Storm Surge Reduction Alternatives for Barnegat Bay

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Executive Summary

A new, high-resolution, hydrodynamic model for the Barnegat Bay estuary; including its vast intertidal areas, has been developed and validated. The Barnegat Bay Inundation Model (BBIMS) has a constant 100m resolution and is nested within the three dimensional Stevens NYHOPS model at its offshore open boundary, providing a link to upstream river flows and downstream to oceanic tidal and storm surge influences, and forced by local meteorology (surface wind and barometric pressure). Wetting and drying of land features in the model's external time step is as low as 0.1 sec in its 2D barotropic mode. This mode provides for the dynamic prediction of depth integrated flood elevations and velocities across land features during inundation events.

The BBIMS was calibrated using the NYHOPS hindcast of Hurricane Sandy. The hindcast utilized Sandy over ocean wind field and atmospheric pressure data, offshore wave and tidal boundary forcing, atmospheric heat fluxes, interior streamflow data and was validated against observed water levels and measured high water marks. A comparison against 6 water level time series measured by USGS tide gauges located in the Barnegat Bay verified that the model is able to capture the spatial and temporal variation of water levels in the Bay observed during Hurricane Sandy. A comparison against the verified high water marks found that the model is capable of hincasting overland water elevation to within 0.63ft (one standard deviation) at 71% of the total water marks measured.

The verified model has been used to study flood pathways during Sandy as well as evaluate the reduction in inundation due to short-term (floodwalls in breach locations) and long-term (inlet surge barriers) flood mitigation. This analysis determined that:

1. The use of a surge barrier across Barnegat Inlet reduced peak flood elevations over approximately two-thirds of the Bay, extending 28 miles from the Route 72 bridge to the northern head of the Bay at Bay Head. North of Barnegat Inlet, peak flood elevations are decreased between 2 to 4 feet and up to 4.5ft along portions of the shoreline. Reduction in flood water elevations of between 2 and 2.5ft extend 3.5 miles south of the inlet and up to 1ft as far south as the Route 72 bridge into LBI.
2. The use of a floodwall to prevent the breaching of the barrier spit at Mantoloking appears to have a small effect on the spatial distribution of peak water elevations in the Barnegat Bay due to Sandy. However; locally, the water elevations are reduced approximately 0.75ft by the floodwall. The amount of water that went through the breach during Sandy was second-order to the amount of water entering the upper Bay from the south.
3. In combination, the inlet surge barrier and floodwall reduces the peak water elevations an additional 0.05ft in the northern portion of the Bay north of Island Beach State Park. Locally, by the breach points, the peak water elevation reduction exceeds 5ft.

The BBIMS is shown to be a valid model that can be used as a flood mitigation tool to model any desired flood mitigation option. Based on the surge barrier and floodwall model assessments preformed in this study, recommendations are provided for additional flood mitigation options to further reduce the overland flood elevation in Barnegat Bay.

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Introduction

Communities along the Barnegat Bay were significantly impacted by Hurricane Sandy along both the Atlantic Ocean and Bay shorelines. Sandy was a harsh reminder of the vulnerability of low lying coastlines to significant inundation damage from coastal storms. The historic storm climatology of the NJ coast indicates that the Barnegat Bay is one area of the coast where storms of the future can be particularly devastating. The bay watershed comprises most of the area of the 36 municipalities within Ocean County, NJ, and is the fastest growing county in the State. 2004 census data estimate that the population increased 7% between 2000 and 2004, rising to over 550,000. As a popular seasonal vacation area, the population rises to around 900,000 or more in the summer when storms are particularly frequent. Flood protection is critical yet there is limited quantitative information available to help make decisions on what is most effective. The Barnegat Bay estuary (Figure 1) is a shallow, sheltered lagoon system that includes, from north to south, the waters of Barnegat Bay proper, Manahawkin Bay, and Little Egg Harbor. For the purposes of this document, Barnegat Bay is used to refer to the whole estuary. The total receiving water area of approximately 117 square miles connects to the Atlantic Ocean through the Little Egg Harbor Inlet in the south, the Barnegat Inlet at its midst, and the Manasquan Inlet through the Point Pleasant canal in the north. The estuary drains an approximately five times larger watershed (660 square miles). Spring tidal ranges in the Bay vary from 3.4ft at Little Egg Inlet to 2.7ft inside the Barnegat Inlet, to as small as 0.35ft at Oyster Creek. Maximum water elevations of greater than 6ft above the tide have been measured in the Bay during significant coastal storm events. The low lying land elevations and population density along the Bayshore make Barnegat Bay communities extremely vulnerable to significant inundation.

In an effort to understand specific vulnerabilities and flood mitigation options within the Barnegat Bay, we have leveraged existing model-based flood zone mapping and risk assessment work to quantify the effectiveness of specific short-term and long-term flood protection measures within the Barnegat Bay. We have developed and validated a new, high-resolution hydrodynamic model for the Barnegat Bay estuary; including its vast intertidal areas. The model is nested to Stevens' existing three-dimensional New York Harbor Observing and Prediction System (NYHOPS) model providing a link to upstream river flows and downstream to oceanic tidal and storm surge influences, and forced by local meteorology (surface wind and barometric pressure). The new hydrodynamic model has been used to study flood pathways during Sandy as well as evaluate the reduction in inundation due to short-term (floodwalls in breach locations) and long-term (inlet surge barriers) flood mitigation. The calibrated and validated model itself is a flood mitigation tool that can be used to model any desired flood mitigation option, including wetland restoration (current research in partnership with Stockton College), oyster reefs, bulkheads, bayshore restoration, among other options.

