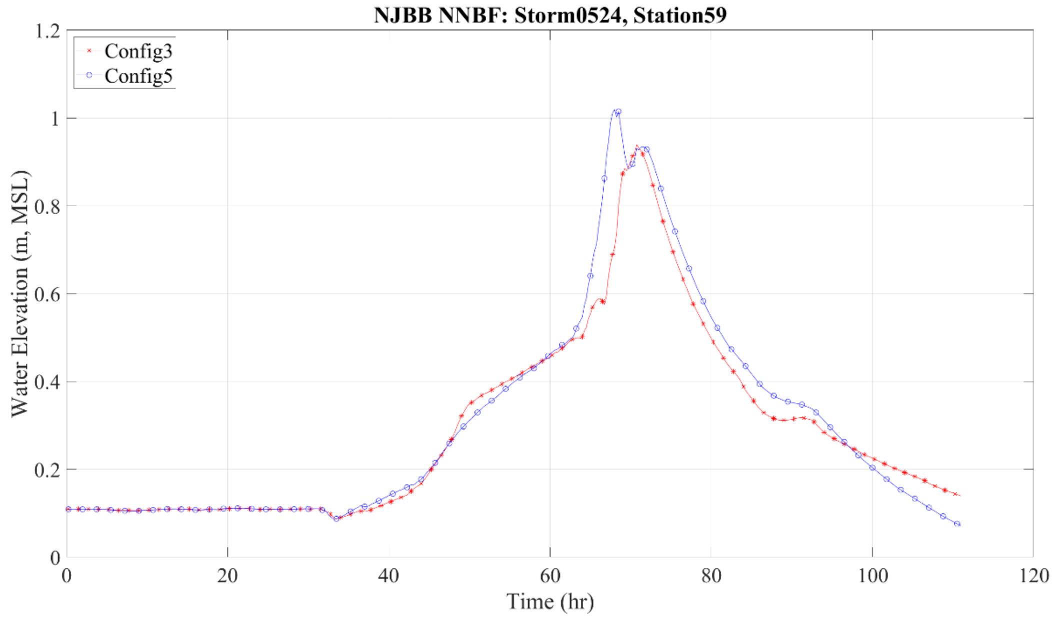

Figure 88 Storm 524 hydrograph for save point 59 "in front of" Brigantine area with and without NNBF

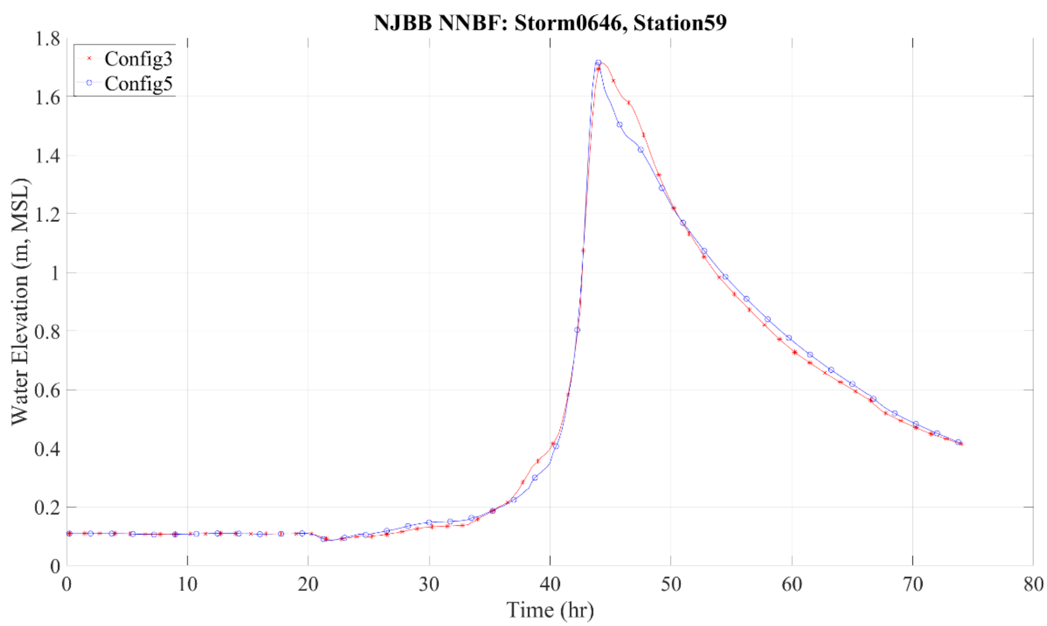

Figure 89 Storm 646 hydrograph for save point 59 "in front of" Brigantine area with and without NNBF

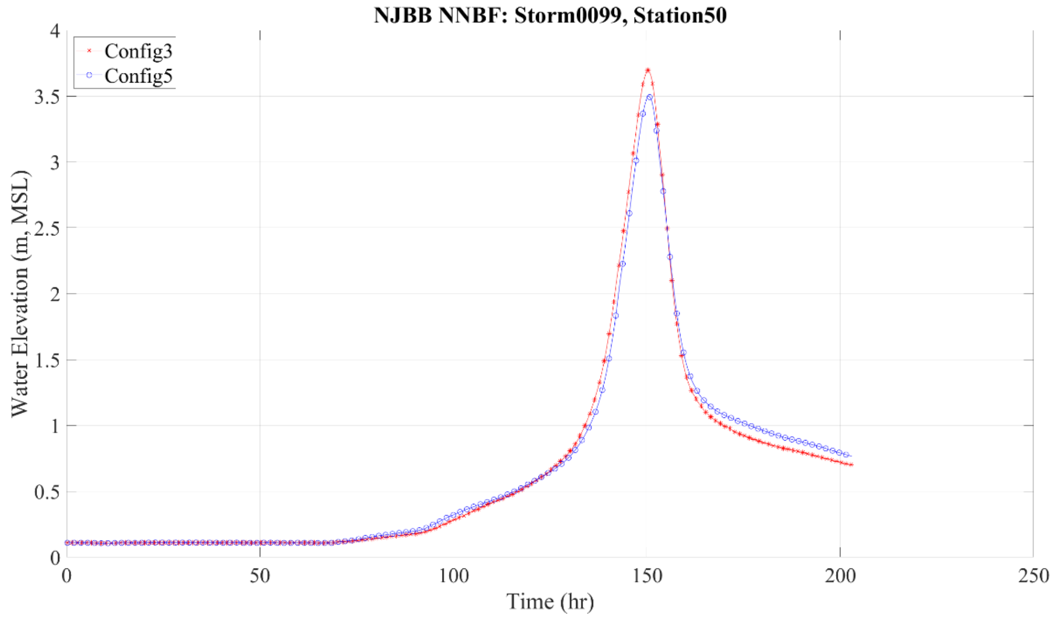

Figure 90 Storm 99 hydrograph for save point 50 "behind" Brigantine area with and without NNBF

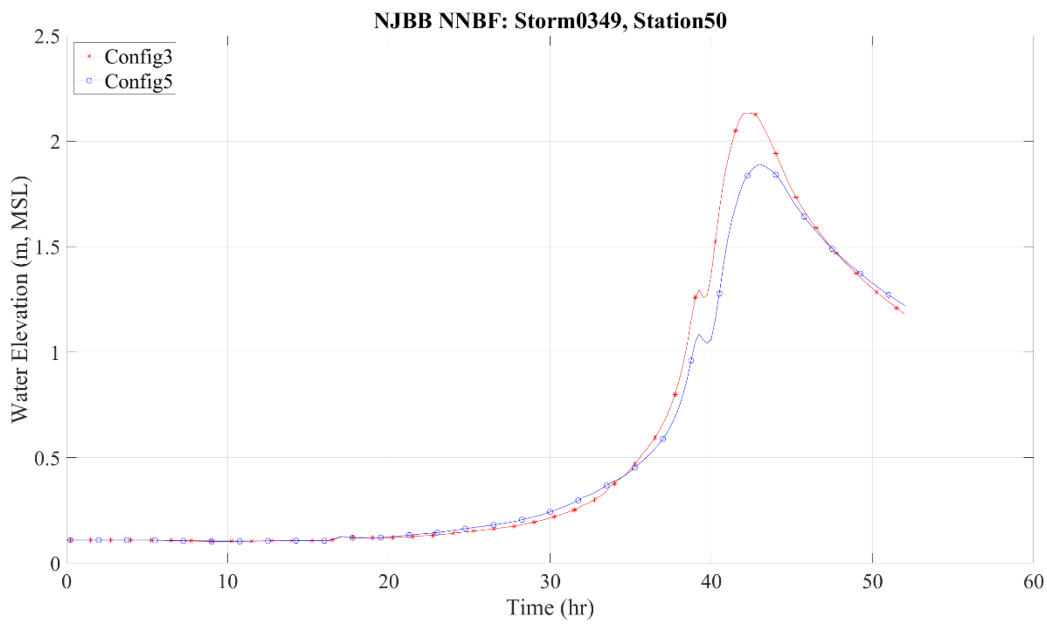

Figure 91 Storm 349 hydrograph for save point 50 "behind" Brigantine area with and without NNBF

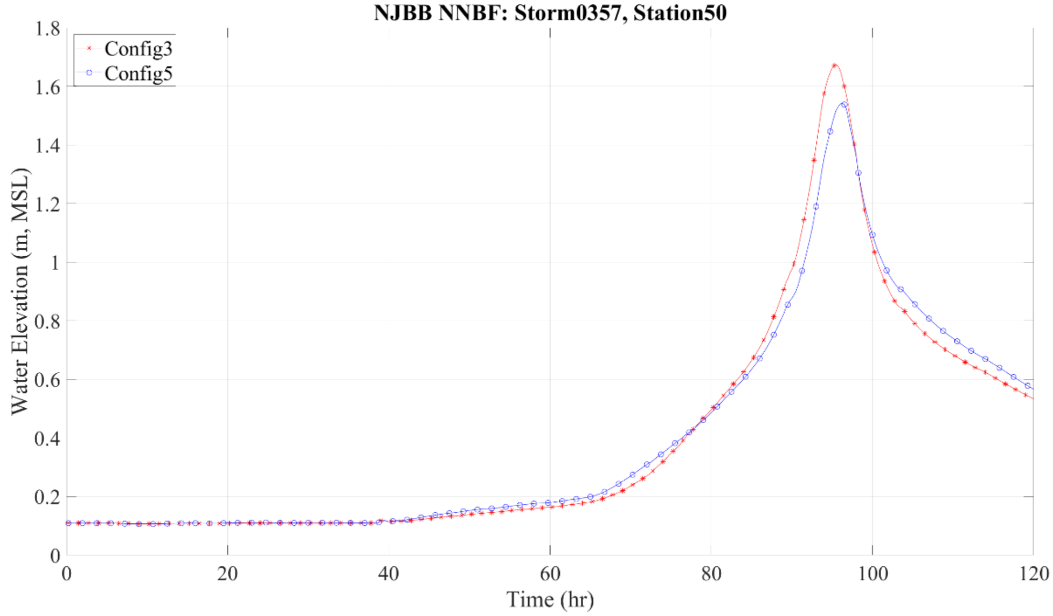

Figure 92 Storm 357 hydrograph for save point 50 "behind" Brigantine area with and without NNBF

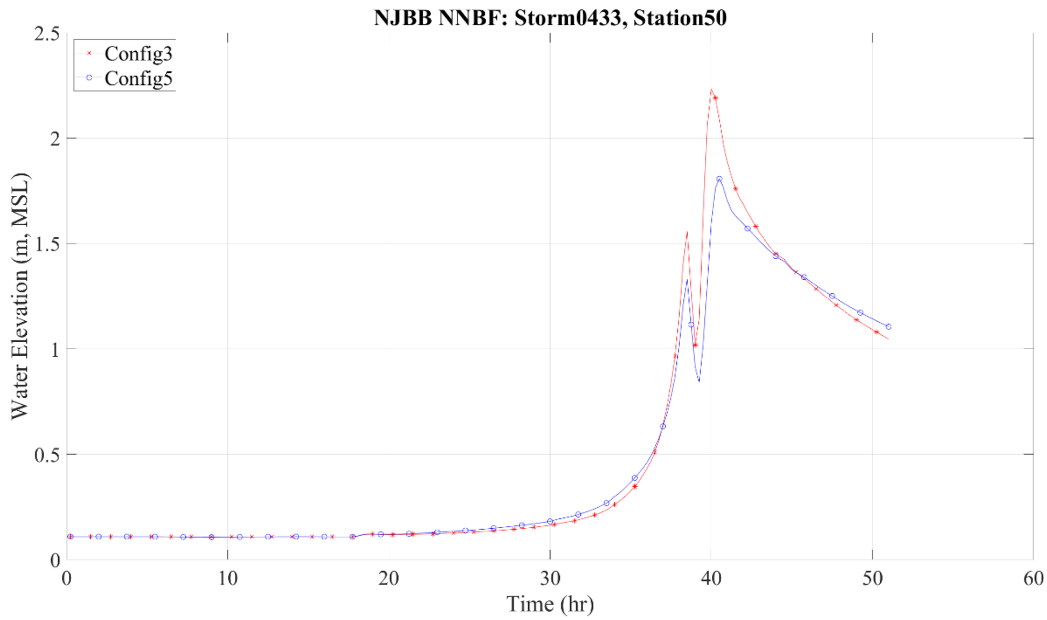

Figure 93 Storm 433 hydrograph for save point 50 "behind" Brigantine area with and without NNBF

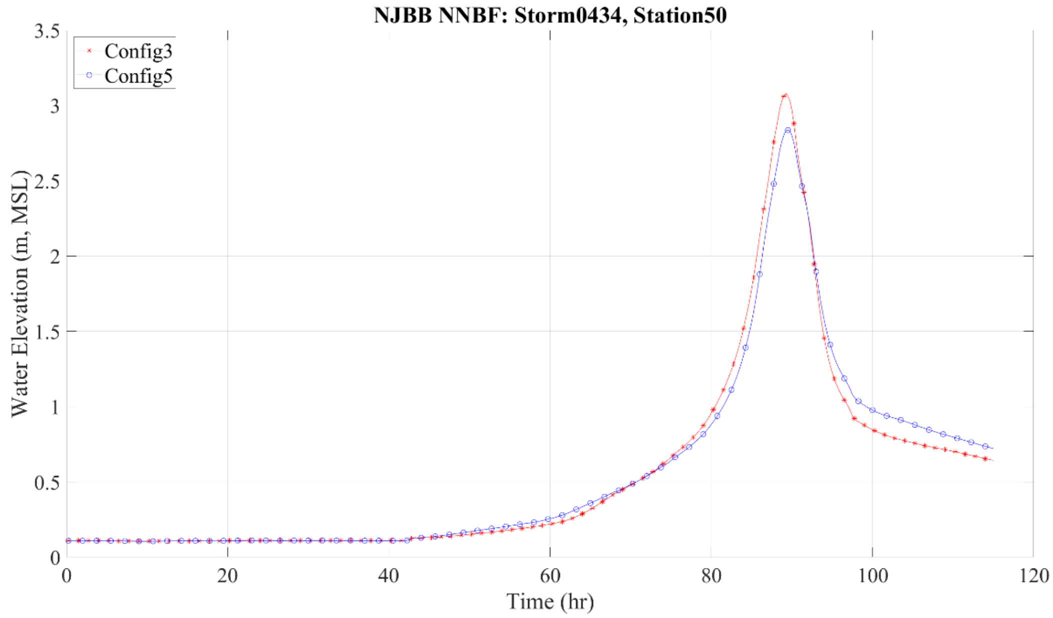

Figure 94 Storm 434 hydrograph for save point 50 "behind" Brigantine area with and without NNBF

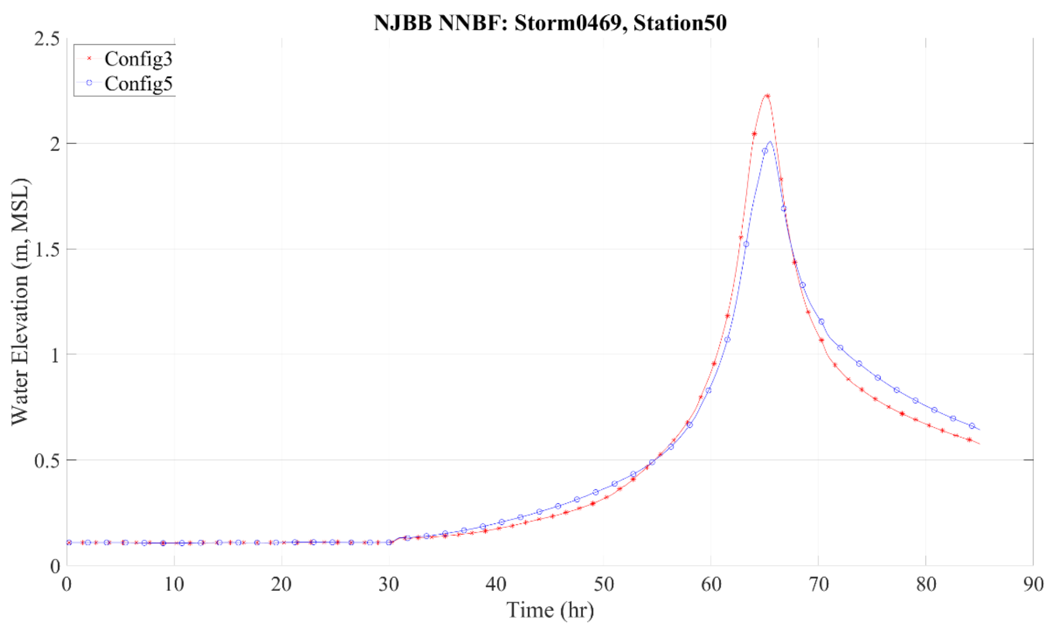

Figure 95 Storm 469 hydrograph for save point 50 "behind" Brigantine area with and without NNBF

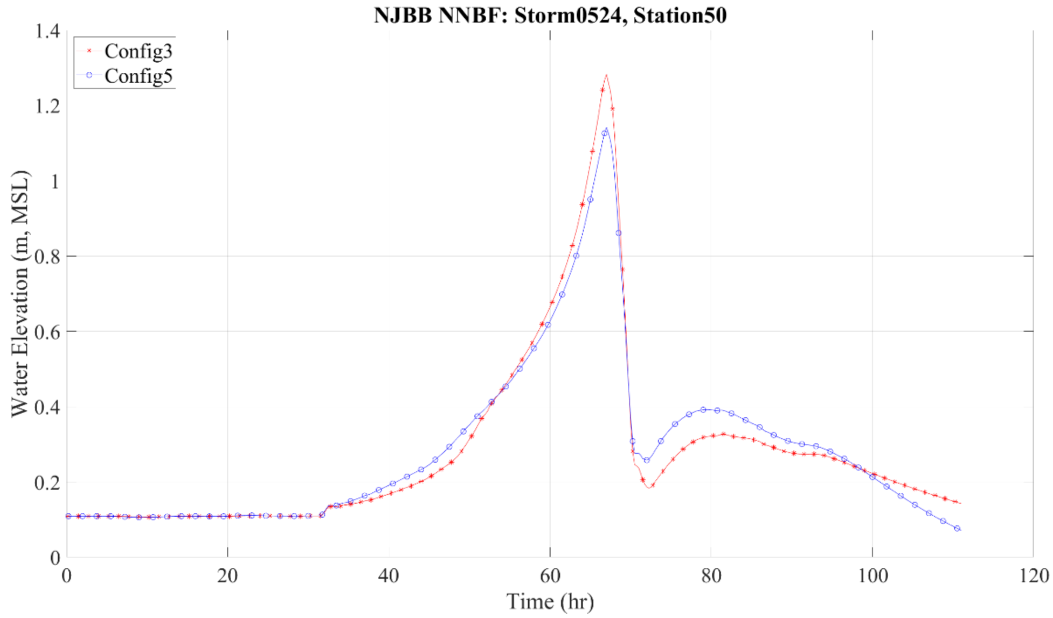

Figure 96 Storm 524 hydrograph for save point 50 "behind" Brigantine area with and without NNBF