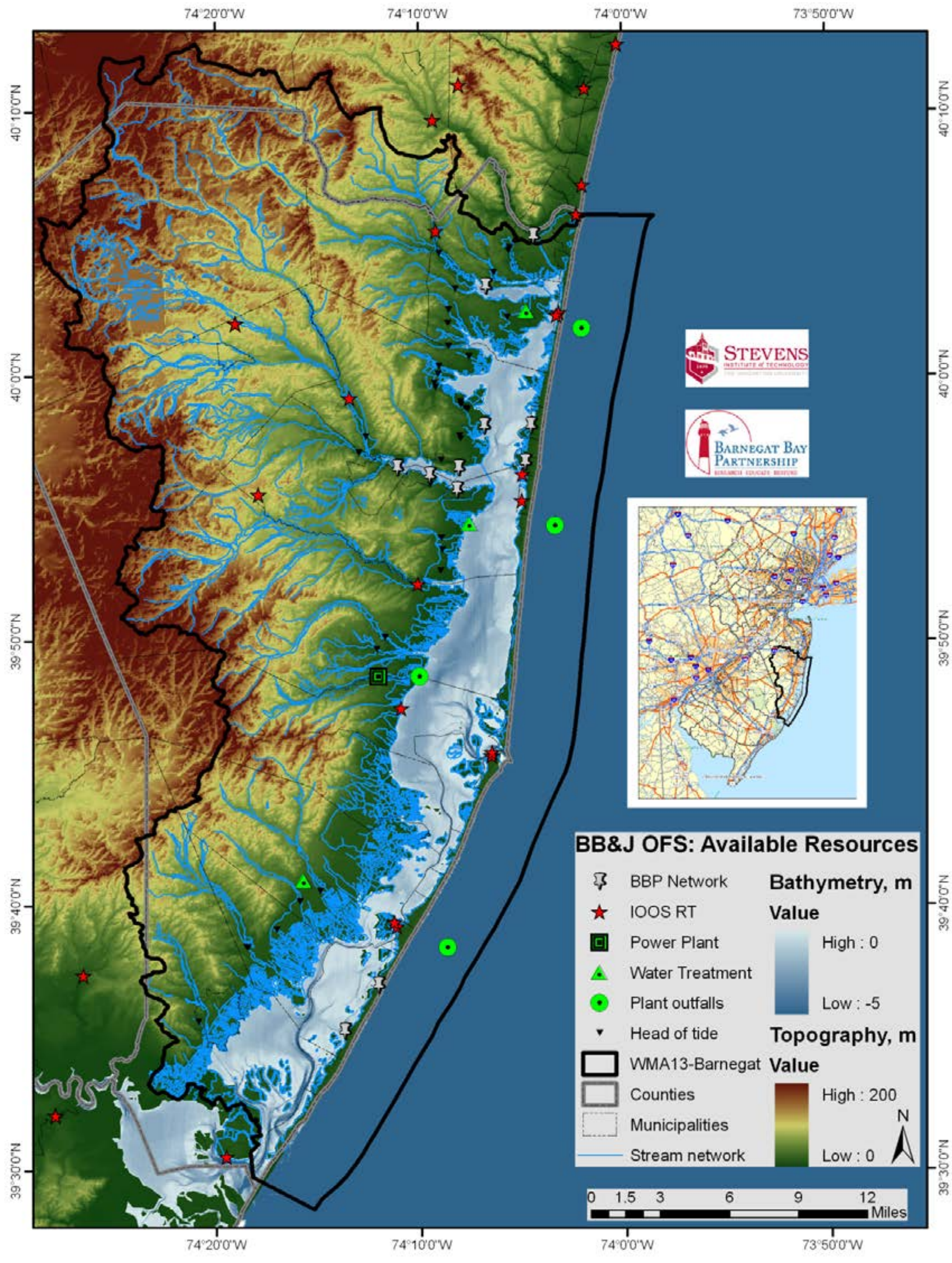

Figure 1. The Barnegat Bay estuary, its watershed surface hydrology and major point sources.

Hurricane Sandy Characteristics and Impacts

Sandy formed as a tropical depression southwest of Jamaica on October 22, 2012. Sandy strengthened to a Category 3 hurricane as it moved northward across Cuba and into the Bahamas before taking a more northeastward track off the eastern seaboard of the United States as a Category 1 hurricane (Figure 2). Although weaker, the size of the storm greatly increased with tropical force winds reaching the eastern seaboard 250 miles from the center of the storm (Figure 3). In the early morning hours of October 29th, Hurricane Sandy encountered an anomalous blocking high pressure system over the North Atlantic that steered the hurricane toward the Mid-Atlantic coast. As Sandy moved over the Gulf Stream it briefly strengthened to a Category 2 hurricane just 12 hours before landfall. Moving over the cooler waters of the continental shelf east of New Jersey, Sandy quickly weakened and began transitioning into an extratropical storm. Hurricane Sandy retained its unusual large wind field until it made landfall on Brigantine Island at 8pm EDT on October 29th.

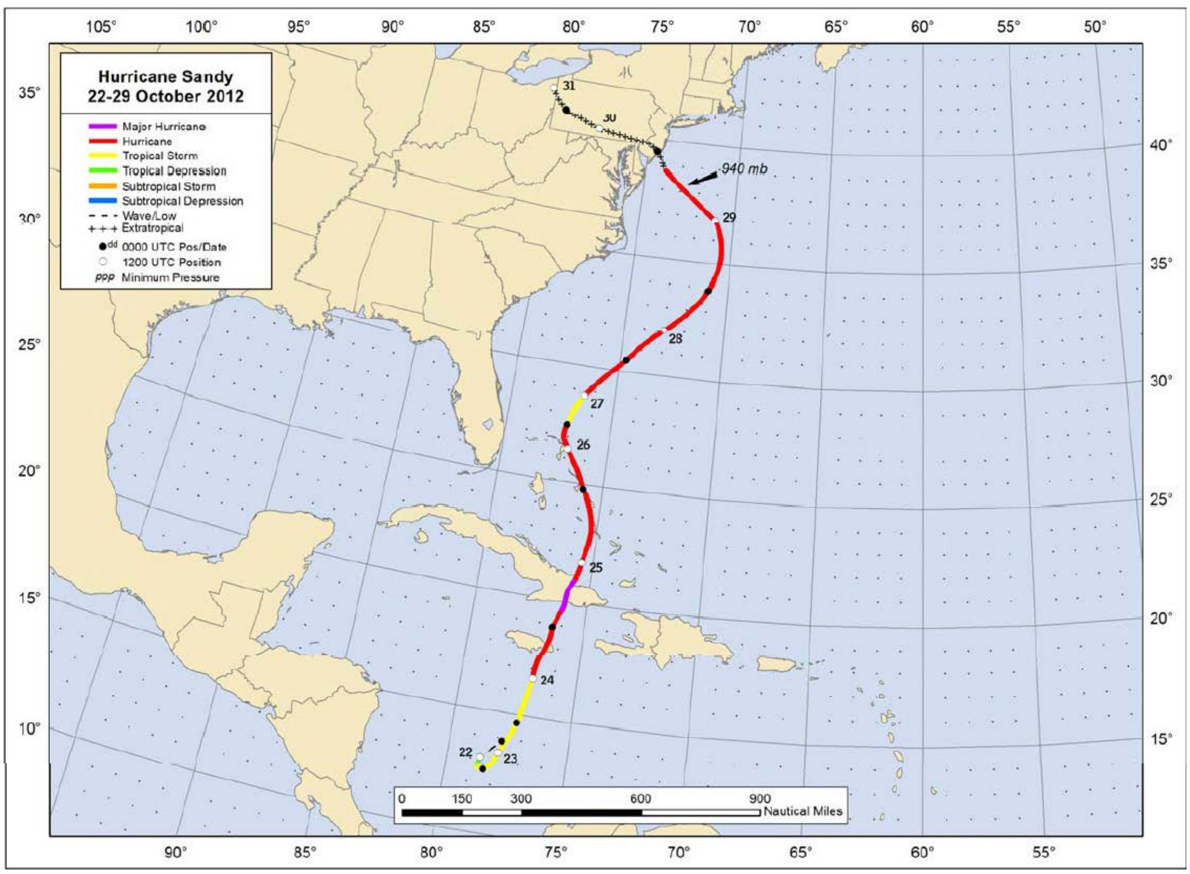

Figure 2. Hurricane Sandy track and intensity (NOAA Hurricane Research Division).