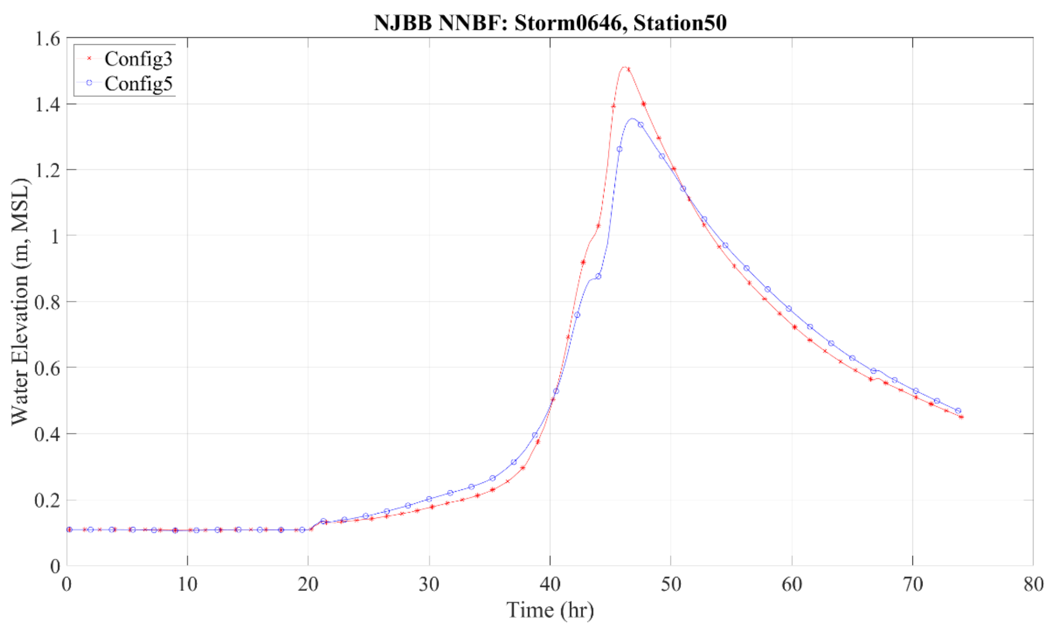

Figure 97 Storm 646 hydrograph for save point 50 "behind" Brigantine area with and without NNBF

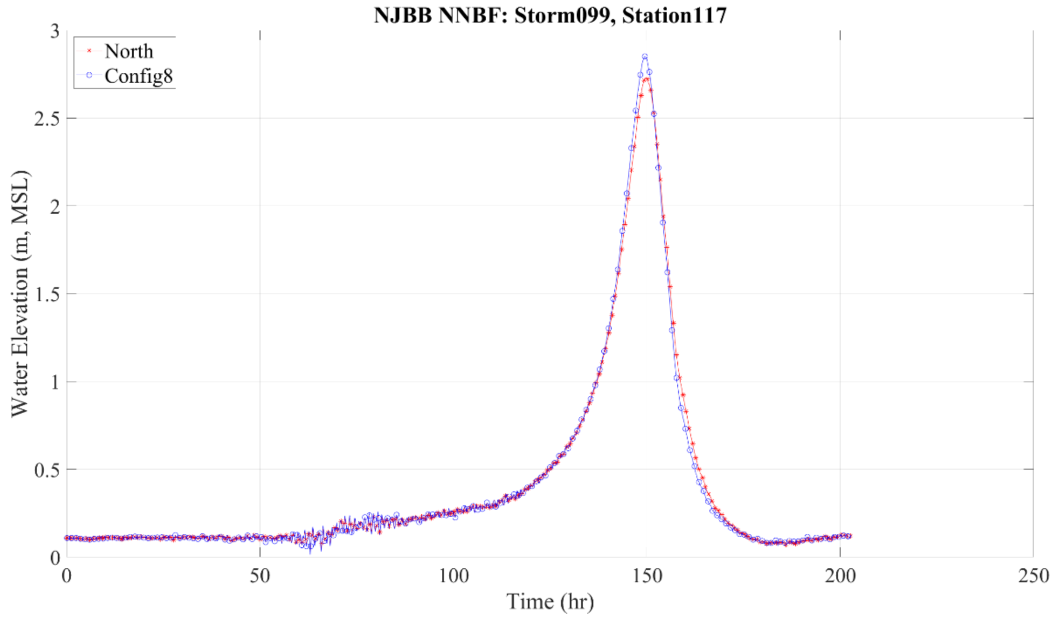

Figure 98 Storm 99 hydrograph for save point 117 "in front of" Great Egg Harbor area with and without NNBF

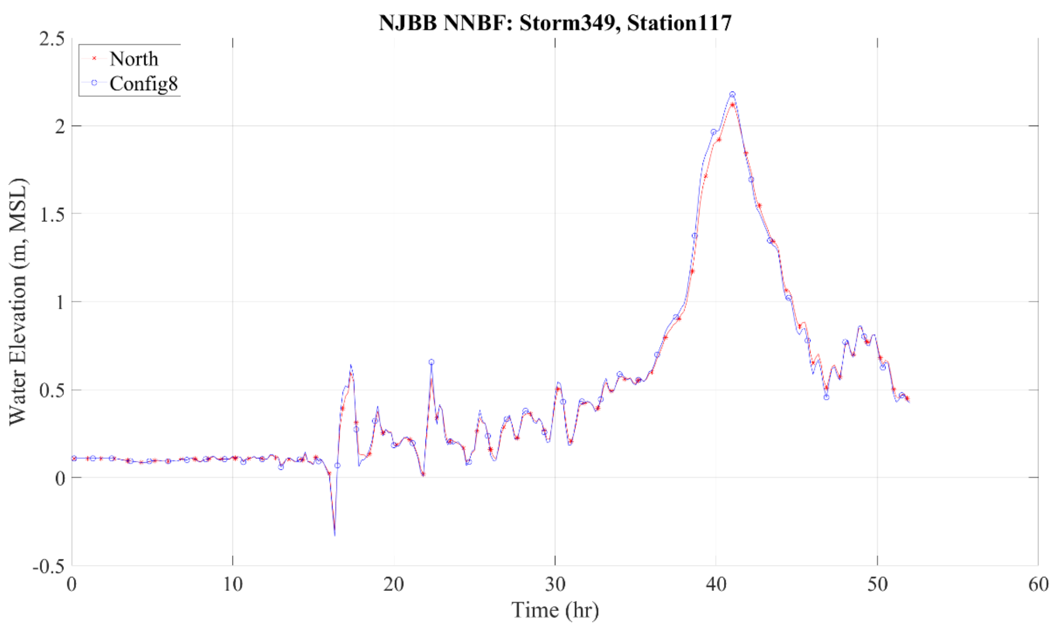

Figure 99 Storm 349 hydrograph for save point 117 "in front of" Great Egg Harbor area with and without NNBF

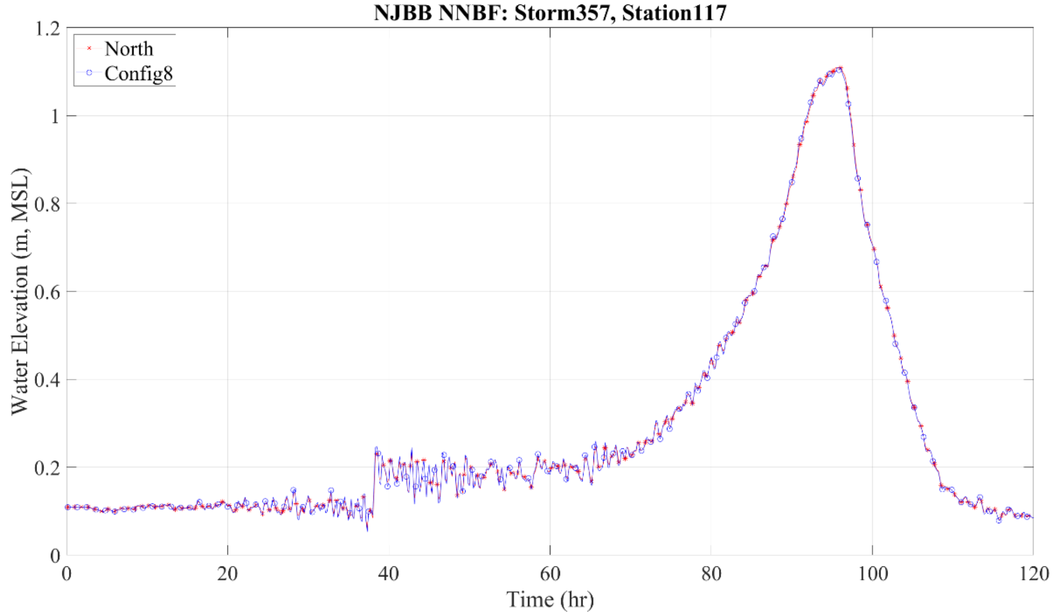

Figure 100 Storm 357 hydrograph for save point 117 "in front of" Great Egg Harbor area with and without NNBF

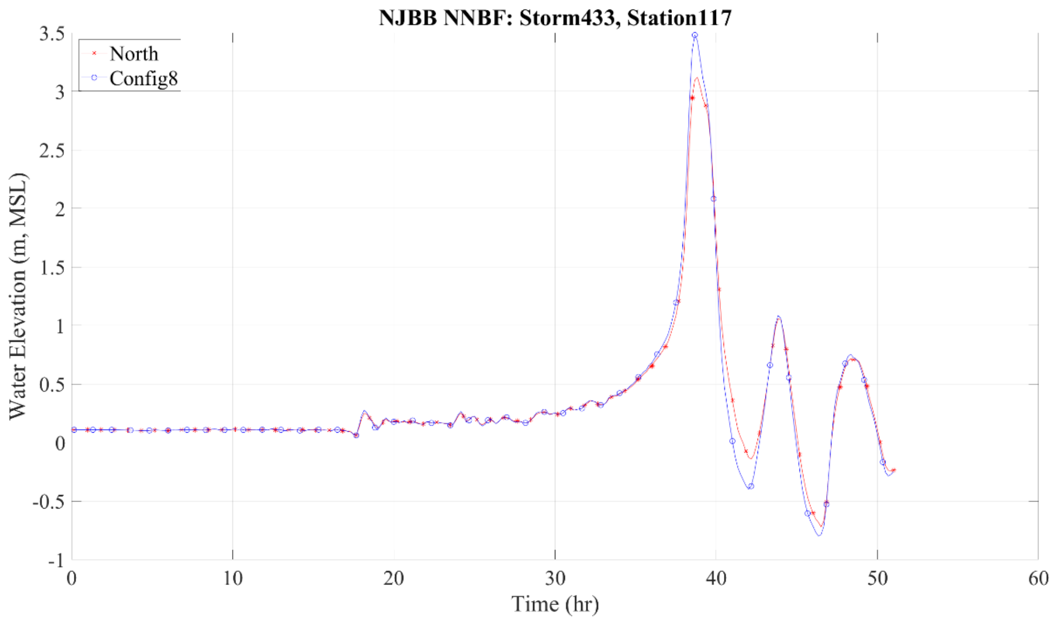

Figure 101 Storm 433 hydrograph for save point 117 "in front of" Great Egg Harbor area with and without NNBF

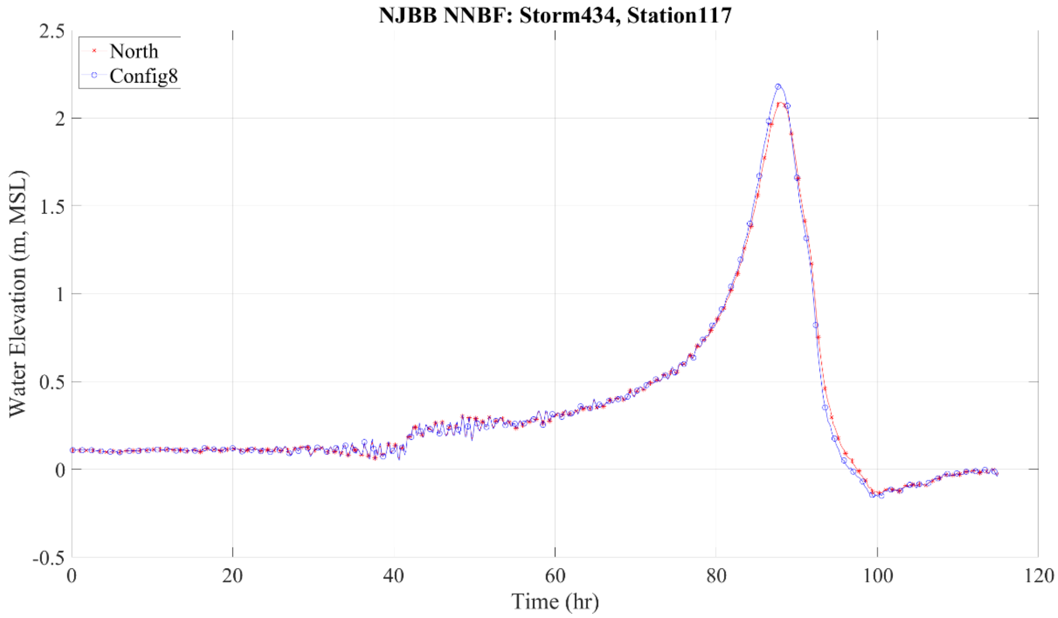

Figure 102 Storm 434 hydrograph for save point 117 "in front of" Great Egg Harbor area with and without NNBF

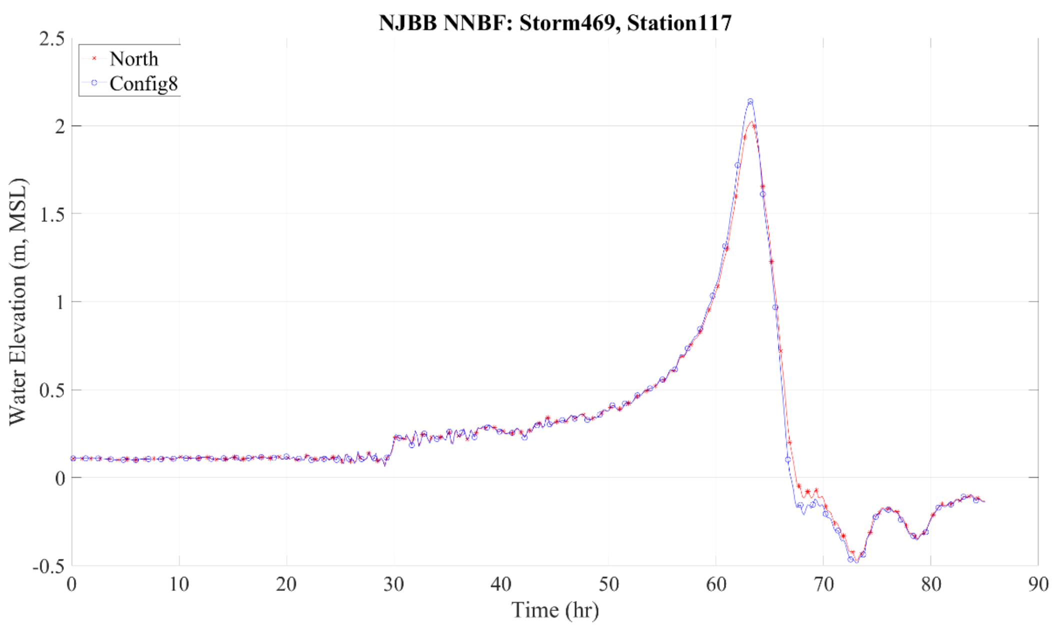

Figure 103 Storm 469 hydrograph for save point 117 "in front of" Great Egg Harbor area with and without NNBF

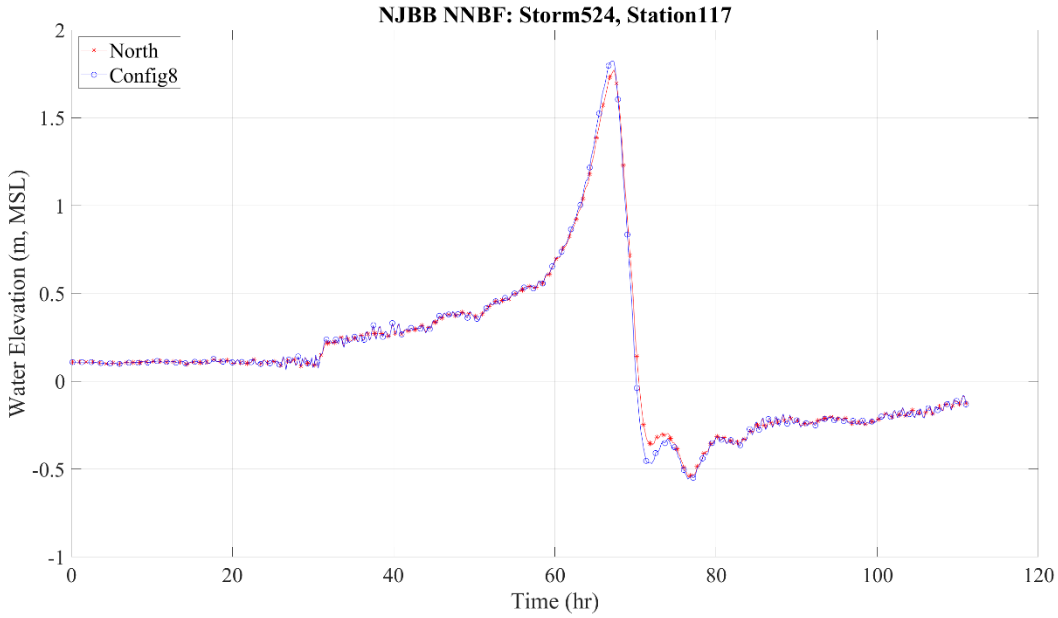

Figure 104 Storm 524 hydrograph for save point 117 "in front of" Great Egg Harbor area with and without NNBF

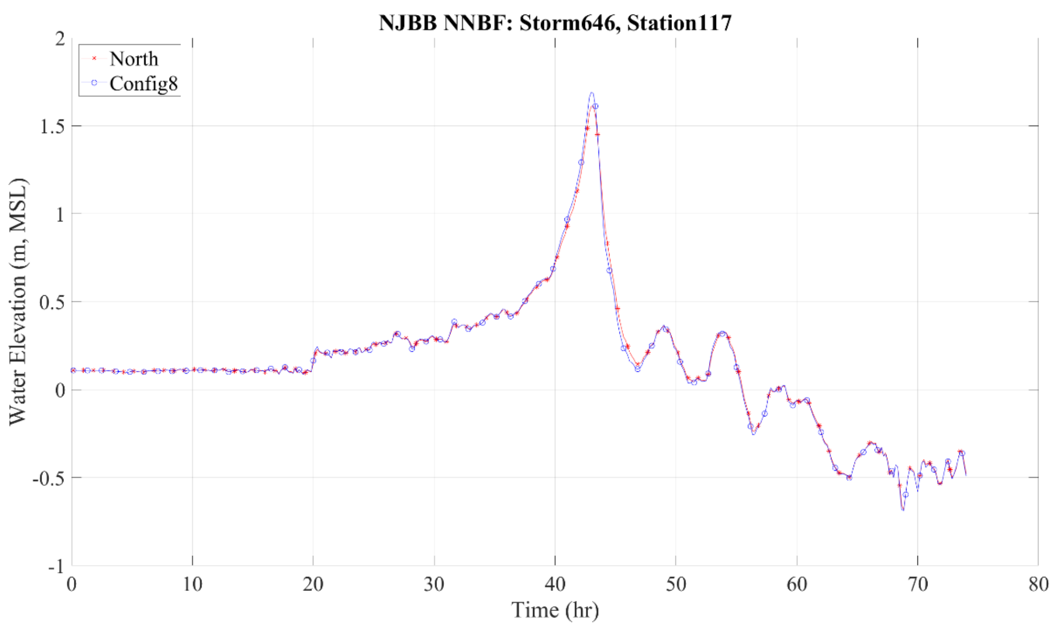

Figure 105 Storm 646 hydrograph for save point 117 "in front of" Great Egg Harbor area with and without NNBF

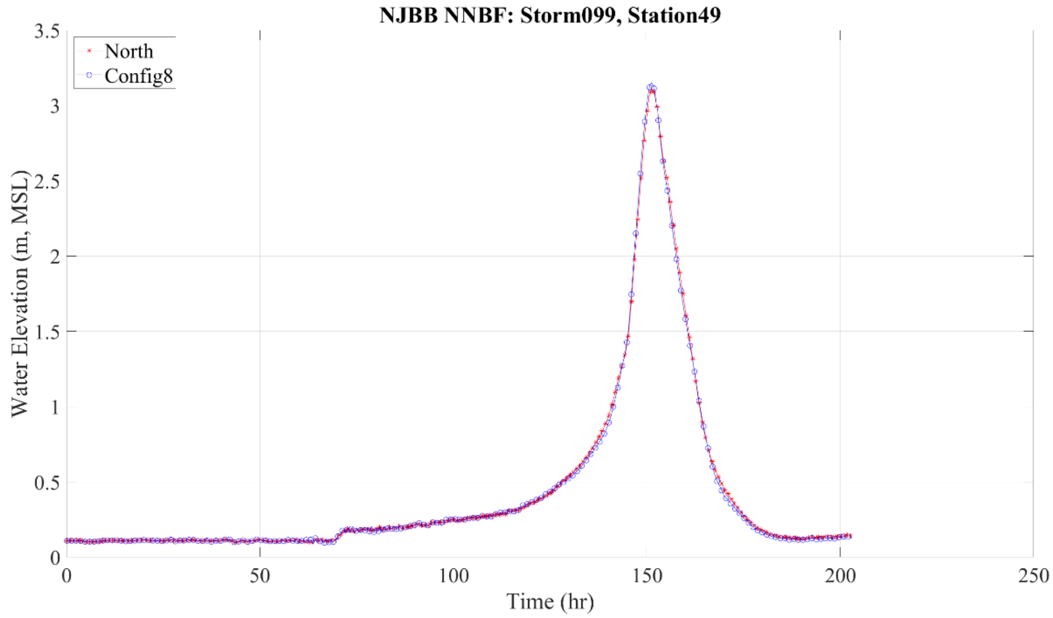

Figure 106 Storm 99 hydrograph for save point 49 "behind" Great Egg Harbor area with and without NNBF

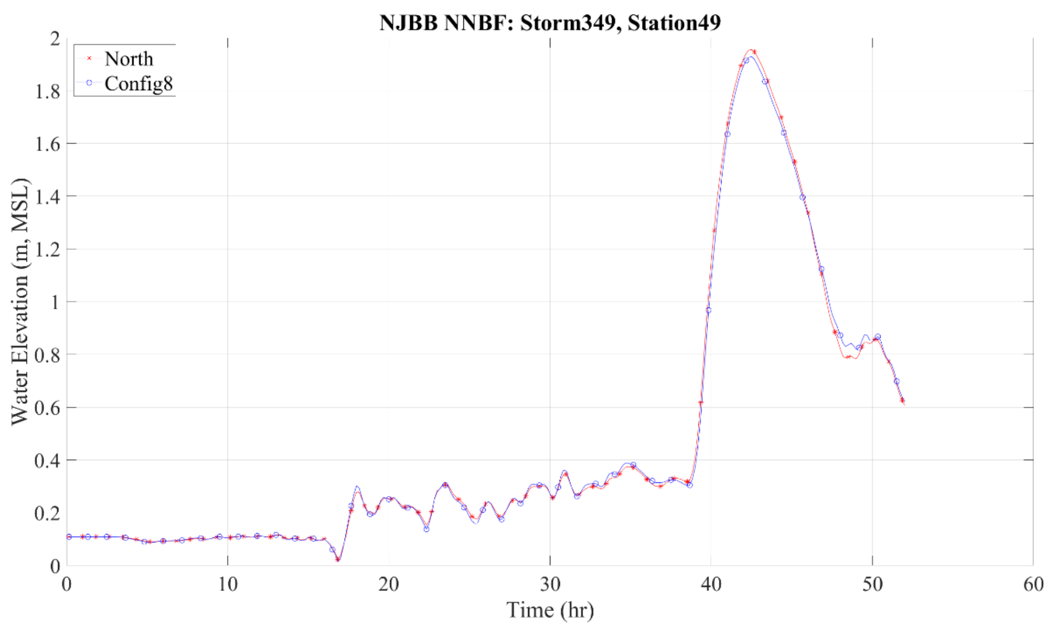

Figure 107 Storm 349 hydrograph for save point 49 "behind" Great Egg Harbor area with and without NNBF

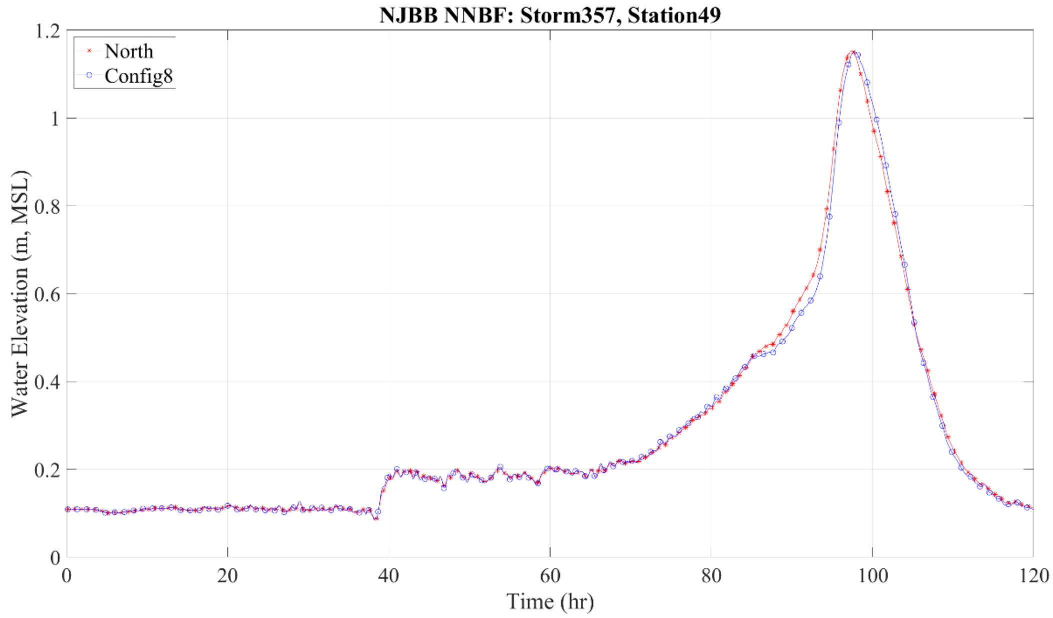

Figure 108 Storm 357 hydrograph for save point 49 "behind" Great Egg Harbor area with and without NNBF

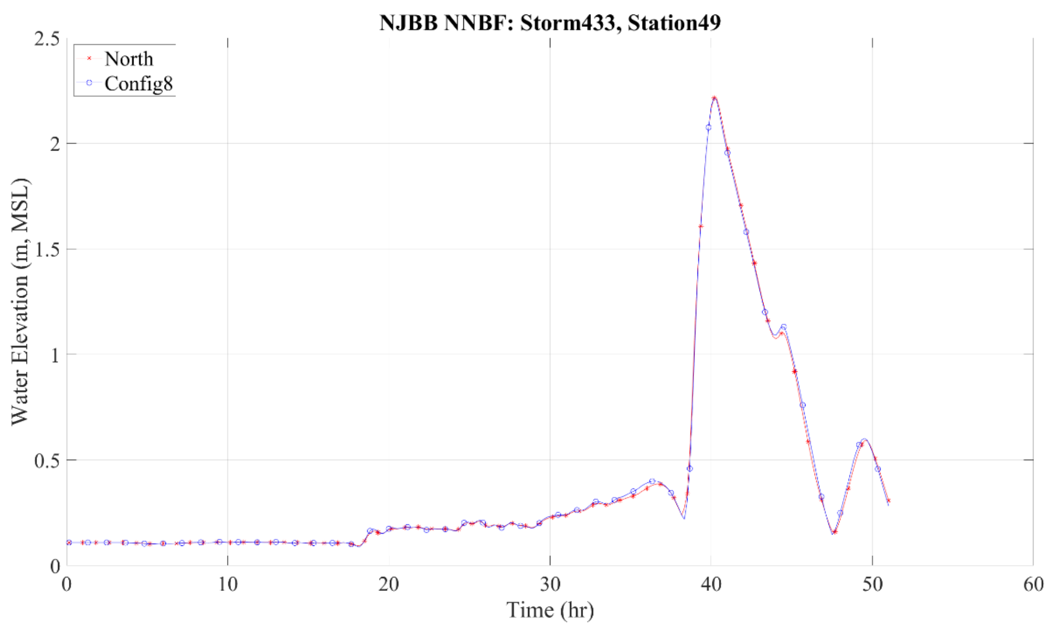

Figure 109 Storm 433 hydrograph for save point 49 "behind" Great Egg Harbor area with and without NNBF

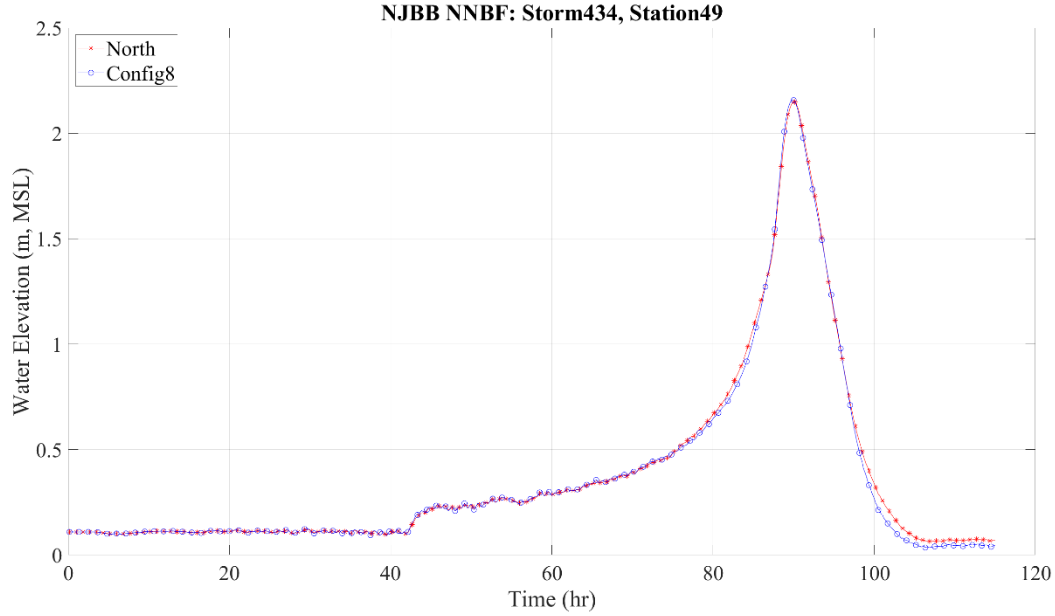

Figure 110 Storm 434 hydrograph for save point 49 "behind" Great Egg Harbor area with and without NNBF

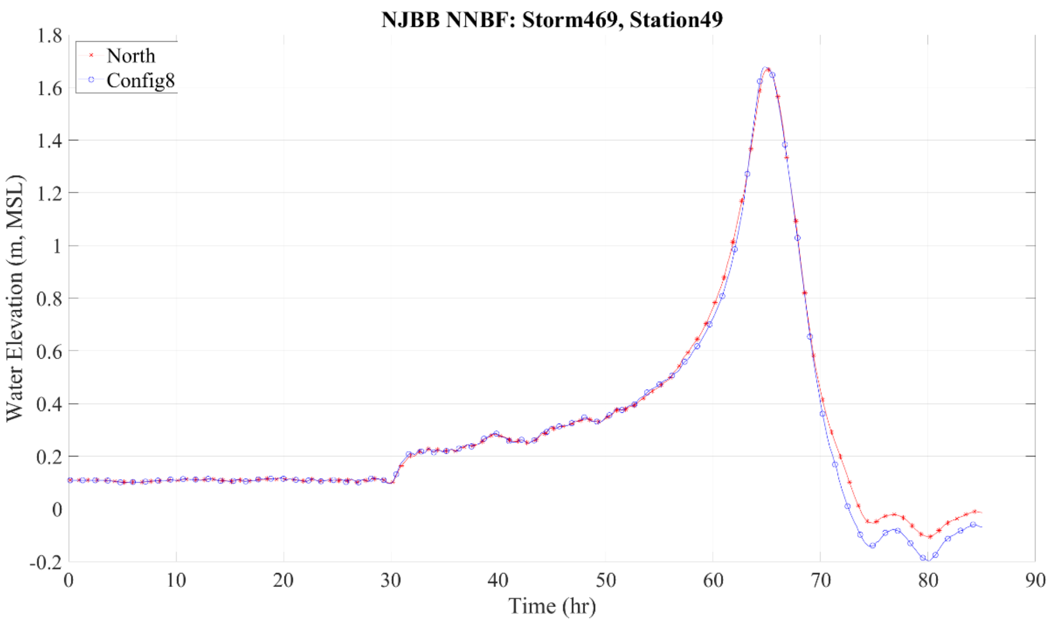

Figure 111 Storm 469 hydrograph for save point 49 "behind" Great Egg Harbor area with and without NNBF

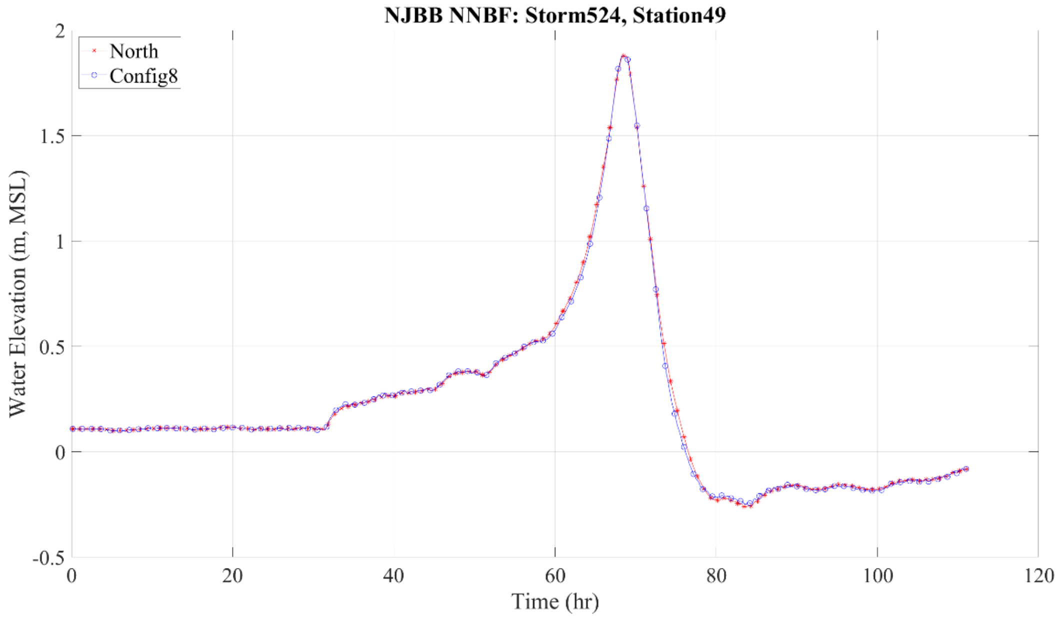

Figure 112 Storm 524 hydrograph for save point 49 "behind" Great Egg Harbor area with and without NNBF

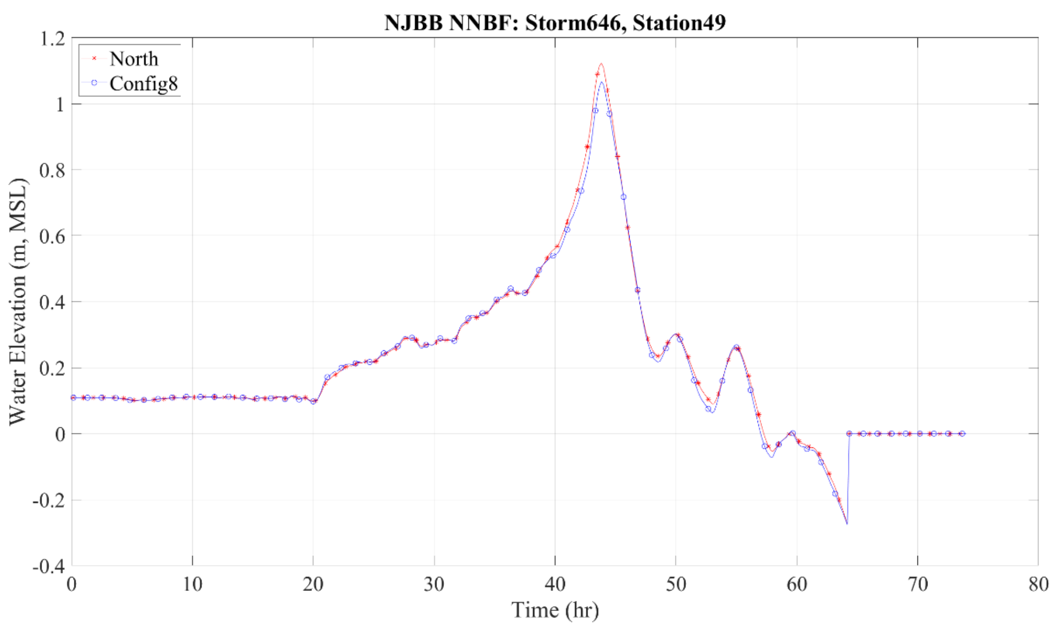

Figure 113 Storm 646 hydrograph for save point 49 "behind" Great Egg Harbor area with and without NNBF

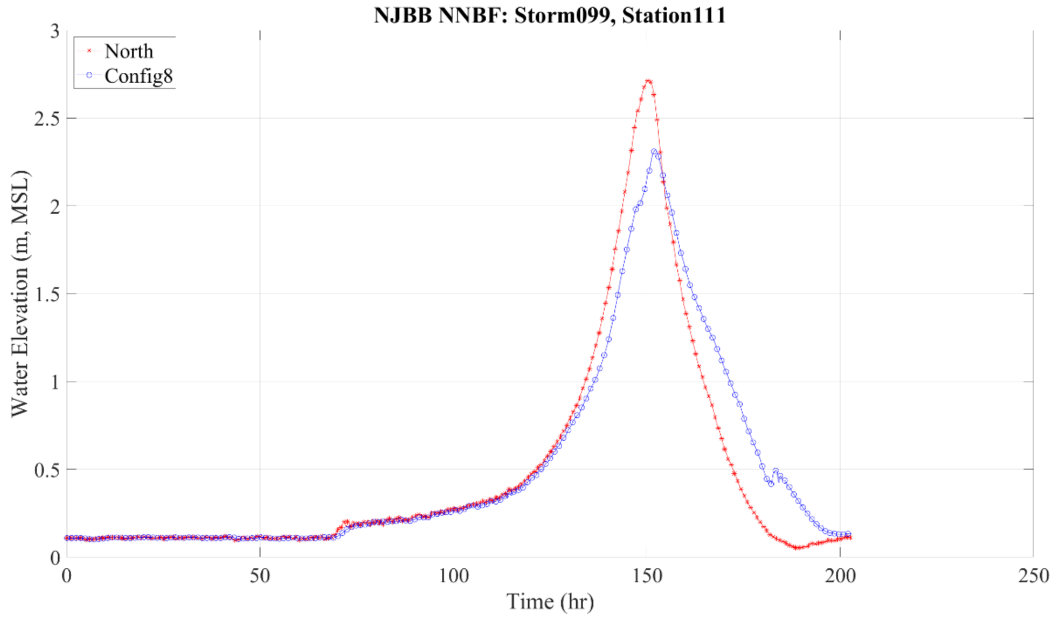

Figure 114 Storm 99 hydrograph for save point 111 "behind" Great Egg Harbor area with and without NNBF