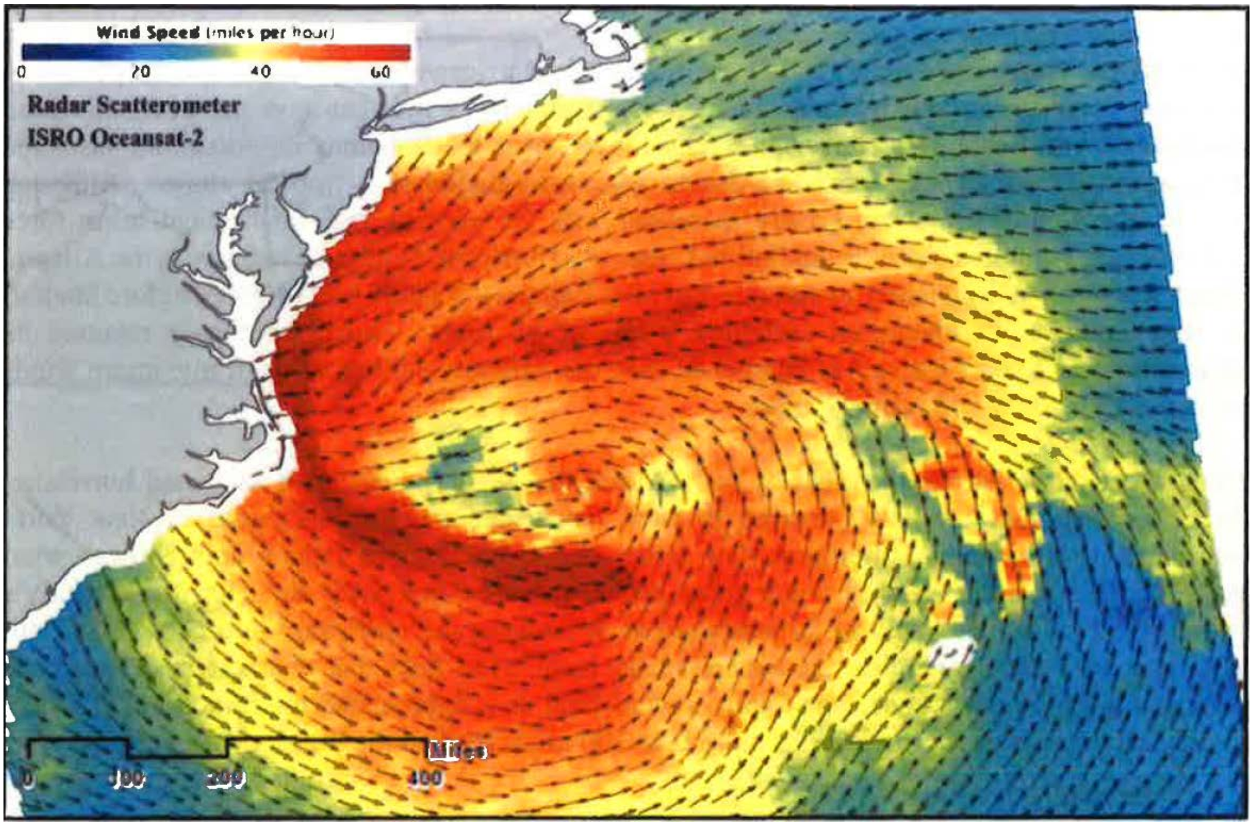

Figure 3. Hurricane Sandy track showing extent of tropical storm force winds (NASA).

Two hours prior to landfall sustained easterly winds of 35 knots, gusting to 60 knots were measured at Sandy Hook, NJ. The large wind field generated an extreme storm surge (abnormal rise of water above the predicted astronomical tide generated by a storm) north of the eye at landfall. Measured water levels ranged from +6.3ft NAVD88 at Atlantic City to +11.3ft NAVD88 at The Battery in New York City. NOAA has determined that the recurrence interval of such extreme water levels ranges from 30 years to >200 years, respectively (USACE, 2013). Hurricane Sandy's large diameter winds also resulted in long fetch lengths over the Mid-Atlantic and subsequent generation of extreme wave heights. Wave heights in excess of 32ft were measured 14 miles east of Sea Bright by NOAA Buoy 44065 located at the entrance to NY Harbor. Along the ocean shoreline, waves can also contribute to the storm surge through wave set-up (increased elevation of water along the coast due to water pushed toward the coast by breaking waves). A wave gauge deployed on the coast at Sea Bright by the USGS measured a peak water level of +16.5ft and a maximum wave crest elevation of +19.5ft NAVD88, indicating that wave set-up added approximately 5ft to the storm surge along the open ocean coast.

Following landfall, Sandy moved west-northwestward into Pennsylvania by October 30th. As Sandy moved across southern New Jersey, the strong east-northeast wind field that battered the NJ coast north of Brigantine abruptly shifted to a 40 knot southerly wind field (Figure 4). Coastal bays in New Jersey that initially experienced a set-down in water levels at the time of landfall, experienced a significant increase in water level as the center of the storm moved inland.