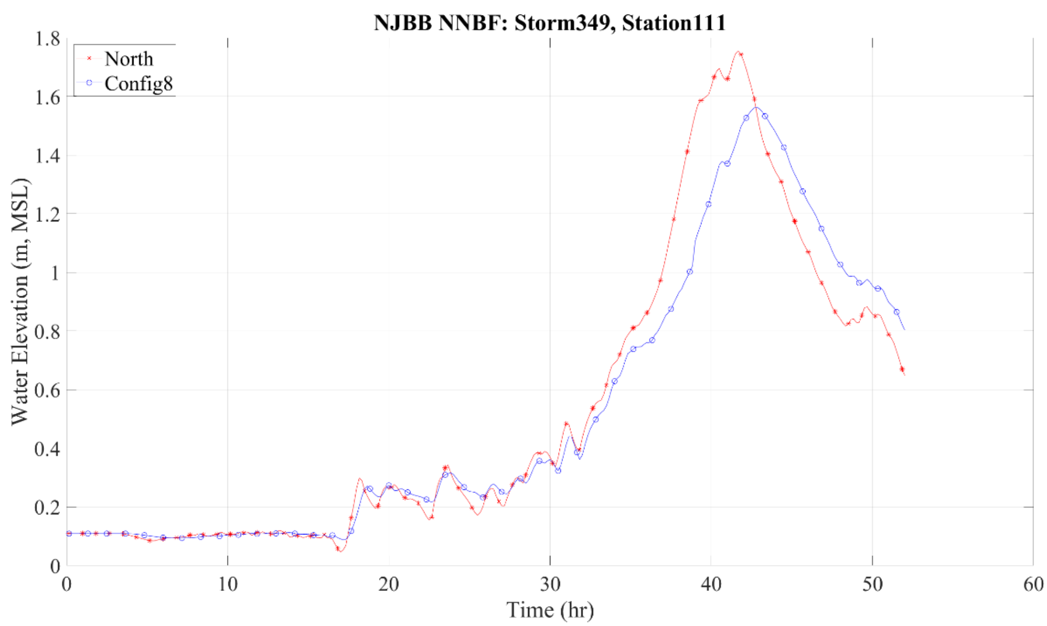

Figure 115 Storm 349 hydrograph for save point 111 "behind" Great Egg Harbor area with and without NNBF

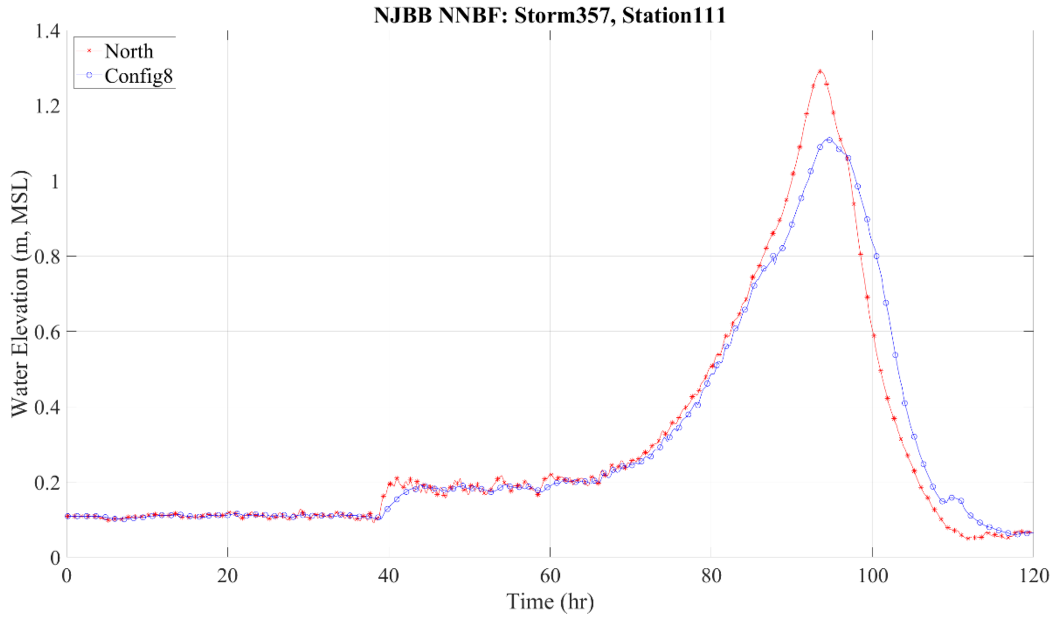

Figure 116 Storm 357 hydrograph for save point 111 "behind" Great Egg Harbor area with and without NNBF

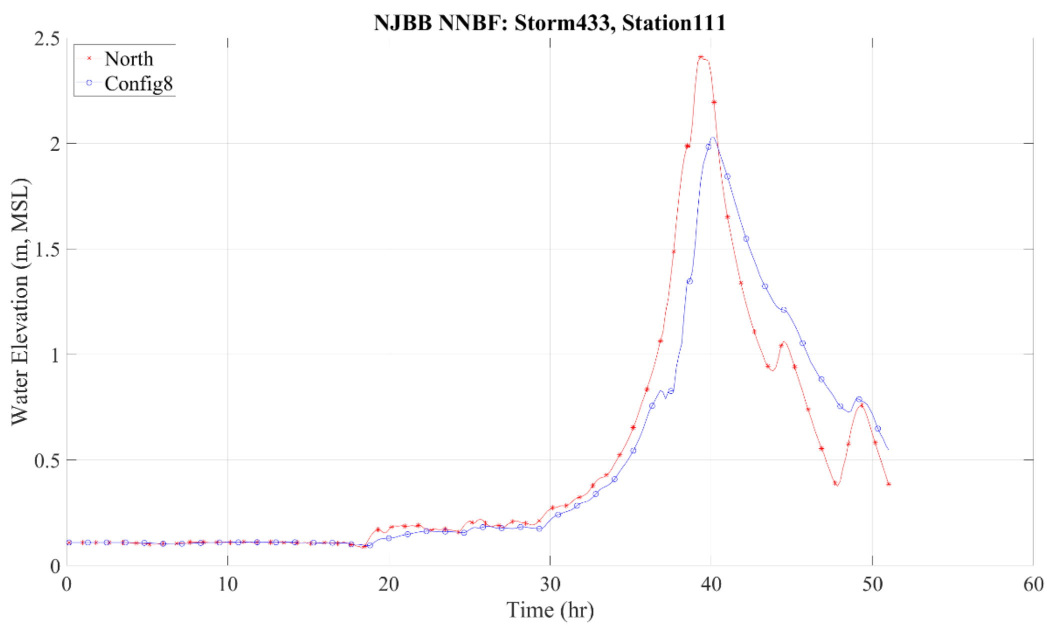

Figure 117 Storm 433 hydrograph for save point 111 "behind" Great Egg Harbor area with and without NNBF

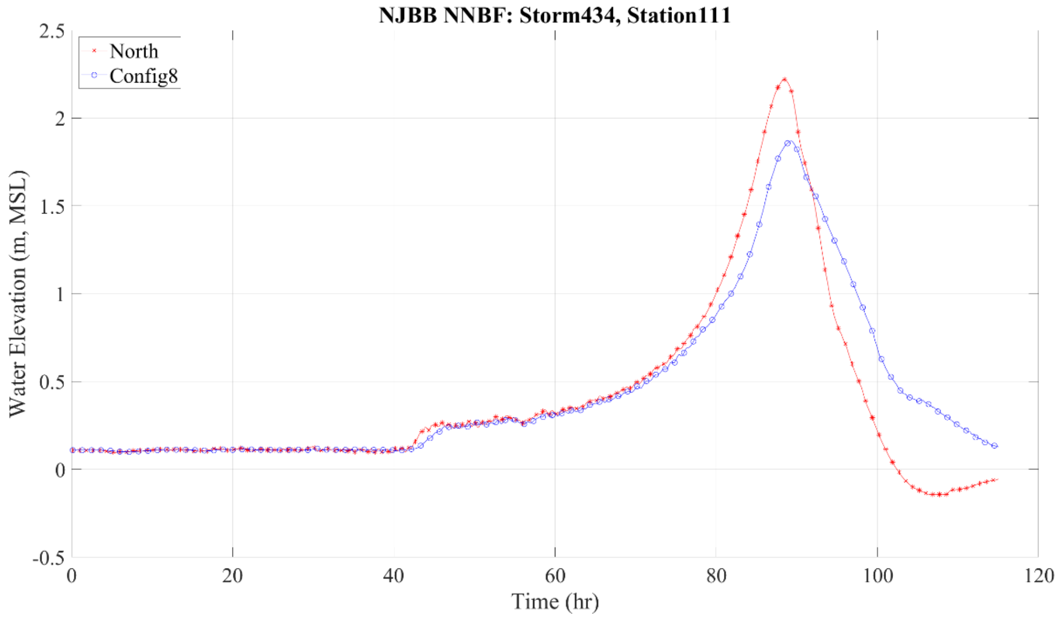

Figure 118 Storm 434 hydrograph for save point 111 "behind" Great Egg Harbor area with and without NNBF

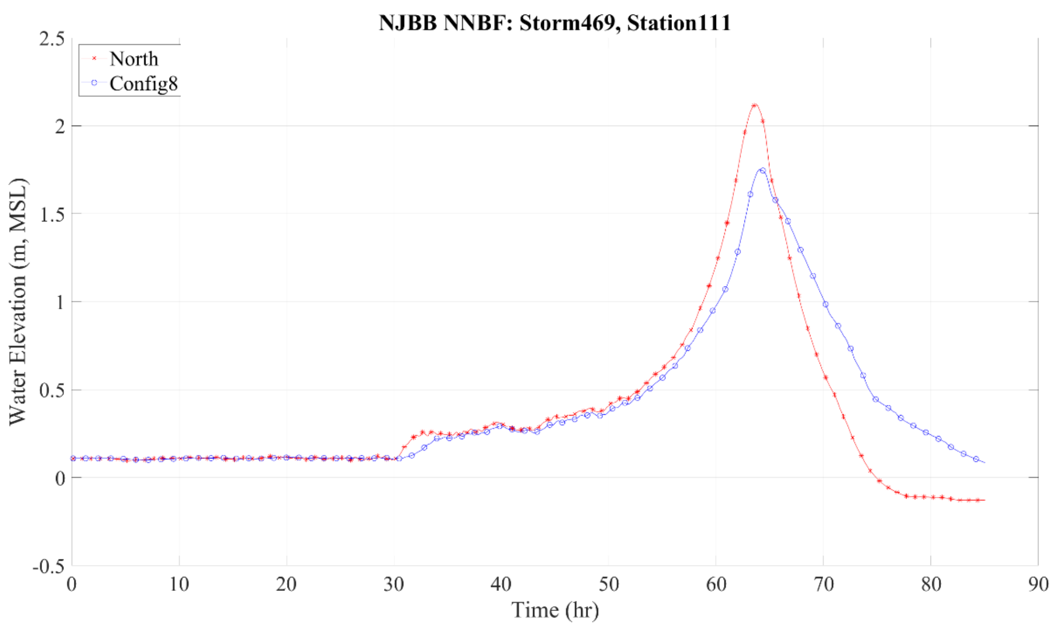

Figure 119 Storm 469 hydrograph for save point 111 "behind" Great Egg Harbor area with and without NNBF

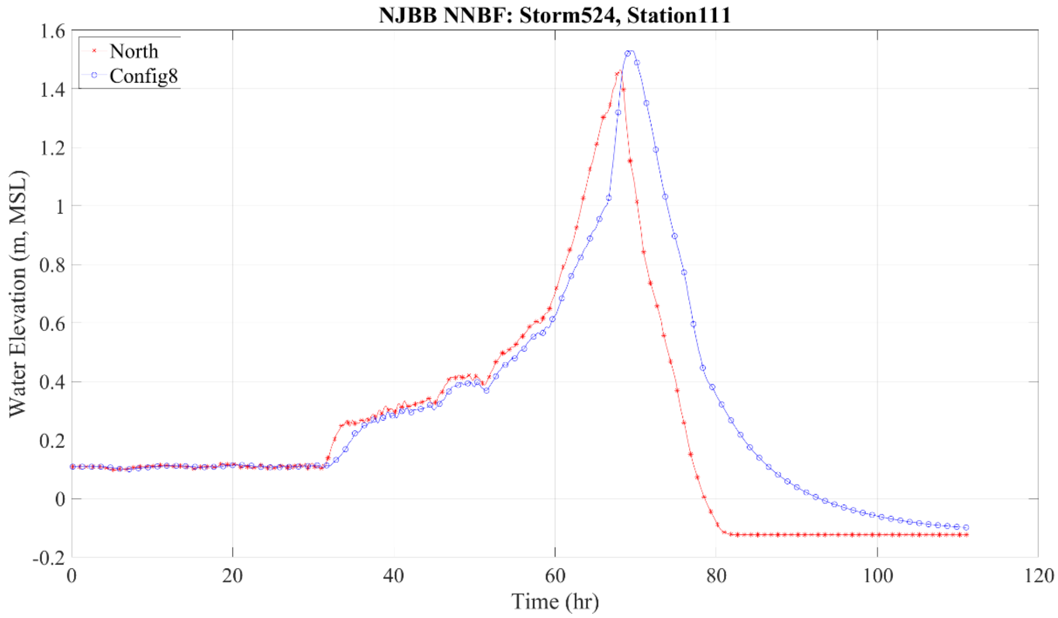

Figure 120 Storm 524 hydrograph for save point 111 "behind" Great Egg Harbor area with and without NNBF

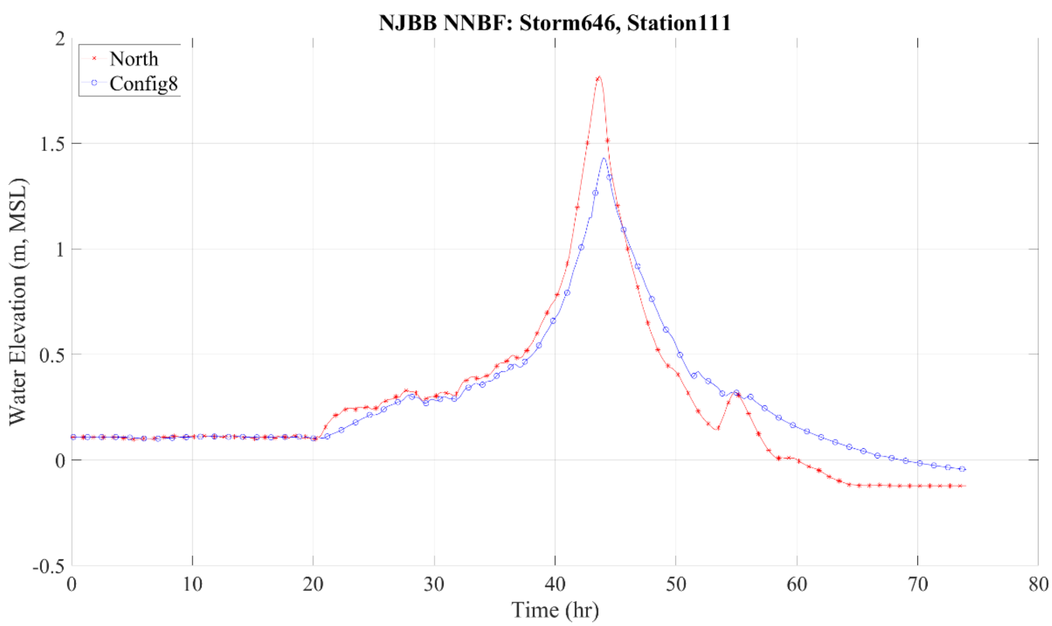

Figure 121 Storm 646 hydrograph for save point 111 "behind" Great Egg Harbor area with and without NNBF