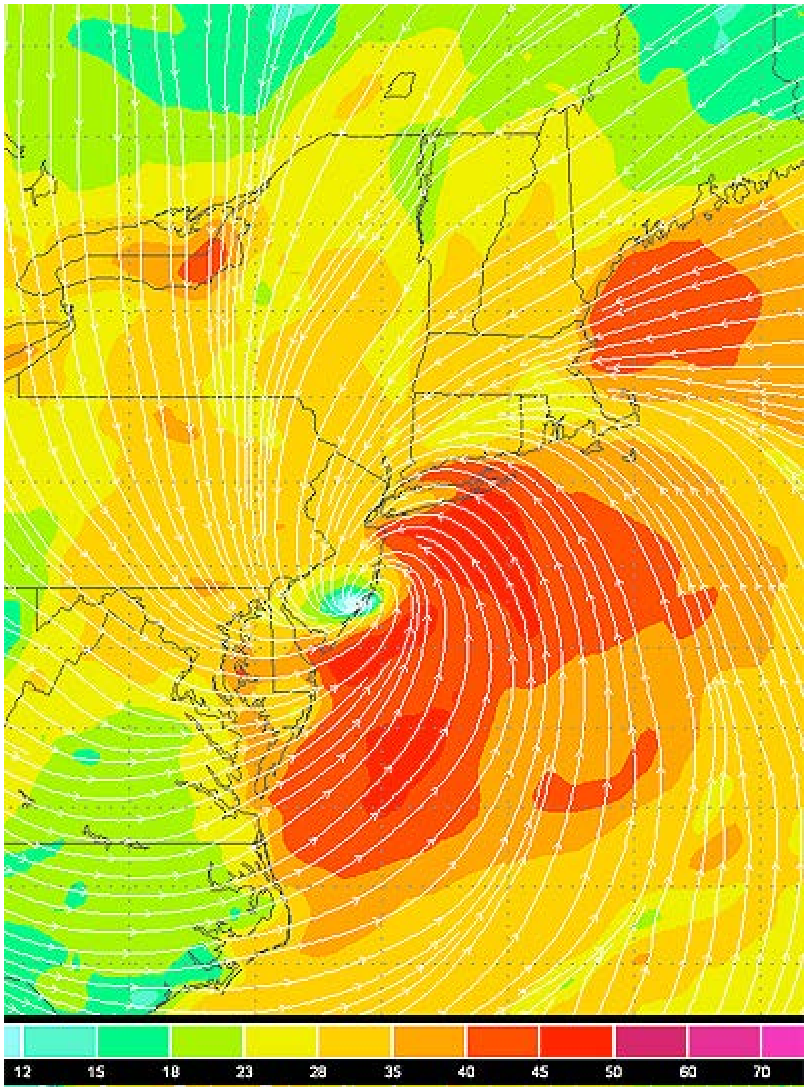

Figure 4. Sandy wind field at landfall showing strong southerly winds to the southeast of the eye.

Sandy caused unprecedented damage to New Jersey's housing, businesses, and infrastructure. Initial FEMA assessments suggest that approximately 71,800 structures in New Jersey were affected by Sandy. Of these, approximately 500 were destroyed and another 5,000 suffered major damage (>50% of the value of the property). The NJ Department of Community Affairs estimated that 40,500 primary residences and over 15,600 rental units in NJ sustained severe or major damage (NJDCA, 2013). In Ocean County alone, immediate post-Sandy FEMA estimates suggest that 22,200 homes were affected, 16,000 suffered minor damage, 1,180 were majorly damaged and 420 were destroyed; representing 56% of all damaged structures in NJ. A majority of the structures affected in the County were inundated by flood waters from the Barnegat Bay.

Barnegat Bay Inundation Modeling System

The Barnegat Bay Inundation Model is an sECOM model application, nested to the larger New York Bight sECOM model (NYHOPS), which is itself nested to an even larger Northwest Atlantic sECOM model (SNAP, Figure 5). sECOM (Blumberg *et al* 1999, Georgas and Blumberg 2010) is a three dimensional, free surface, hydrostatic, primitive equation estuarine and coastal ocean circulation model (Figure 6). Prognostic variables include water level, 3D circulation fields (currents, temperature, salinity, density, viscosity, and diffusivity), significant wave height and period. It is a successor model to the ECOM/POM combination that is in use by almost 3000 research groups around the world with over 600 papers having been published with them as the modeling engine (Blumberg and Mellor 1987). Its operational forecast application to the New York / New Jersey Harbor Estuary and surrounding waters (NYHOPS) is found online (http://www.stevens.edu/maritimeforecast) dating back to 2006 (Bruno *et al* 2006, Fan *et al* 2006, Georgas *et al* 2009a, Georgas 2010), and includes forecasts of chromophoric dissolved organic matter and associated aquatic optical properties through coupling to an RCA-based water quality model (Georgas *et al* 2009b).

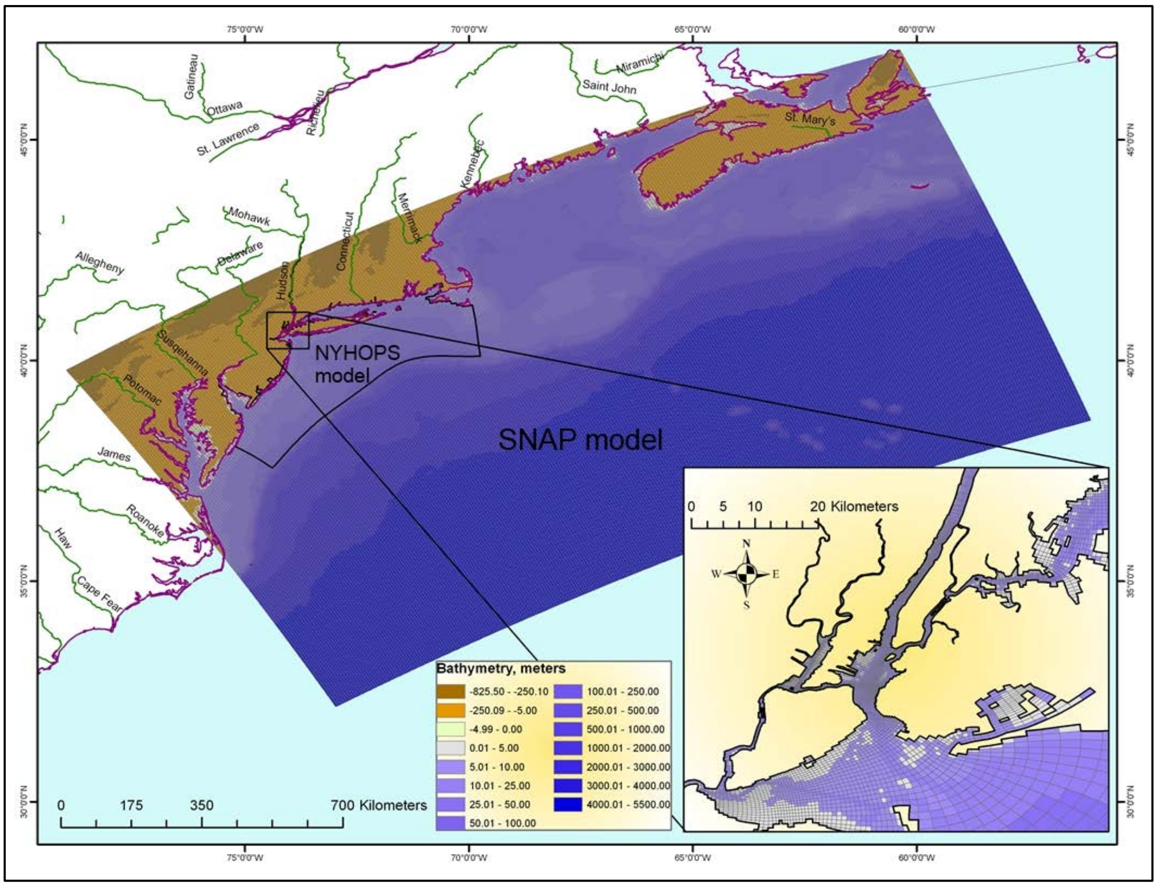

Figure 5. Stevens Northwest Atlantic Prediction (SNAP) model domain, showing the New York Harbor Observing and Prediction System (NYHOPS) model nested within it. The Barnegat Bay Inundation Model is itself nested within NYHOPS.