Appendix B: STWAVE auxiliary modeling results

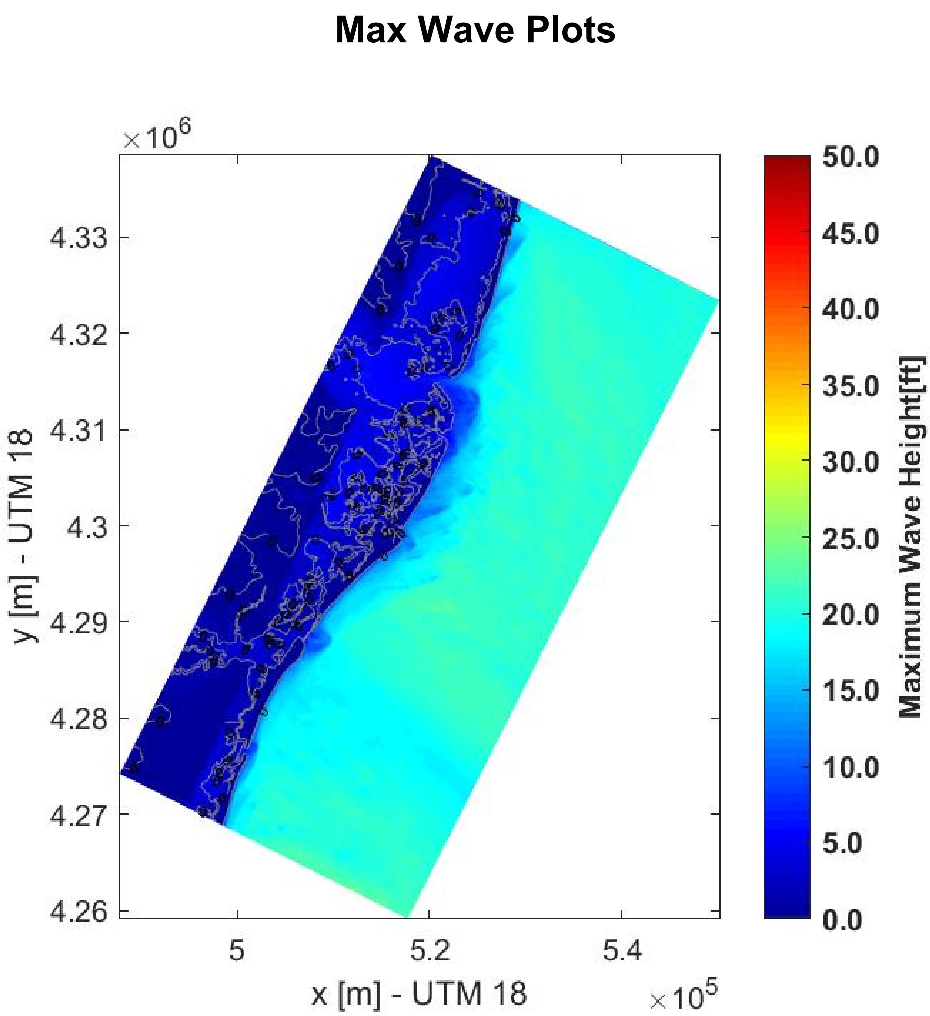

Figure *122*: ST0099 Configuration 3

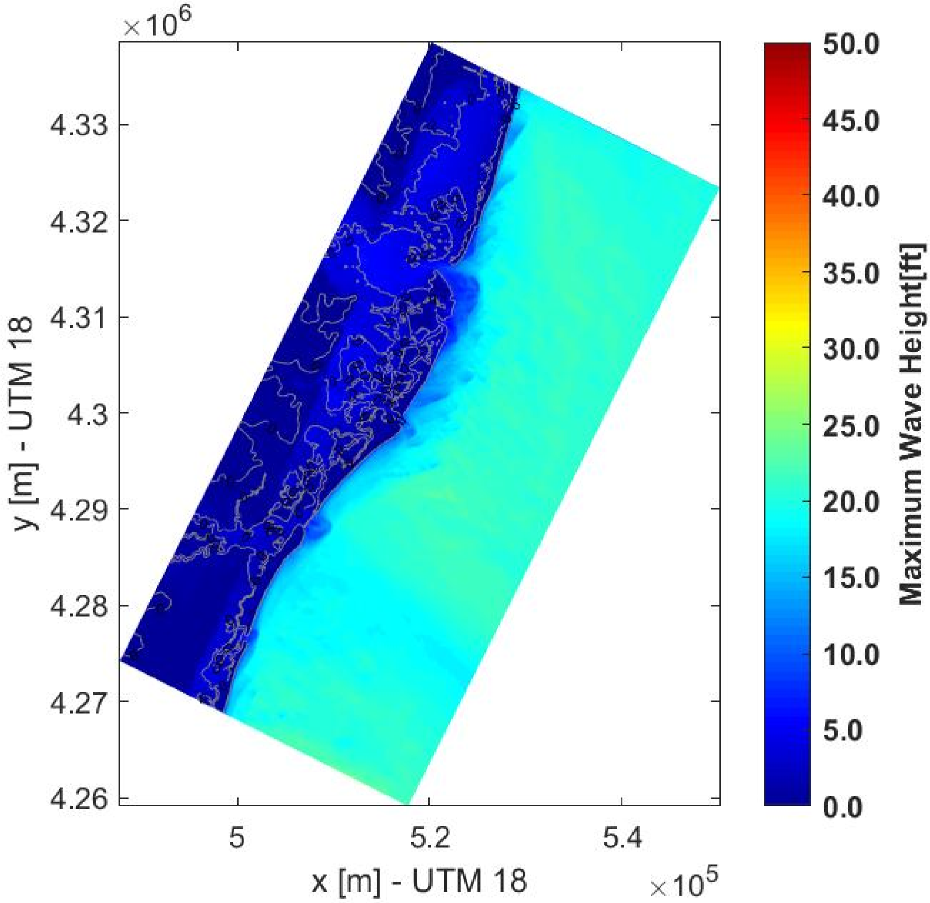

Figure *123*: ST0099 Configuration 5

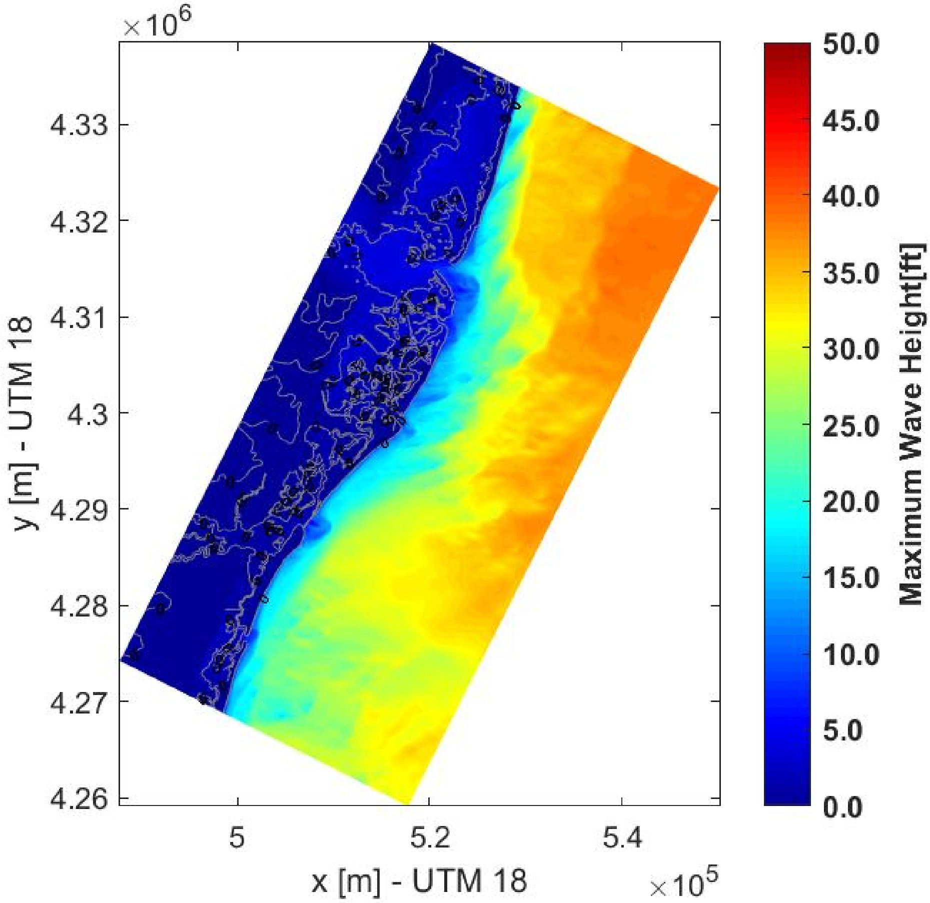

Figure *124*: ST0349 Configuration 3

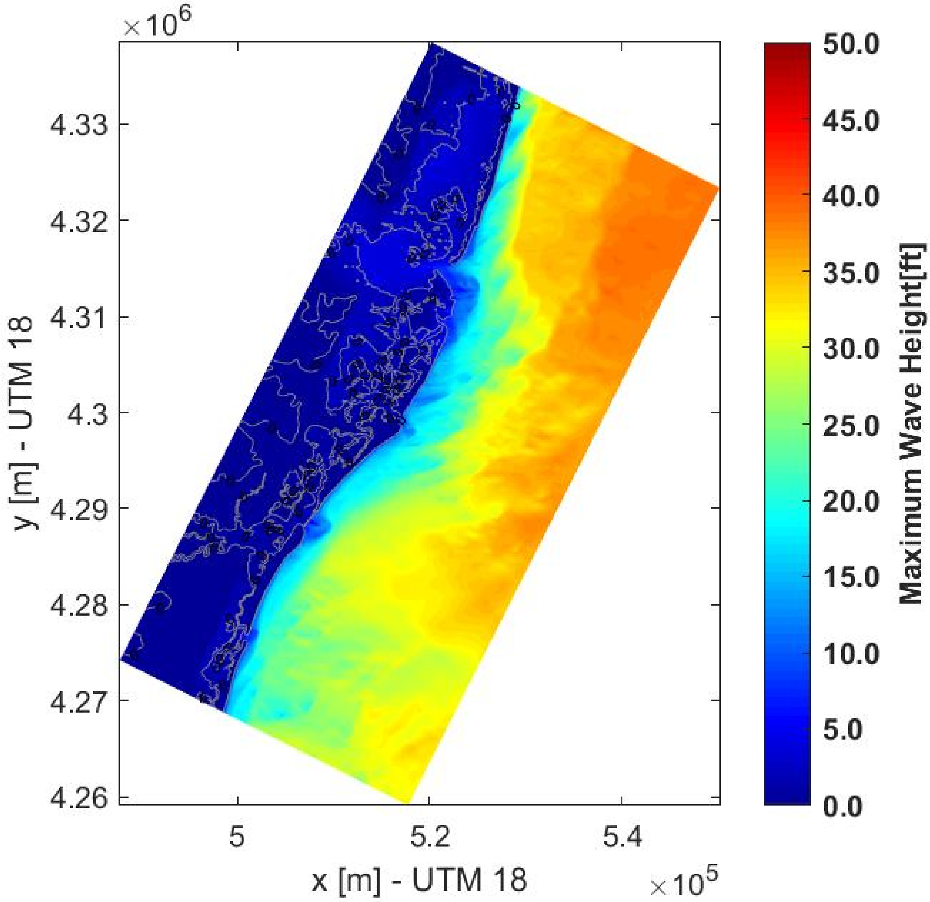

Figure *125*: ST0349 Configuration 5

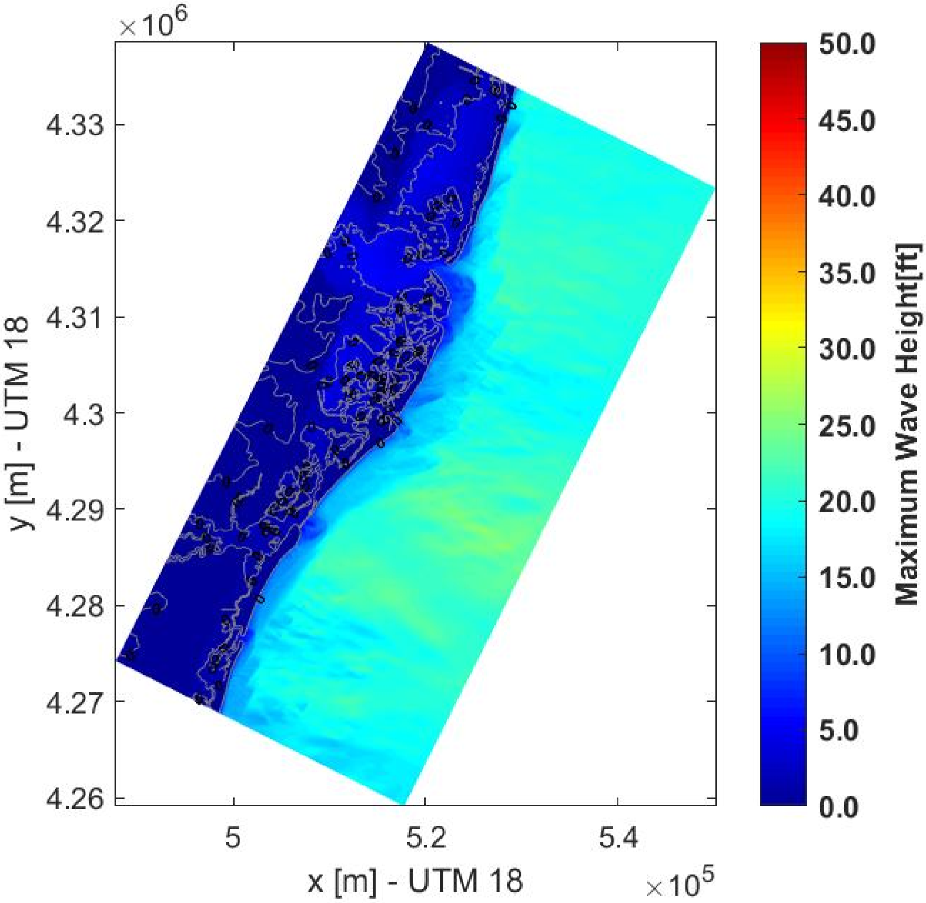

Figure *126*: ST0350 Configuration 3

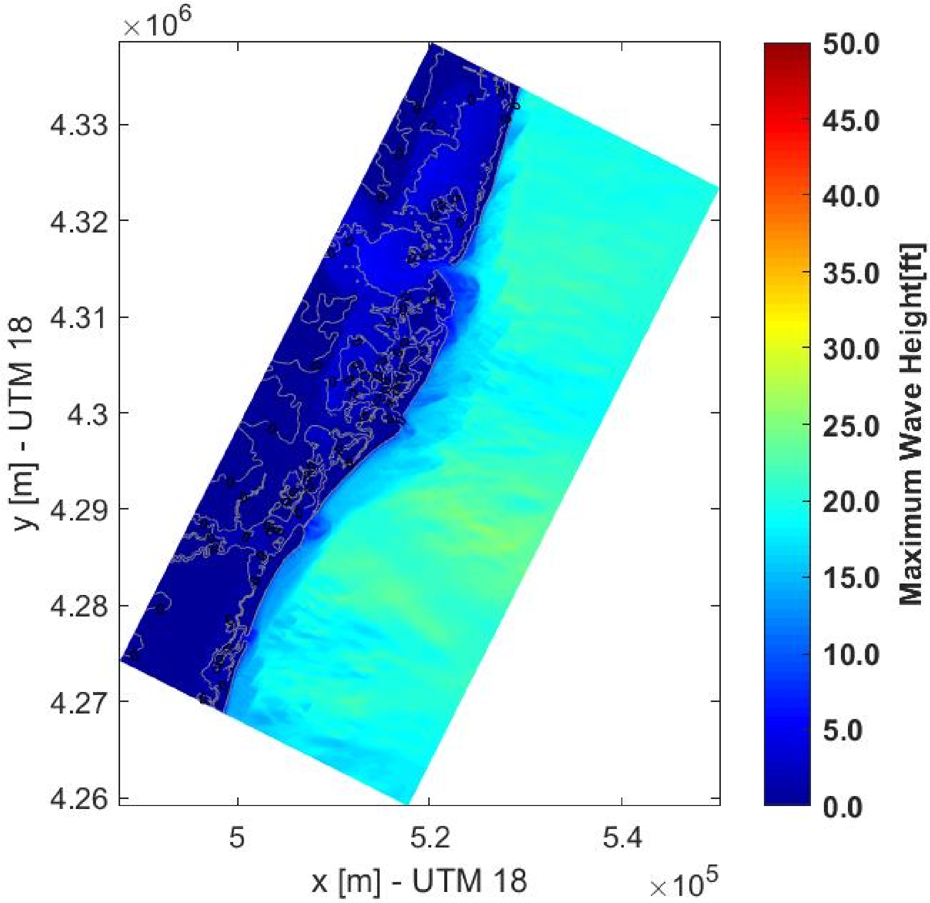

Figure *127*: ST0350 Configuration 5

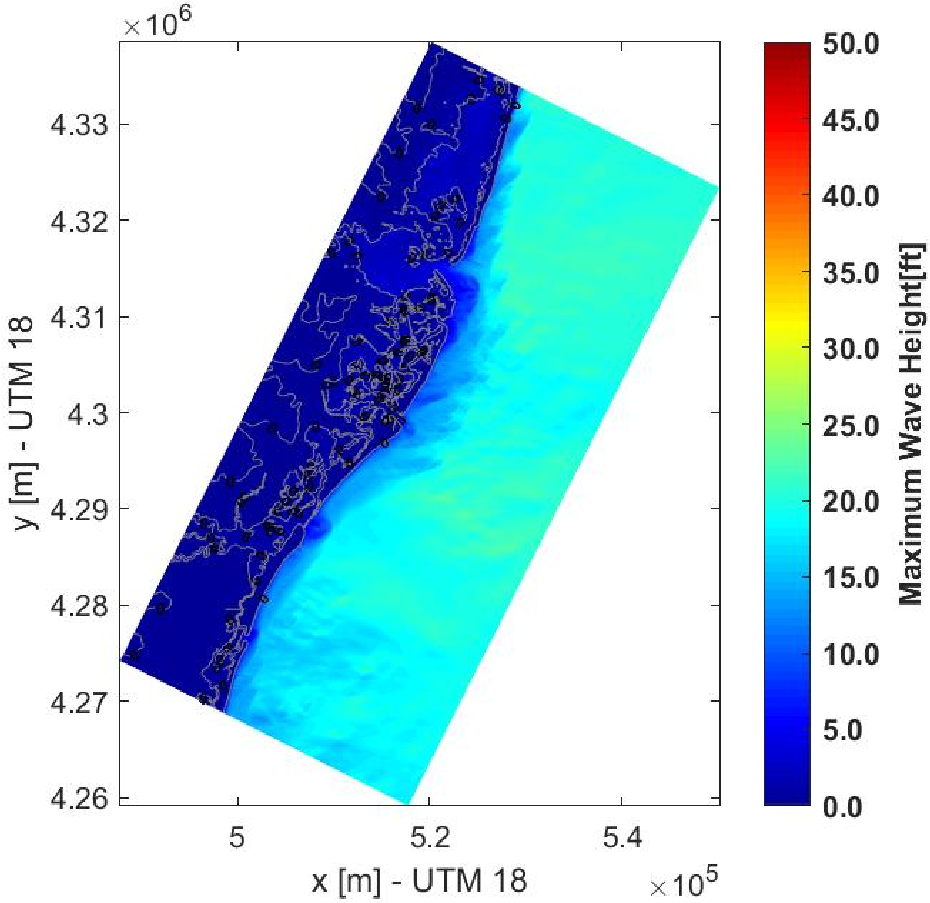

Figure *128*: ST0357 Configuration 3

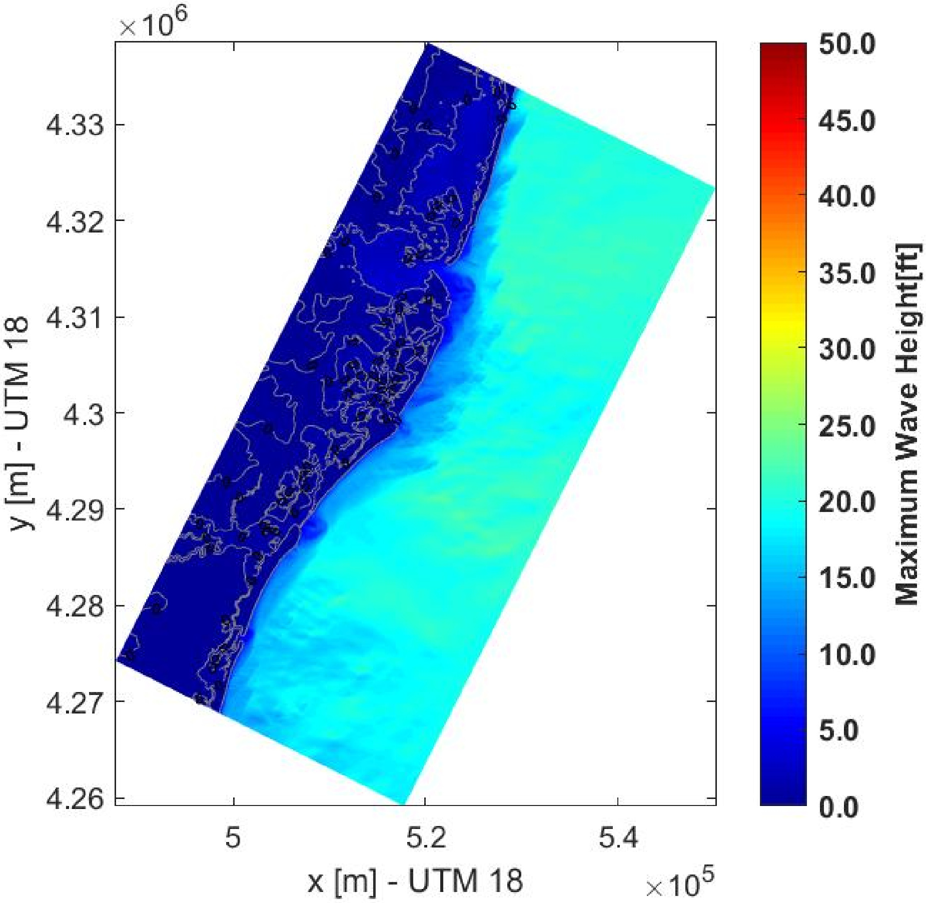

Figure *129*: ST0357 Configuration 5

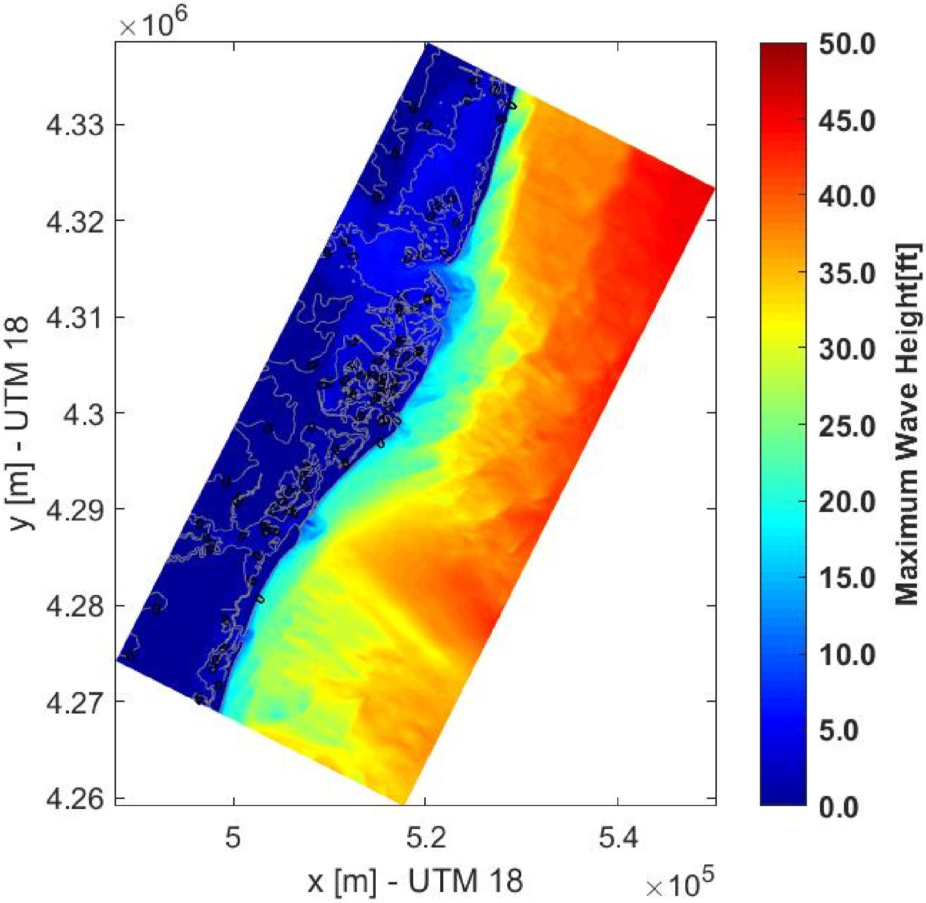

Figure *130*: ST0433 Configuration 3