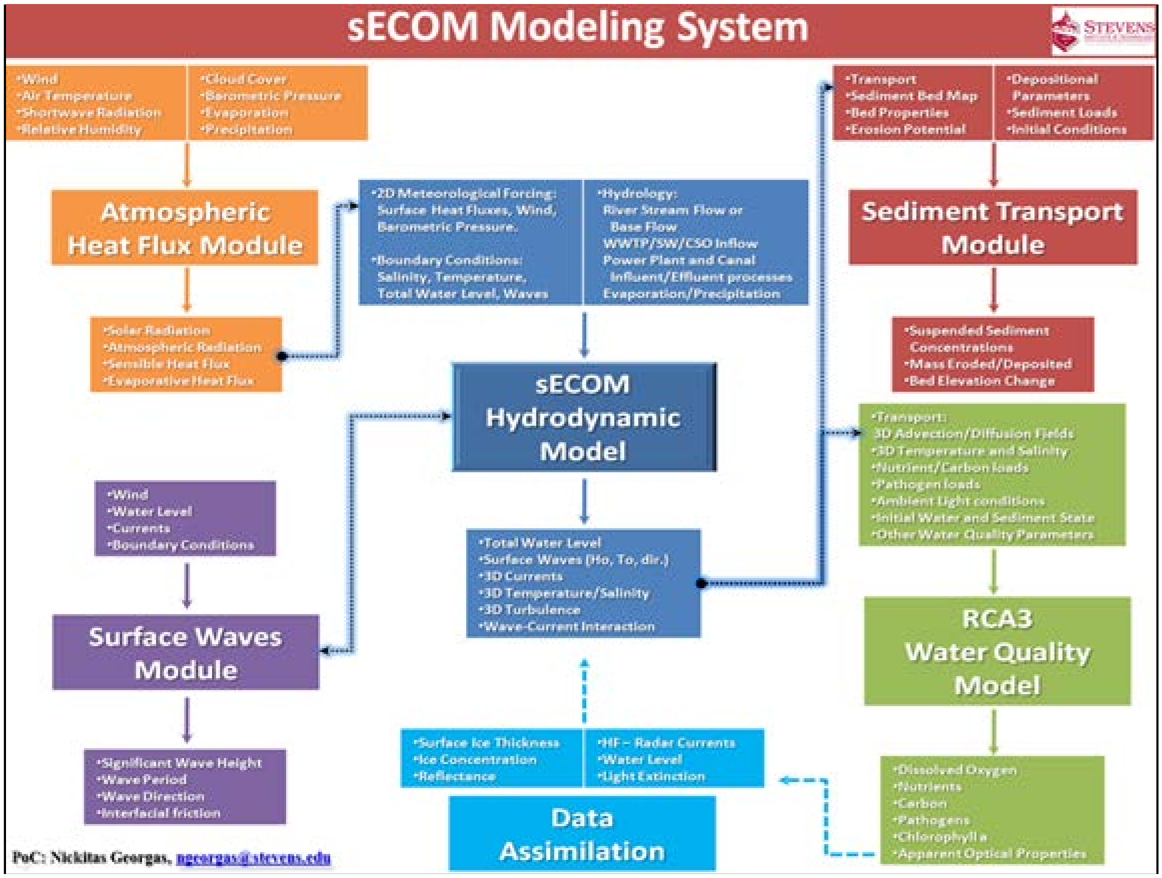

Figure 6. Schematic of the sECOM Modeling System showing computational modules.

The recursive MPDATA advection-antidiffusion algorithm (Smolarkiewicz 1984, Smolarkiewicz and Clark 1986, Smolarkiewicz and Grabowski 1990) is used to solve the thermodynamic (T, S, turbulence) advection-diffusion equations. ECOM/POM incorporates the Mellor-Yamada 2.5 level turbulent closure model (Mellor and Yamada 1982) that provides a realistic parameterization of vertical mixing processes, and a version of the Smagorinsky (1963) horizontal mixing scheme for subgrid scale horizontal shear dispersion. The model is forced in the open ocean lateral boundaries by total water level, waves, and long-term thermohaline conditions, at the surface with a two-dimensional meteorological wind stress and heat flux submodel, and internally with thermodynamic inputs from river, stream, and water pollution control plant discharges, and thermal power plant recirculation cells. Quadratic friction is applied at the bottom based on internally calculated friction coefficients that include wave boundary layer effects (Grant and Madsen 1979, Georgas *et al* 2007, Georgas 2010), and at the free surface through assimilation of surface ice cover friction (Georgas, 2012).

The code is written in standard FORTRAN 77, and can be easily modified. Significant features are included, such as robust explicit wetting-and-drying (W&D) and thin-dam (obstruction grid) formulations, new coupled wave and atmospheric modules, surface ice cover friction, and complete Climate and Forecasting Conventions (CF 1.4) compliance of the NetCDF outputs. When run in 3D mode as in NYHOPS, the code employs a mode-splitting technique to integrate in time the barotropic (2D) primitive shallow water equations separately from the baroclinic (3D) advection-diffusion equations that may run on a larger timestep. The "external' barotropic mode time step is restricted by the Courant-Friedrichs-Levy- (CFL-) stability-criterion and is set to 1s in NYHOPS. The "internal' baroclinic mode can usually converge with a larger time step (10s for NYHOPS), saving computational time. The two time steps are seamlessly integrated with a leap-frog scheme.

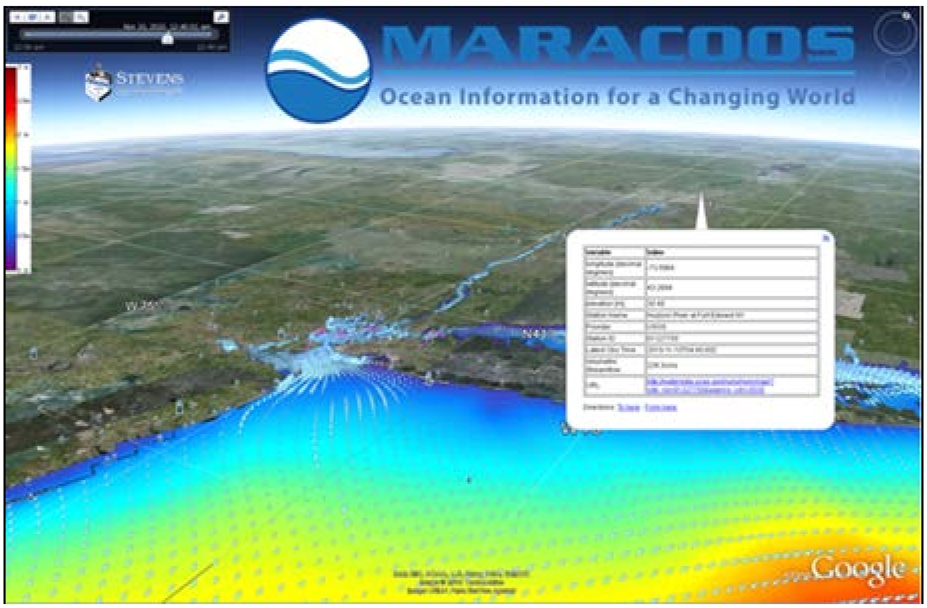

Figure 7. Google interface for NYHOPS model forecasts.