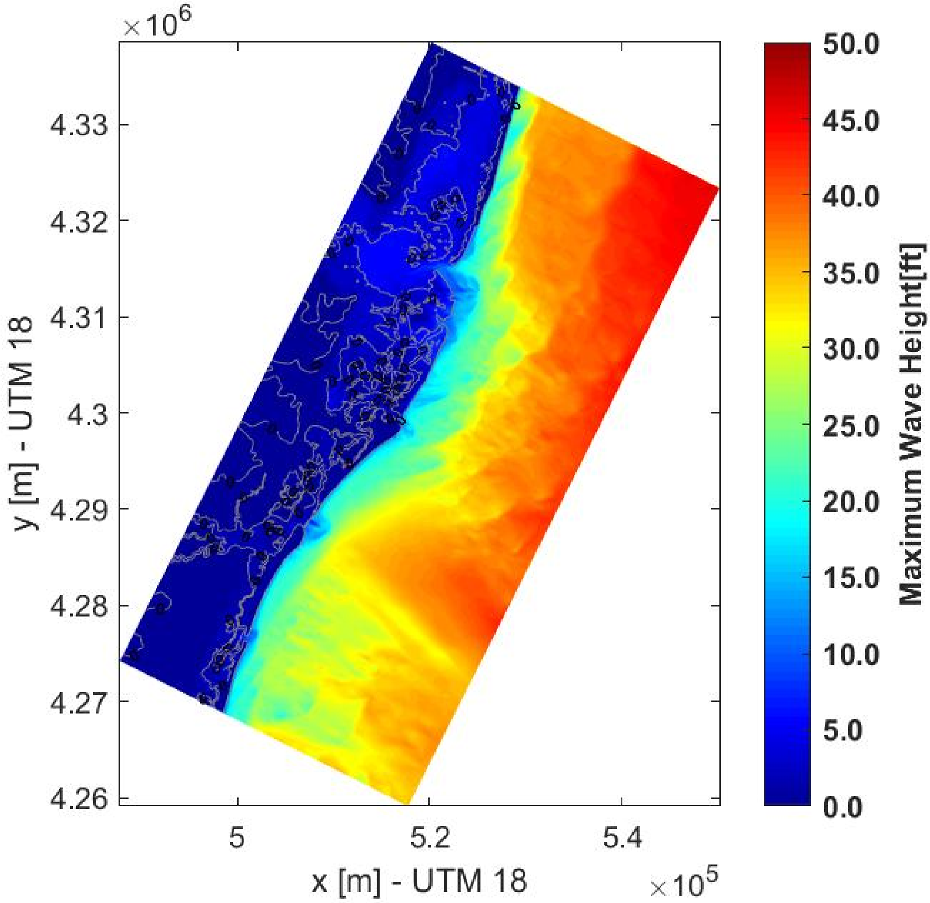

Figure *131*: ST0433 Configuration 5

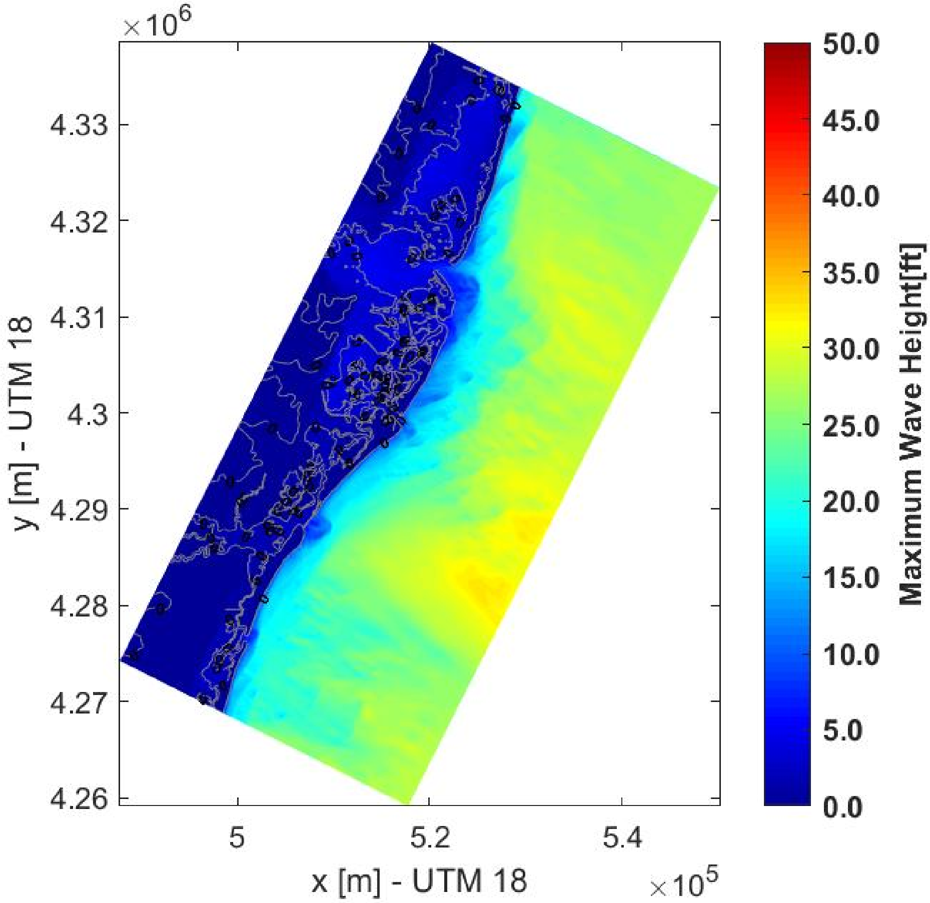

Figure *132*: ST0434 Configuration 3

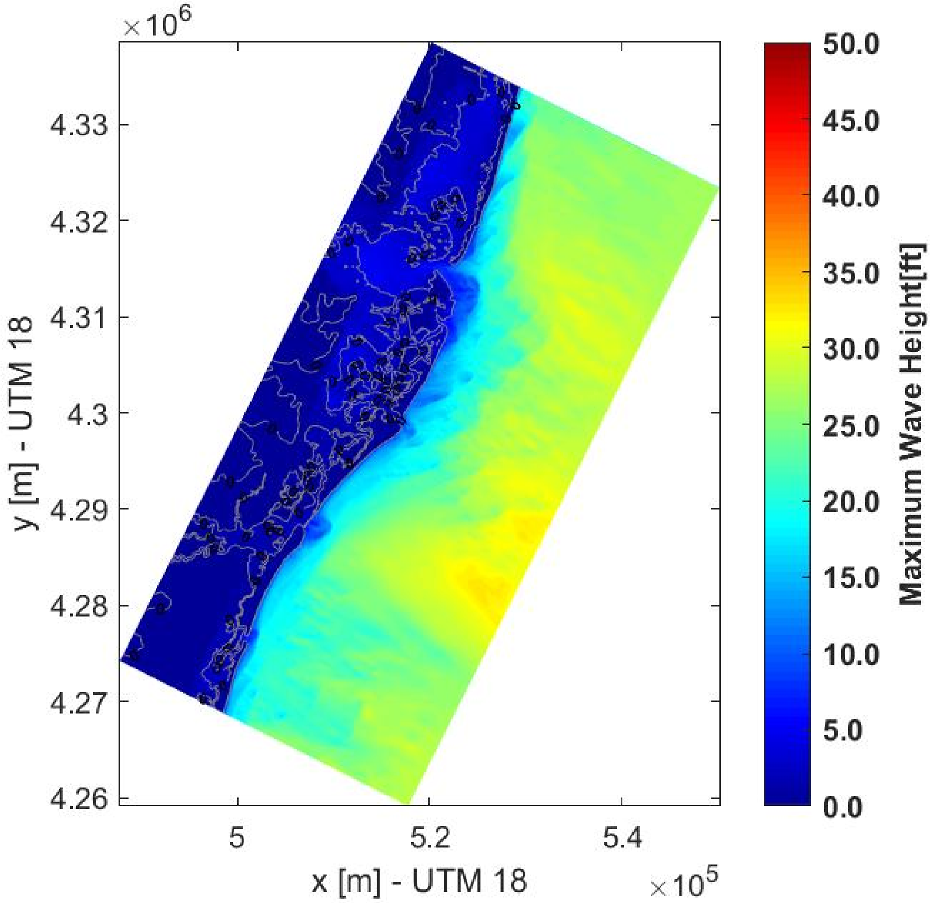

Figure *133*: ST0434 Configuration 5

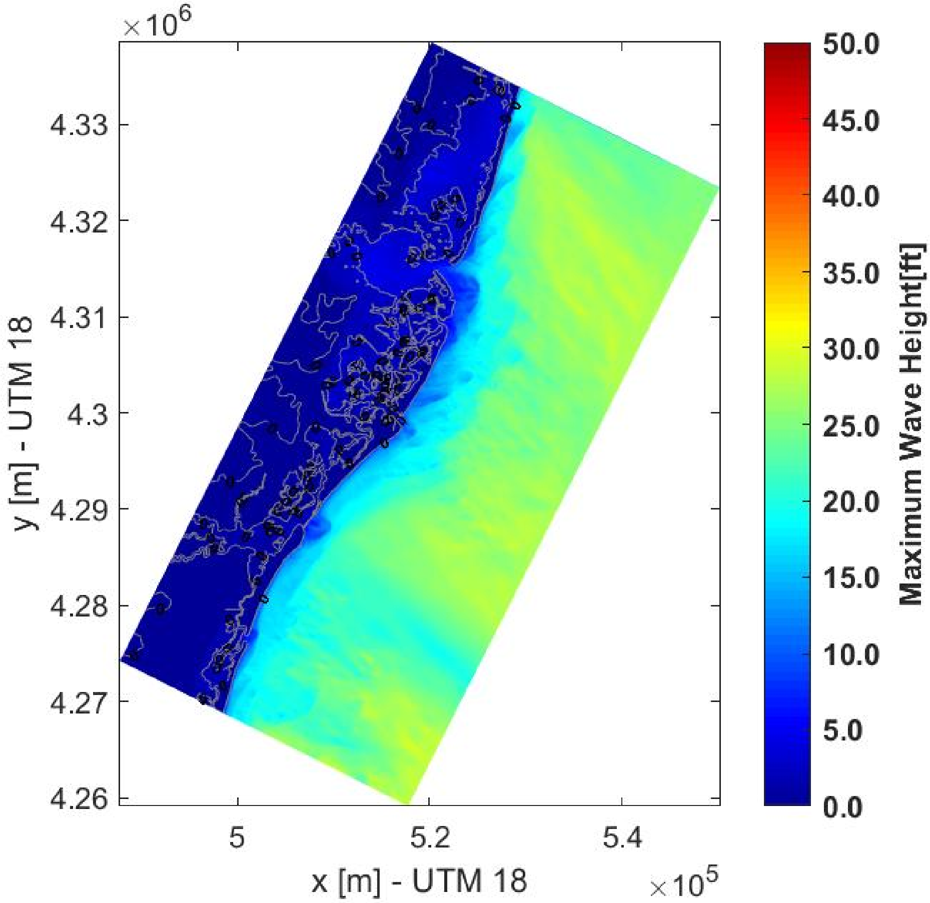

Figure *134*: ST0469 Configuration 3

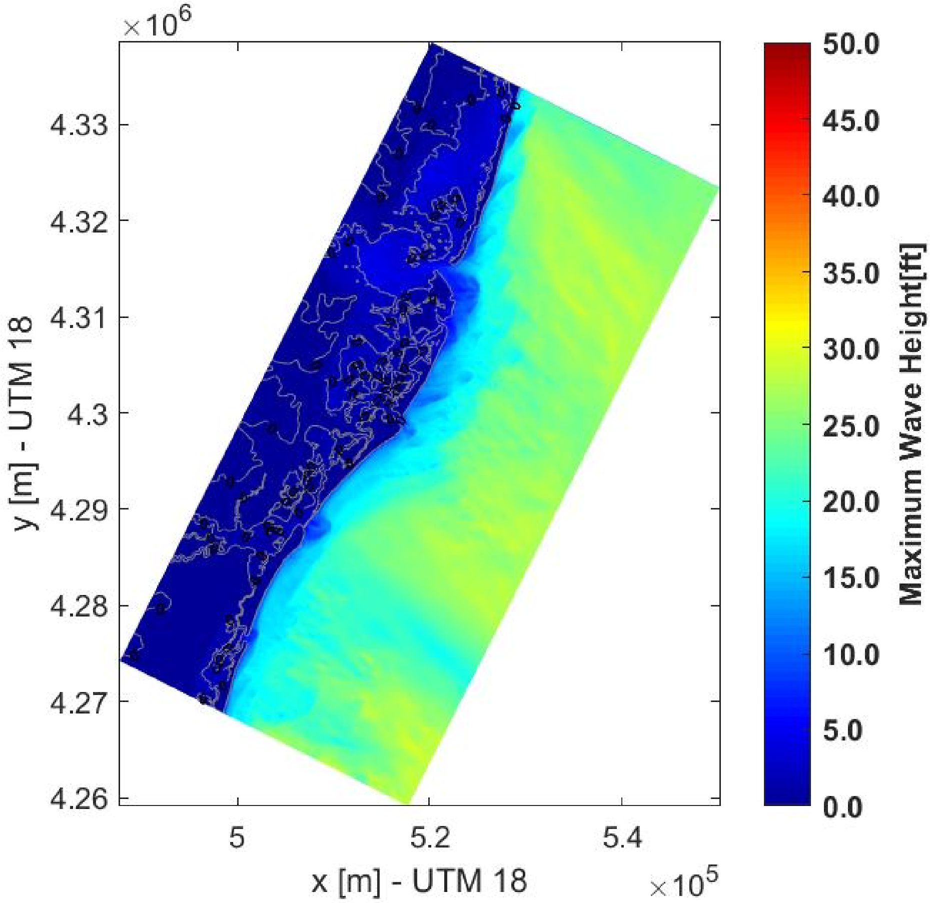

Figure *135*: ST0469 Configuration 5

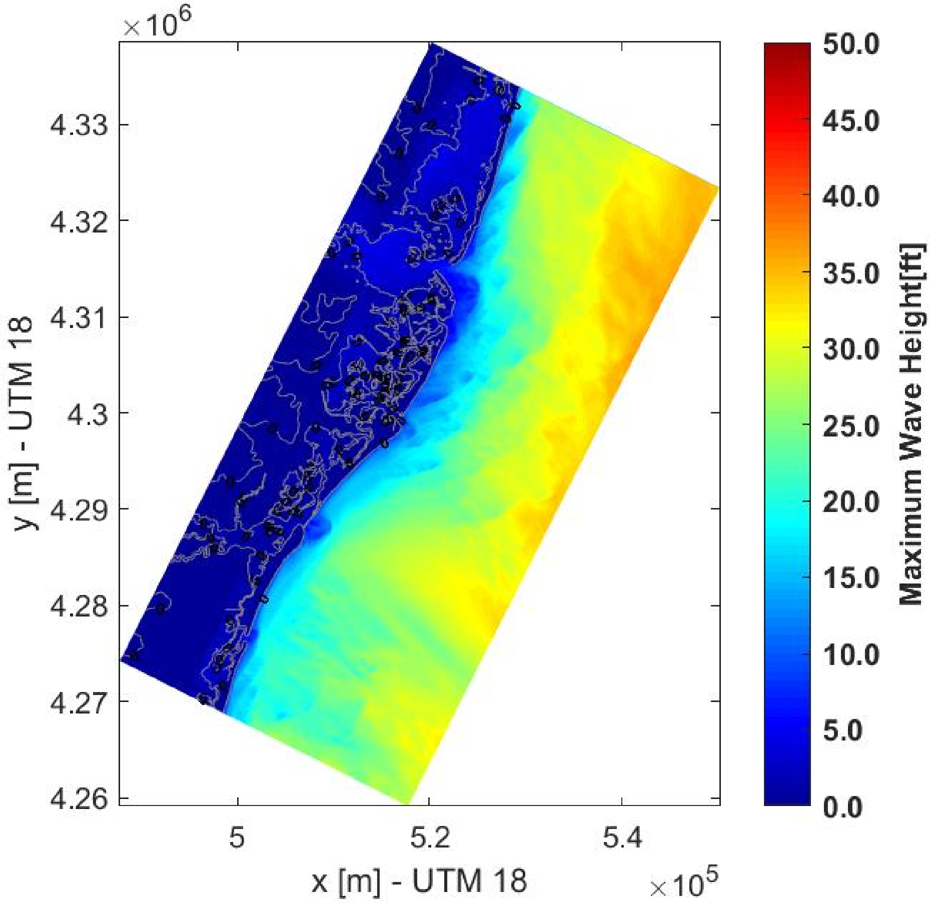

Figure *136*: ST0524 Configuration 3

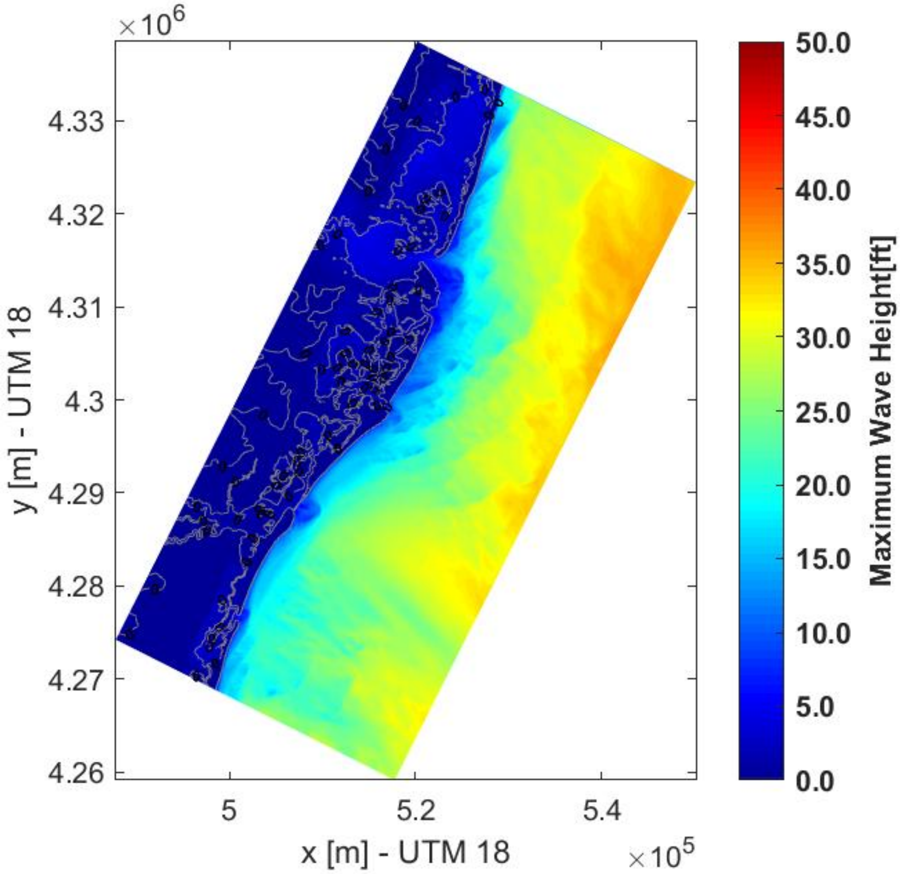

Figure 137: ST0524 Configuration 5

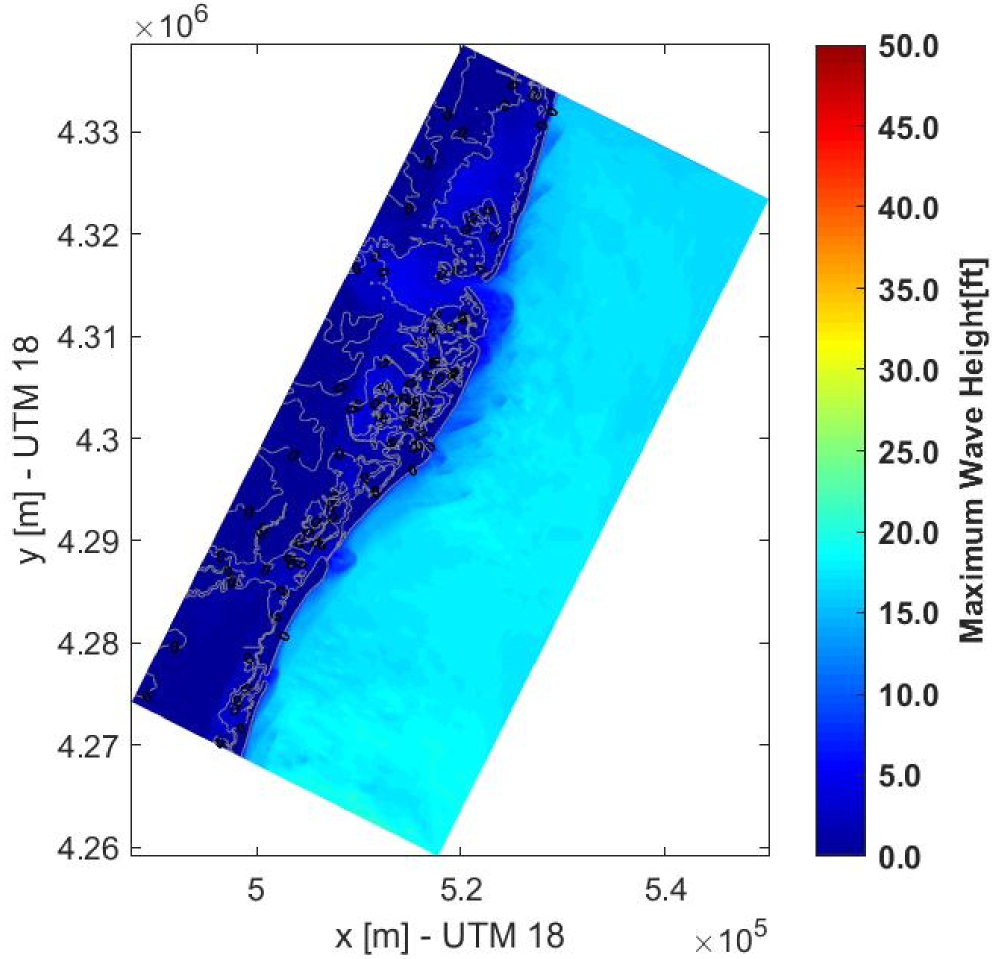

Figure 138: ST00636 Configuration 3

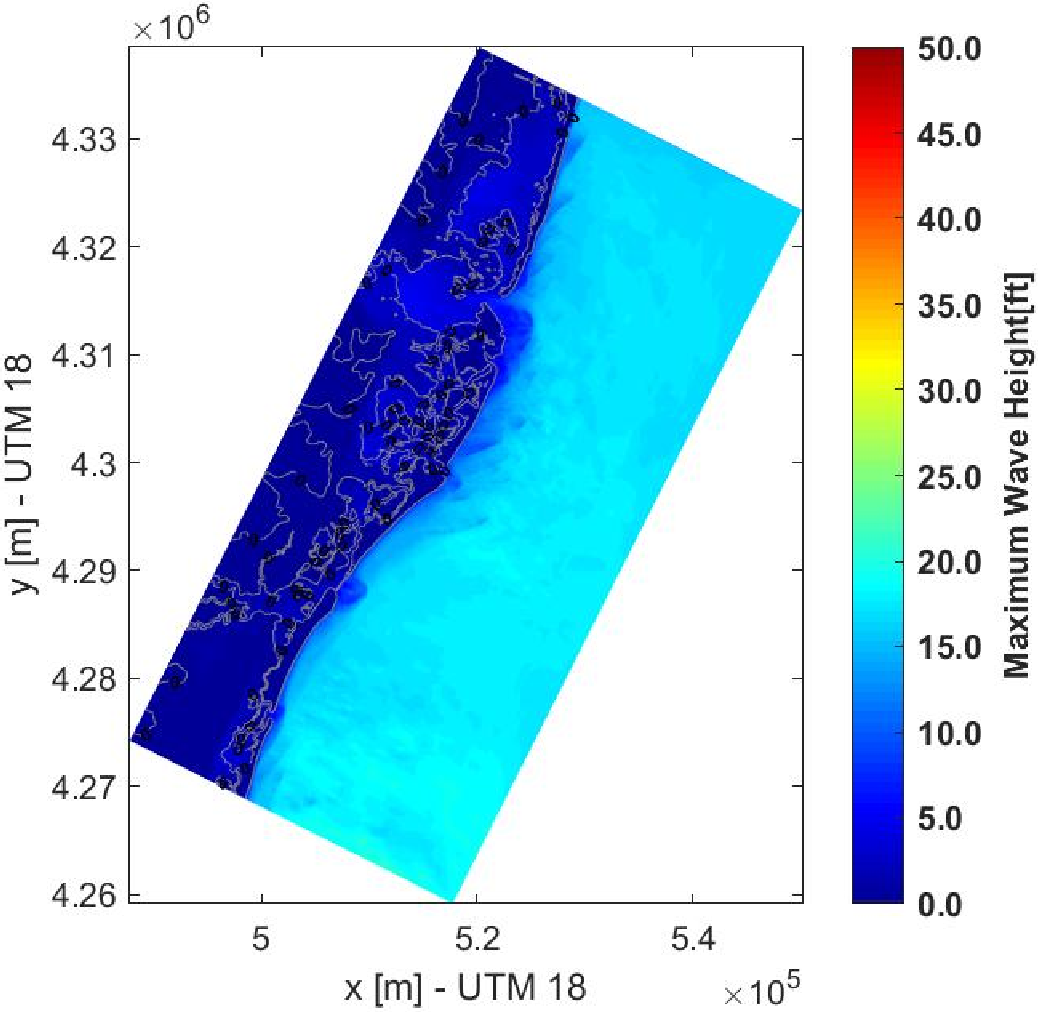

Figure 139: ST0636 Configuration 5

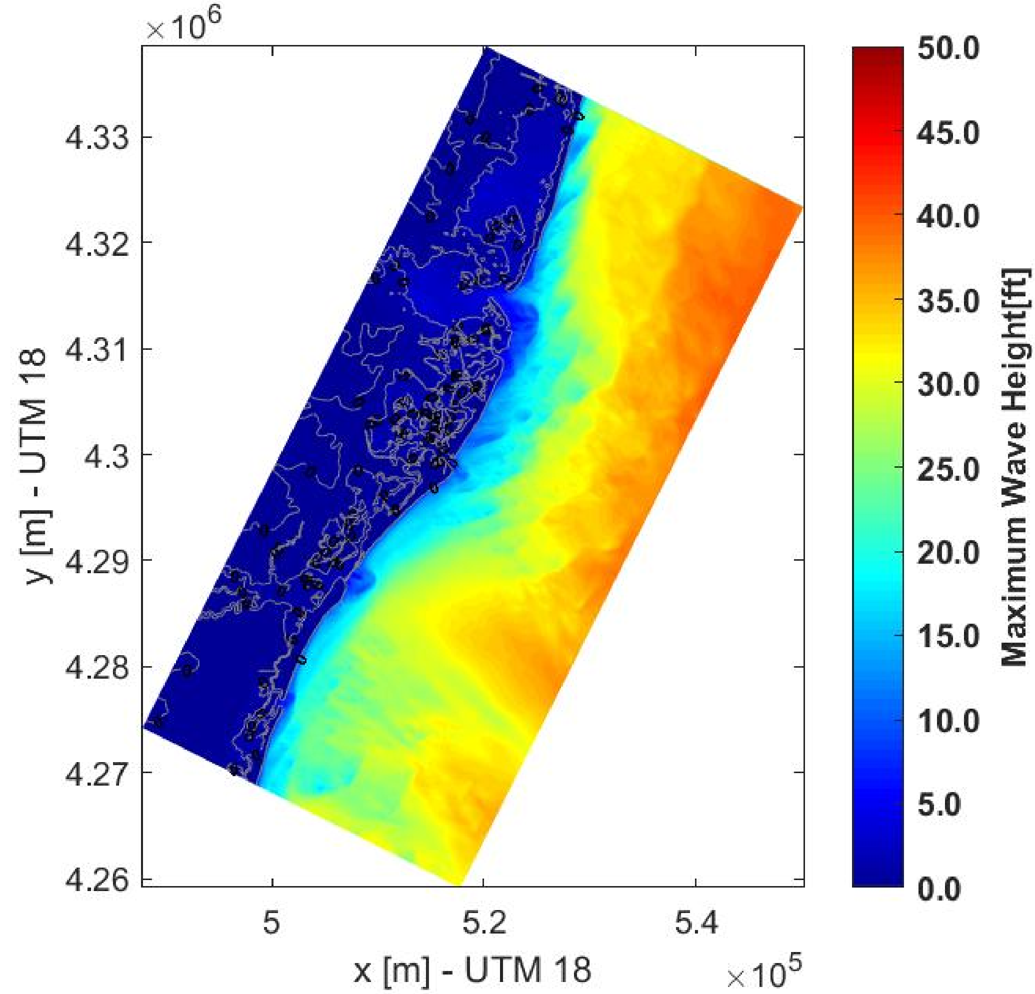

Figure 140: ST0646 Configuration 3

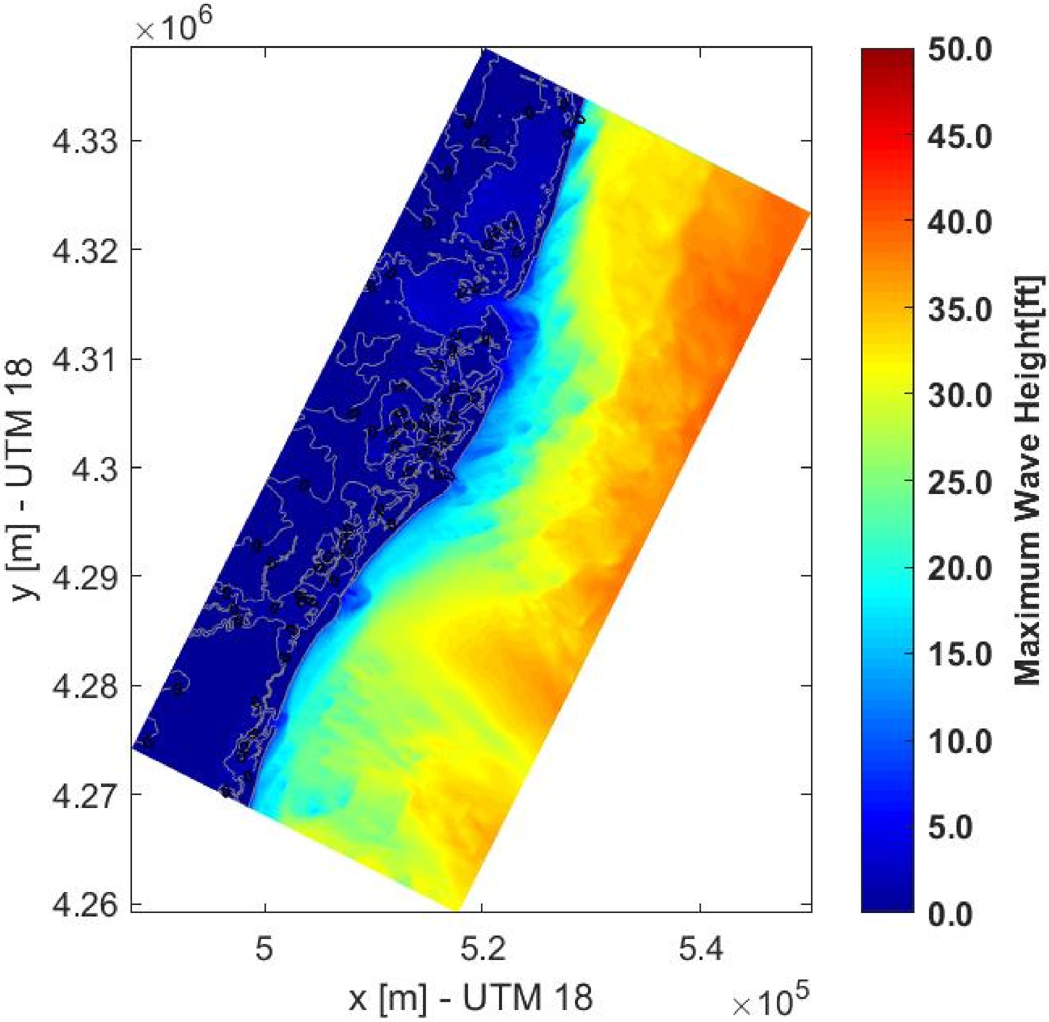

Figure 141: ST0646 Configuration 5

Time Series Plots

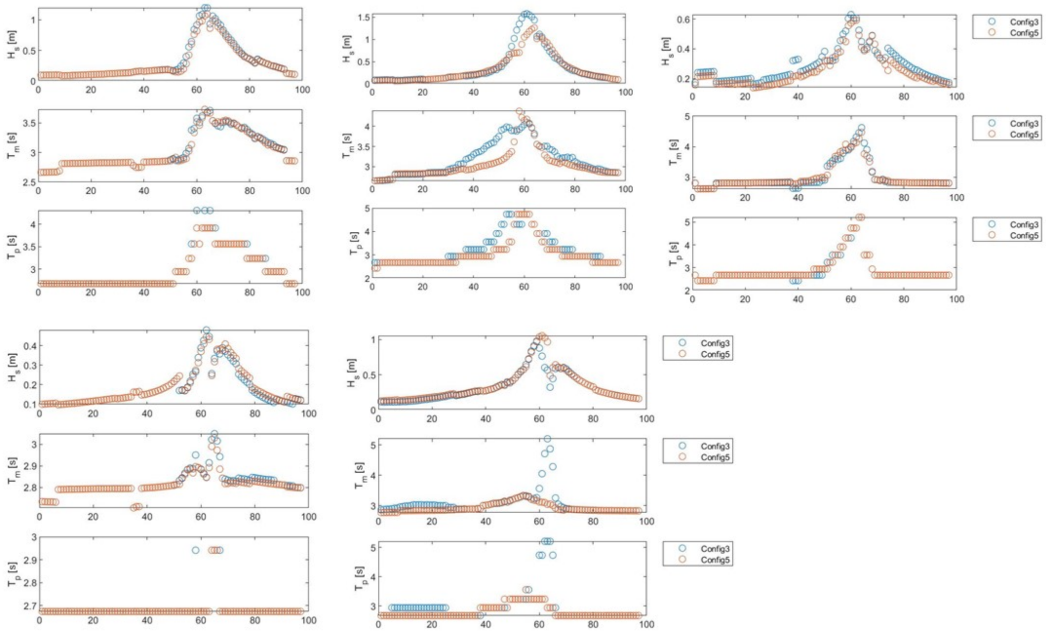

Figure *142*: Time series of significant wave height, peak period, and mean period for Storm 99. Top row, from left to right is station 49, 50, 59. Bottom row, from left to right is station 111, 117. Configuration 3 is shown in blue, Configuration 5 in orange.

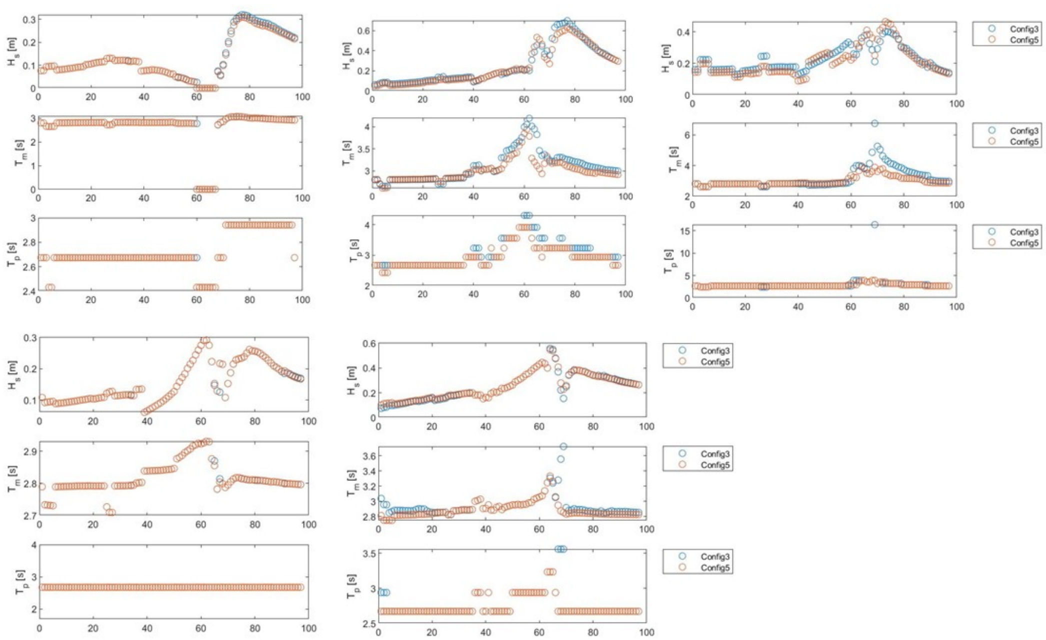

Figure *143*: Time series of significant wave height, peak period, and mean period for Storm 349. Top row, from left to right is station 49, 50, 59. Bottom row, from left to right is station 111, 117. Configuration 3 is shown in blue, Configuration 5 in orange.