In its NYHOPS application to the waters of New York and New Jersey (Georgas *et al* 2009a, Georgas and Blumberg 2010, Georgas 2010, Figure 7), the computational domain is discretized on an Arakawa "C" finite-difference curvilinear grid (147x452 horizontal cells, 15,068 of which are designated as water). The NYHOPS grid (Figure 5) encompasses the entire Hudson-Raritan (New York/New Jersey Harbor) Estuary, the Long Island Sound, and the New Jersey and Long Island coastal ocean. The resolution of the grid ranges from approximately 7.5km at the open ocean boundary to less than 50m in several parts of the NY/NJ Harbor Estuary. In order to resolve coastline features that could not be resolved on the NYHOPS grid cell scale, most notably the NJ Atlantic coast barrier islands, 96 cell interfaces across which transport or mixing is disallowed ("thin dams") have been defined. In the vertical, the model uses a sigma-coordinate system with bathymetrically-stretched sigma layers to permit better representation of bottom topography. The current vertical resolution of the NYHOPS grid is 10 sigma (bottom-following) layers at depths shallower than 200m, providing forecasts at 150,680 points averaged every 10 minutes.

After many years of continuous model development, the accuracy and applicability of sECOM has improved markedly. Several comprehensive skill assessment studies have been carried out (Fan *et al* 2006, Georgas *et al* 2007, Bhushan *et al* 2009, Georgas and Blumberg 2008 and 2010, DiLiberto *et al* 2011) and in each case sECOM's performance has been exemplary. Today the model is used in the NYHOPS domain with confidence to address the emergency issues as we safe navigation, water quality concerns, and beach erosion and flooding. sECOM's forecasts are shared daily with the NWS, USCG, and NOAA OR&R. They are also now being used effectively by the recreational community - sailors, power boaters, swimmers, and fishermen.

The Barnegat Bay Inundation Model (BBIMS) has a constant 100m resolution and is nested within the three dimensional NYHOPS model at its offshore open boundary. The grid and bathymetry is shown in Figure 8. The wetting and drying model's external time step is as low as 0.1 sec in its 2D barotropic mode.

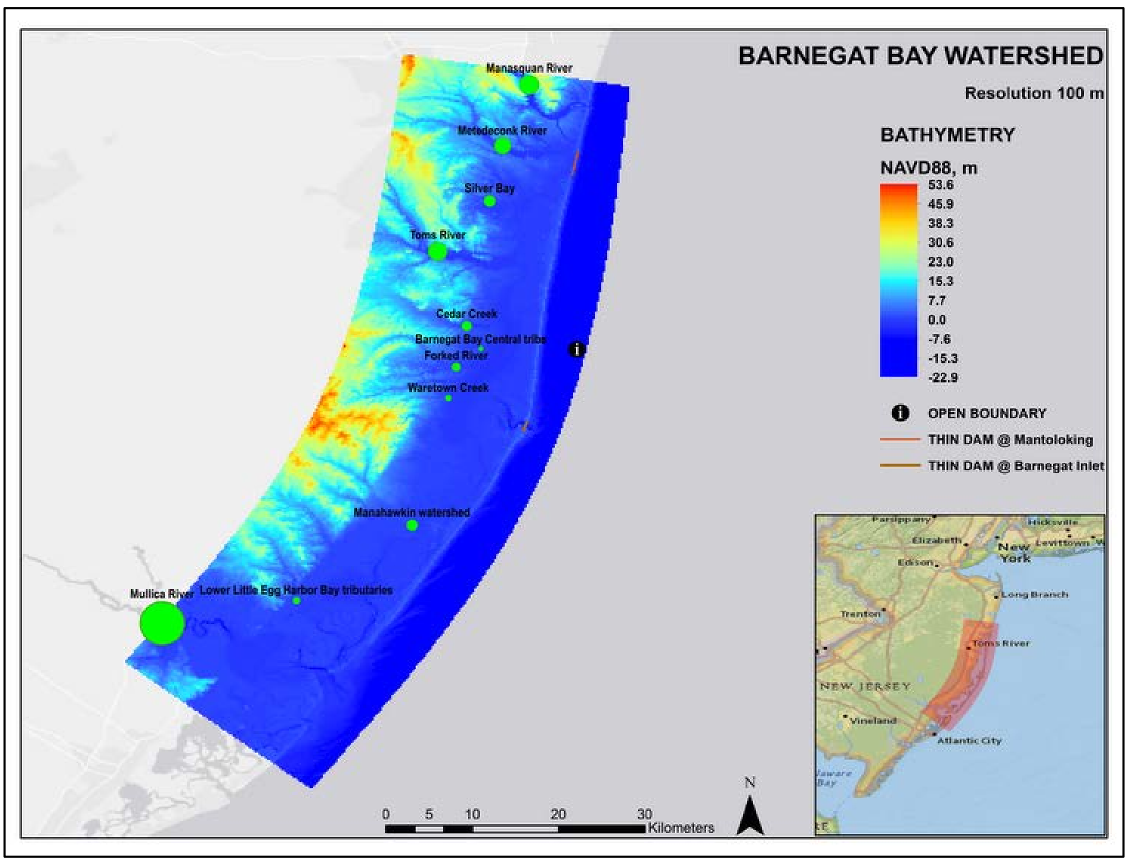

Figure 8. Barnegat Bay Inundation Model. Bathymetry, resolution, open boundary, and significant river discharges as modeled in this work.

Model Application for Sandy

The BBIMS was calibrated using the NYHOPS hindcast of Hurricane Sandy. The hindcast utilized Sandy over ocean wind field and atmospheric pressure data, offshore wave and tidal boundary forcing, atmospheric heat fluxes, interior streamflow data and was validated against observed water levels. The resulting time series of water level was used to force the offshore boundary of the nested BBIMS, the atmospheric pressures and wind fields were used as surface forcing across the BBIMS domain, while river inflows were based on USGS gages adjusted by sub-watershed (Figures 9 and 10).