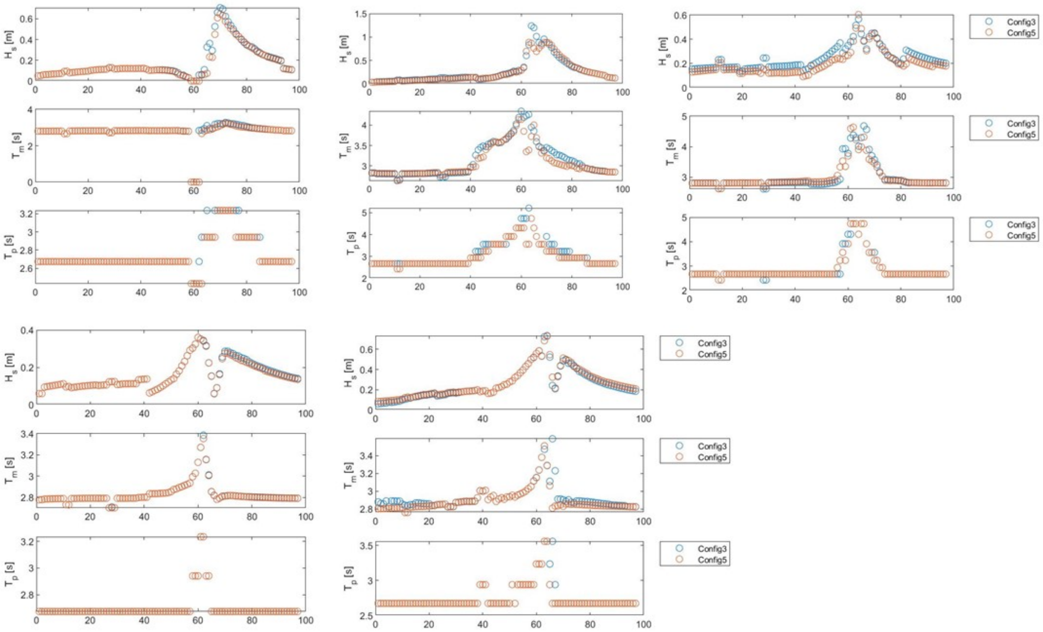

Figure *144*: Time series of significant wave height, peak period, and mean period for Storm 350. Top row, from left to right is station 49, 50, 59. Bottom row, from left to right is station 111, 117. Configuration 3 is shown in blue, Configuration 5 in orange.

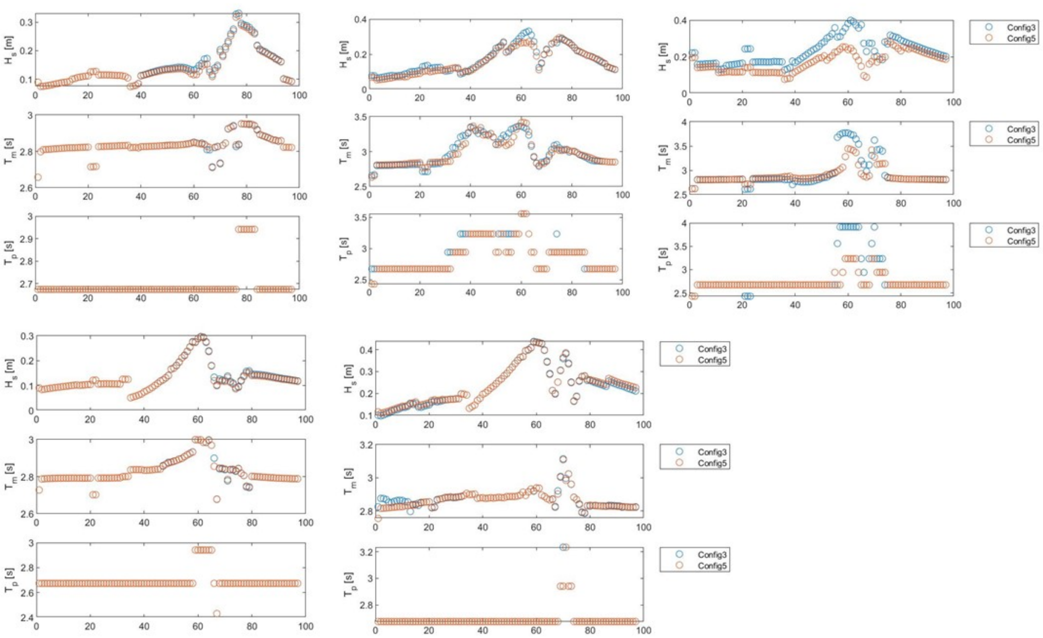

Figure *145*: Time series of significant wave height, peak period, and mean period for Storm 357. Top row, from left to right is station 49, 50, 59. Bottom row, from left to right is station 111, 117. Configuration 3 is shown in blue, Configuration 5 in orange.

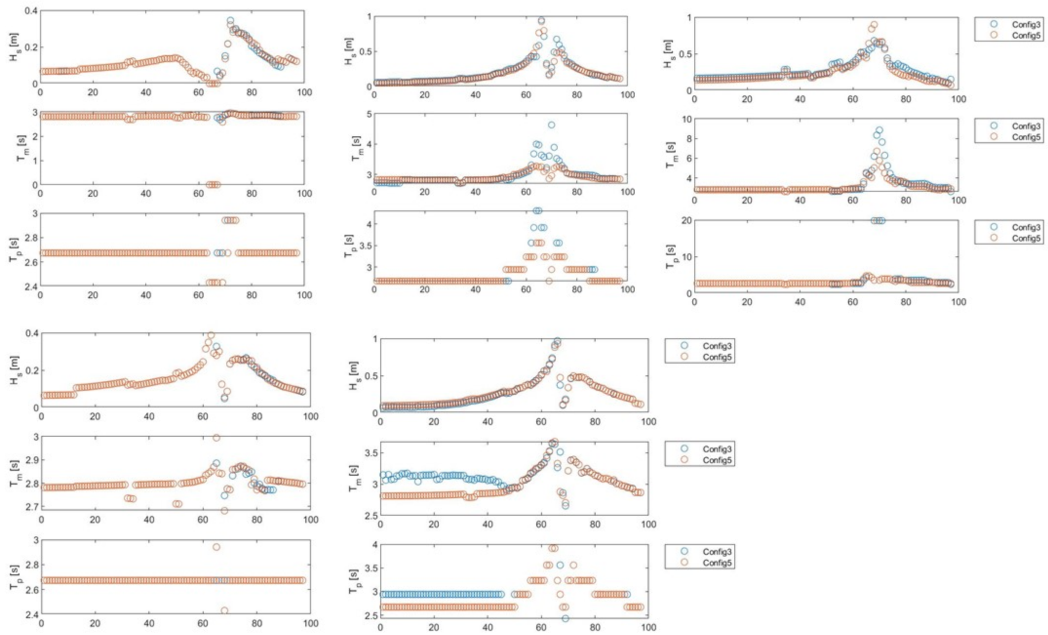

Figure *146*: Time series of significant wave height, peak period, and mean period for Storm 433. Top row, from left to right is station 49, 50, 59. Bottom row, from left to right is station 111, 117. Configuration 3 is shown in blue, Configuration 5 in orange.

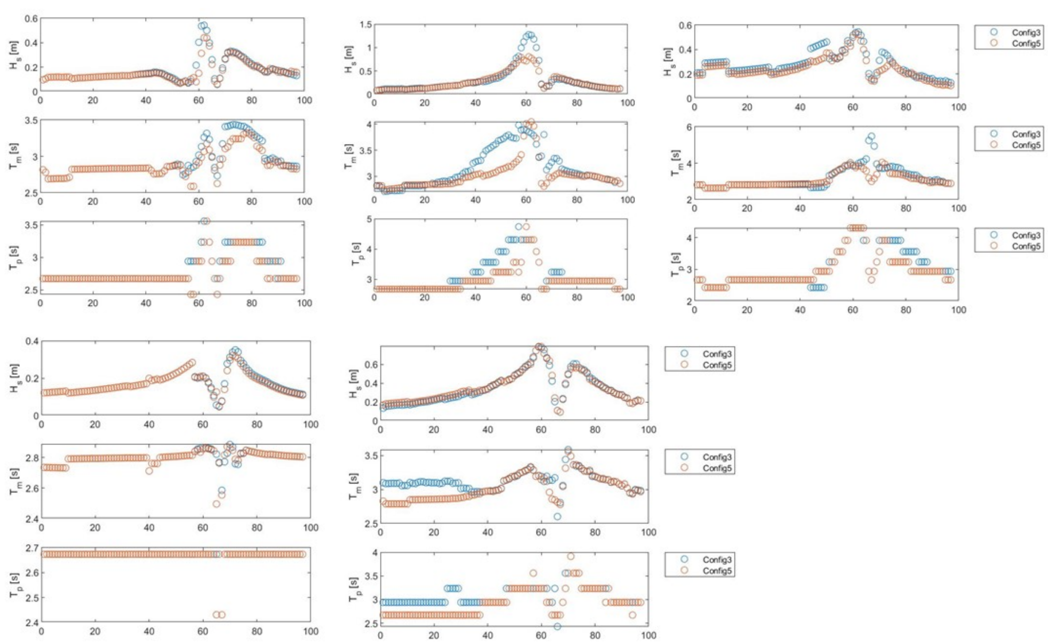

Figure *147*: Time series of significant wave height, peak period, and mean period for Storm 434. Top row, from left to right is station 49, 50, 59. Bottom row, from left to right is station 111, 117. Configuration 3 is shown in blue, Configuration 5 in orange.

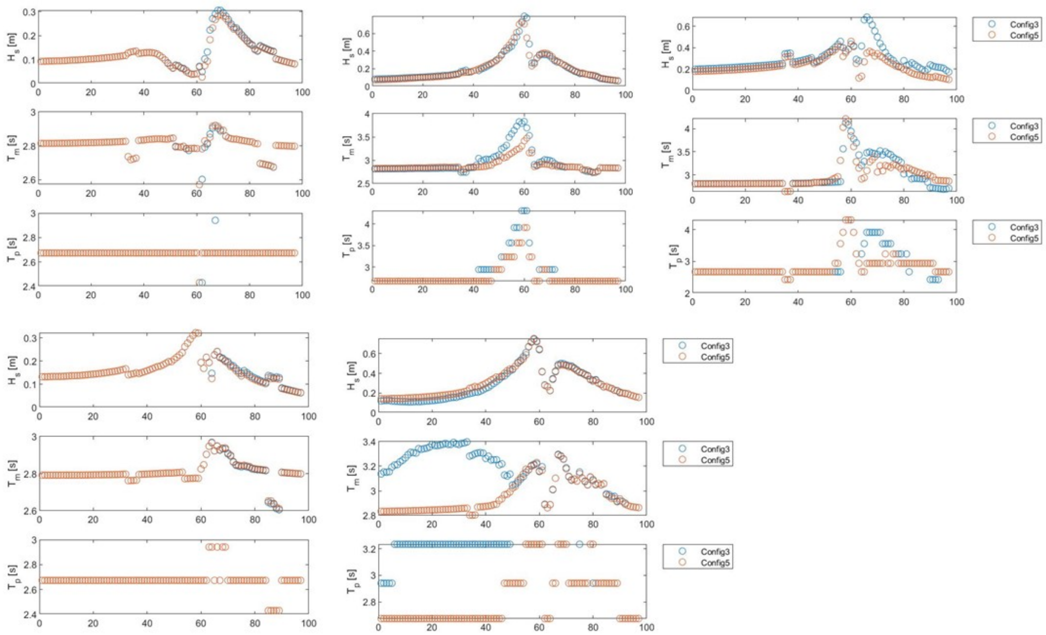

Figure *148*: Time series of significant wave height, peak period, and mean period for Storm 469. Top row, from left to right is station 49, 50, 59. Bottom row, from left to right is station 111, 117. Configuration 3 is shown in blue, Configuration 5 in orange.

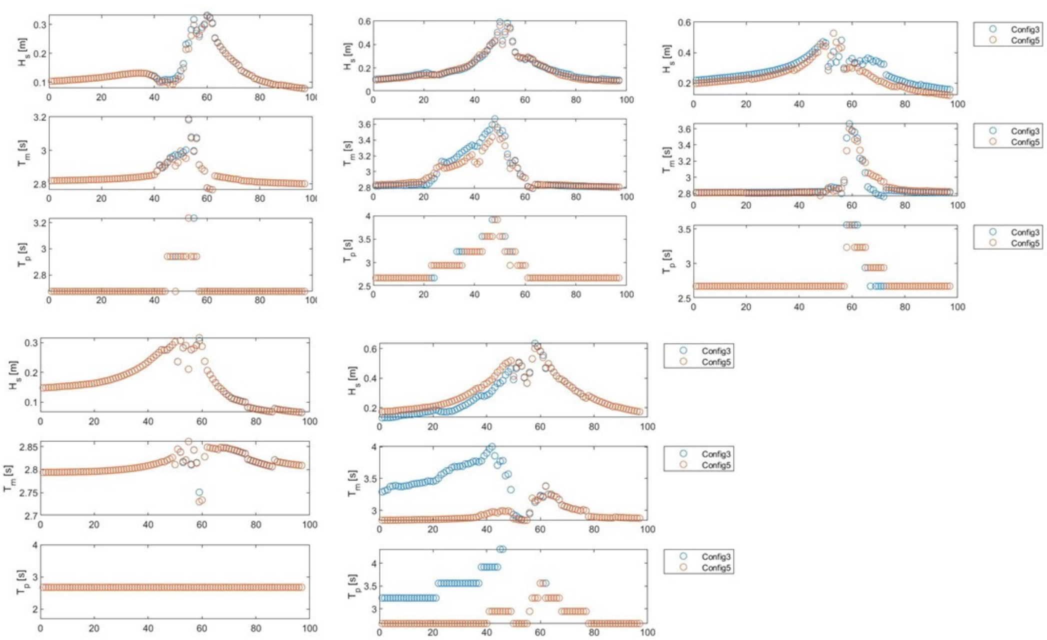

Figure *149*: Time series of significant wave height, peak period, and mean period for Storm 524. Top row, from left to right is station 49, 50, 59. Bottom row, from left to right is station 111, 117. Configuration 3 is shown in blue, Configuration 5 in orange.

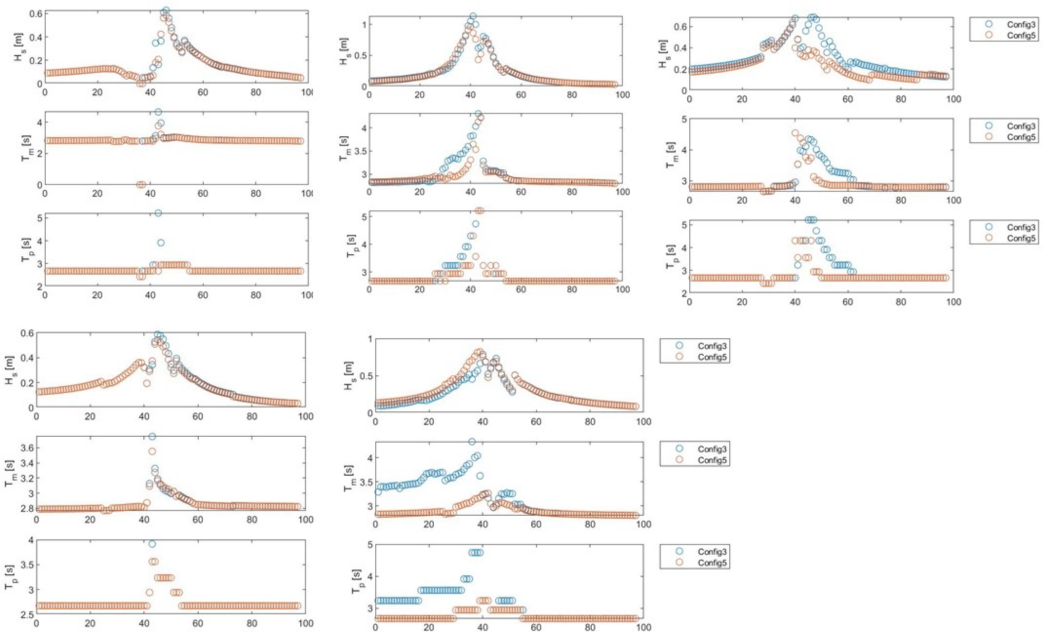

Figure *150*: Time series of significant wave height, peak period, and mean period for Storm 636. Top row, from left to right is station 49, 50, 59. Bottom row, from left to right is station 111, 117. Configuration 3 is shown in blue, Configuration 5 in orange.

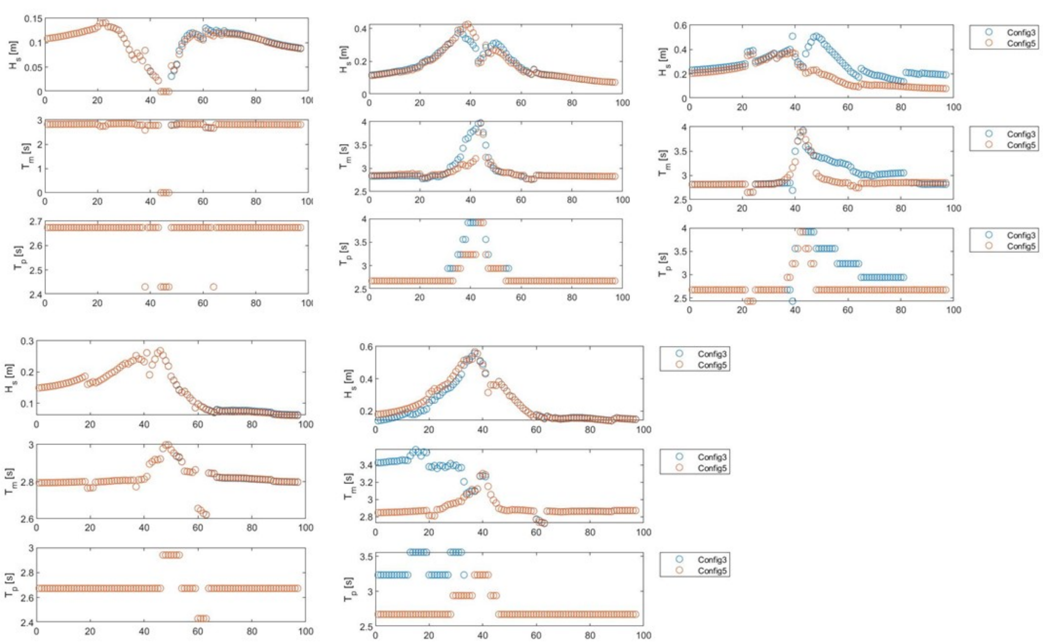

Figure *151*: Time series of significant wave height, peak period, and mean period for Storm 646. Top row, from left to right is station 49, 50, 59. Bottom row, from left to right is station 111, 117. Configuration 3 is shown in blue, Configuration 5 in orange.