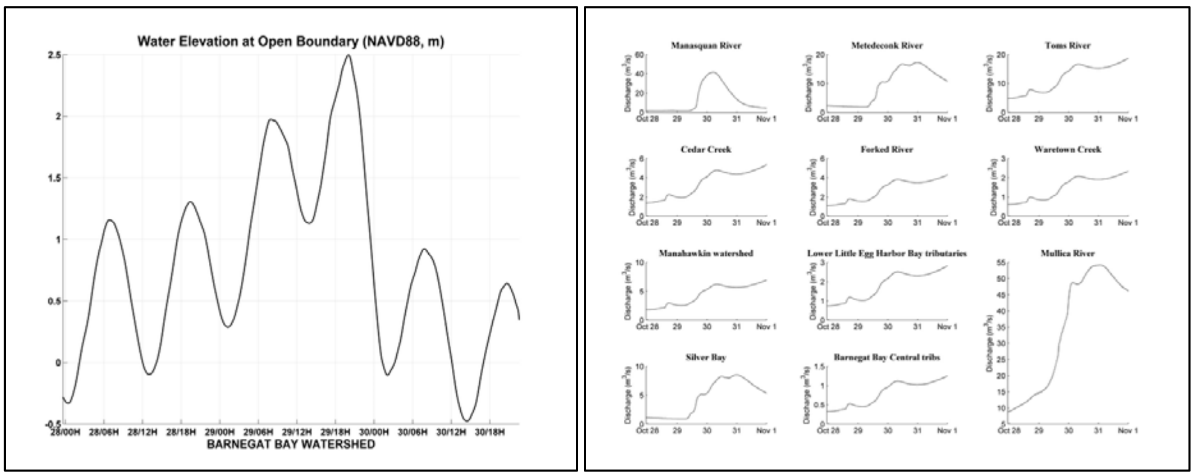

Figure 9. Offshore elevation (left panel) from the NYHOPS hindcast at the location indicated as (i) in Figure 8, and distributed estimates of river discharges (right panel) based on USGS gages used in the BBIMS application for Sandy.

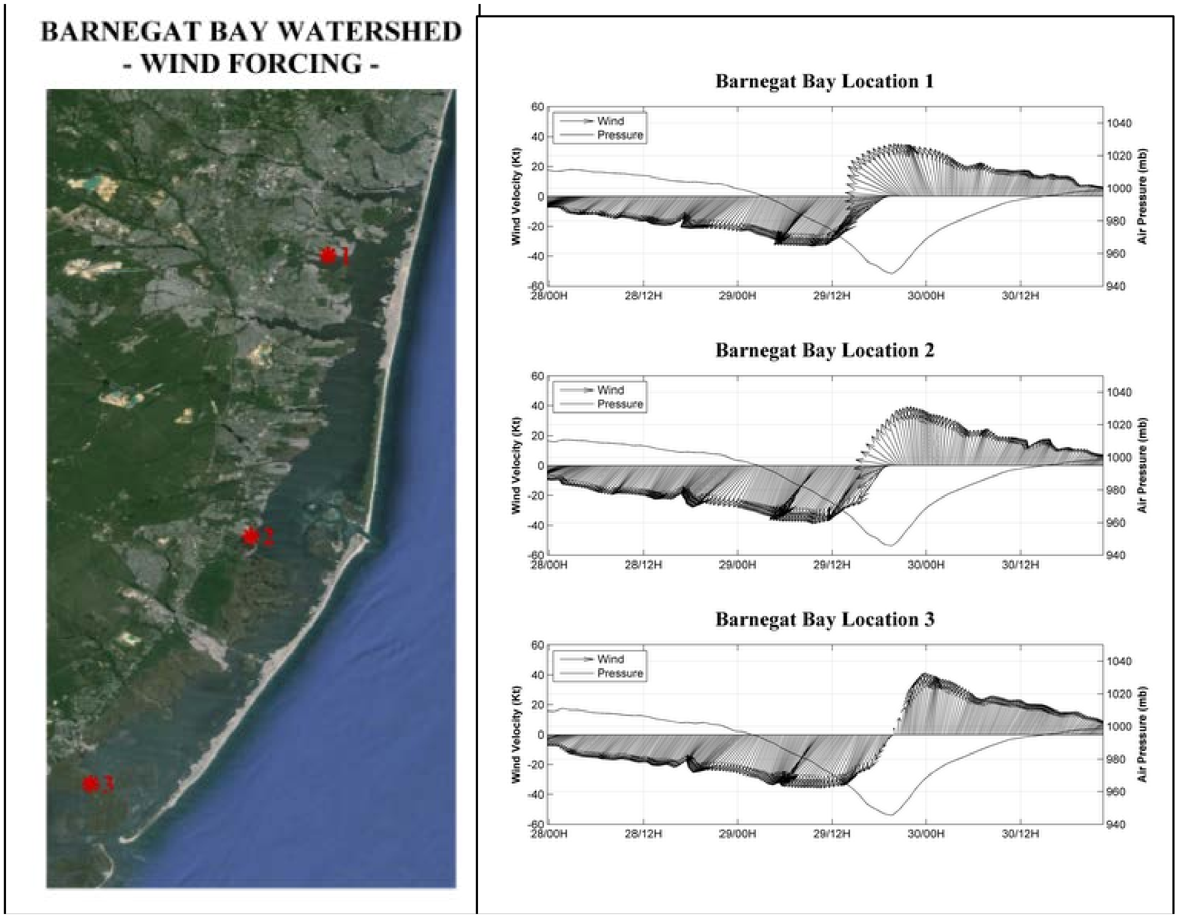

Figure 10. Time series of surface wind and barometric pressure at three interior Barnegat Bay locations

The model simulation begins at midnight EDT on October 28th and ends at midnight EDT October 31st. The model domain for the calibration runs is shown in Figure 11. The location of the two water level time series plotted in the lower right hand corner are indicated by the blue and red boxes in the upper left hand plot. The blue line is the time series of open ocean water levels and the red line is the predicted water level in the Bay west of Mantoloking, NJ.

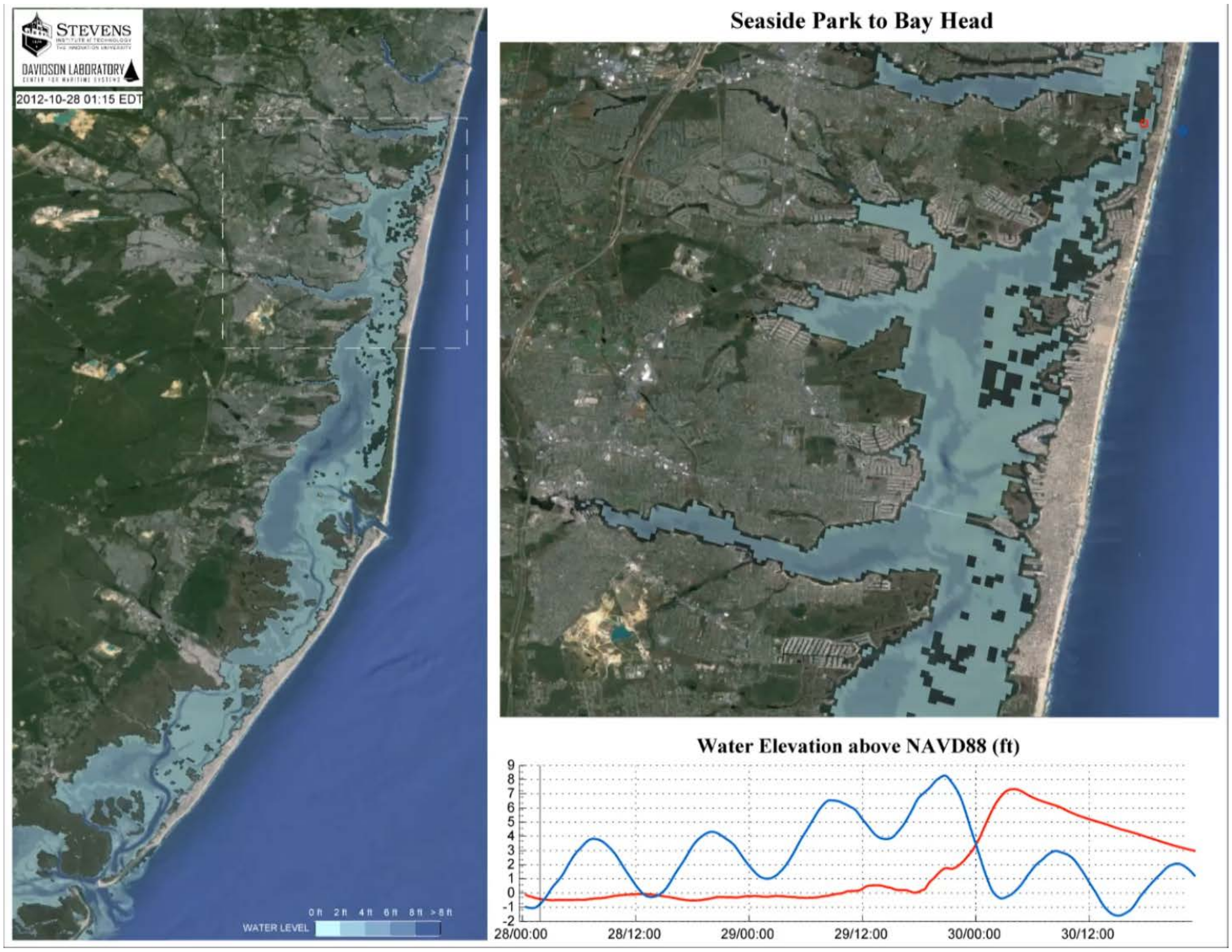

Figure 11. BBIMS Calibration Model Domain.

The morning high tide prior to Sandy's landfall occurred at 7:45 EDT on the oceanfront and reached an elevation of approximately 6.5 t NAVD88 (Figure 12). Note on the figure that time is indicated in the upper left corner and corresponds to the vertical grey solid line on the time series plot. Water levels in the upper Barnegat Bay are at an elevation of 0ft NAVD88. At the southern end of the Bay there appears to be an area of overwash at the very southern end of Long Beach Island (LBI) and minor flooding in Tuckerton and along the bay shoreline of LBI. High tide in the upper Barnegat Bay occurs 5hours after high water along the oceanfront (Figure 13). At this time (12:45 EDT) the lower Bay continues to experience minor flooding while the upper Bay shows almost a set-down in water levels.

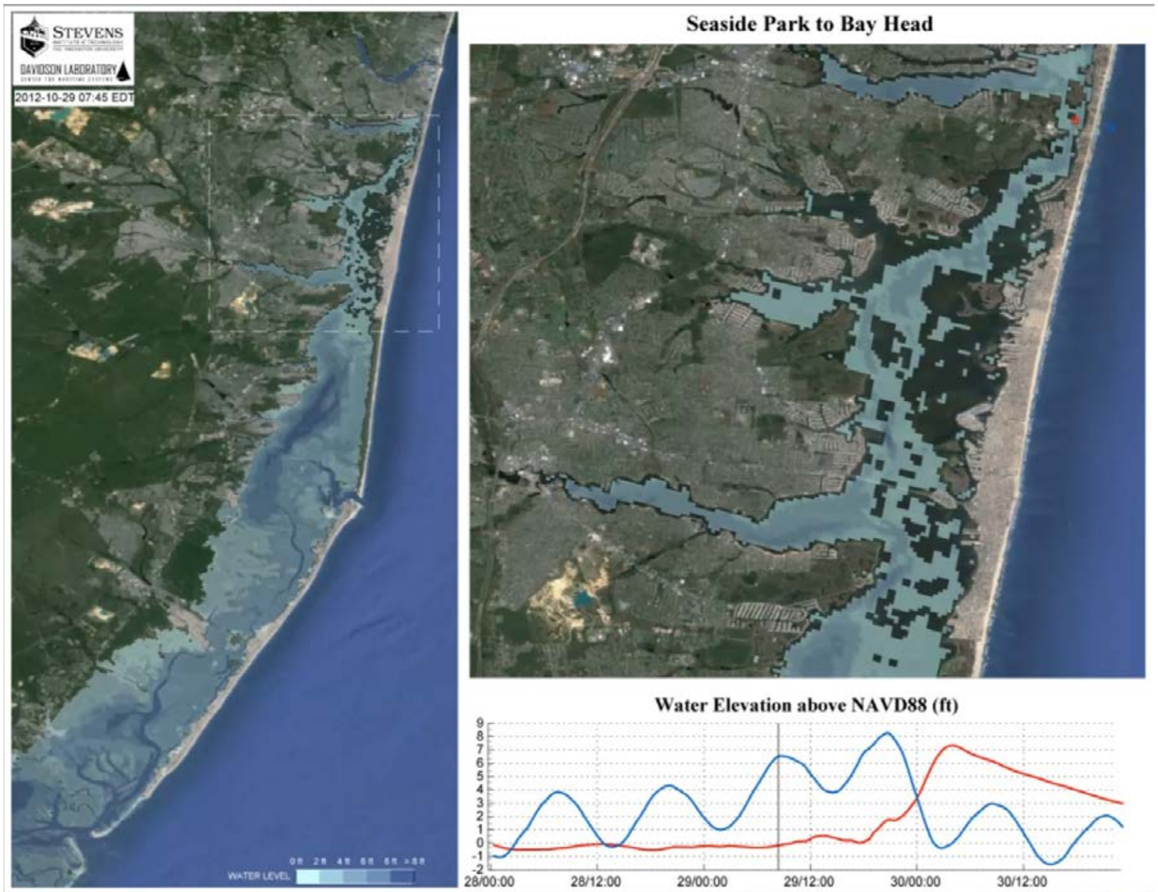

Figure 12. Water levels at morning high tide on October 29, 2012.

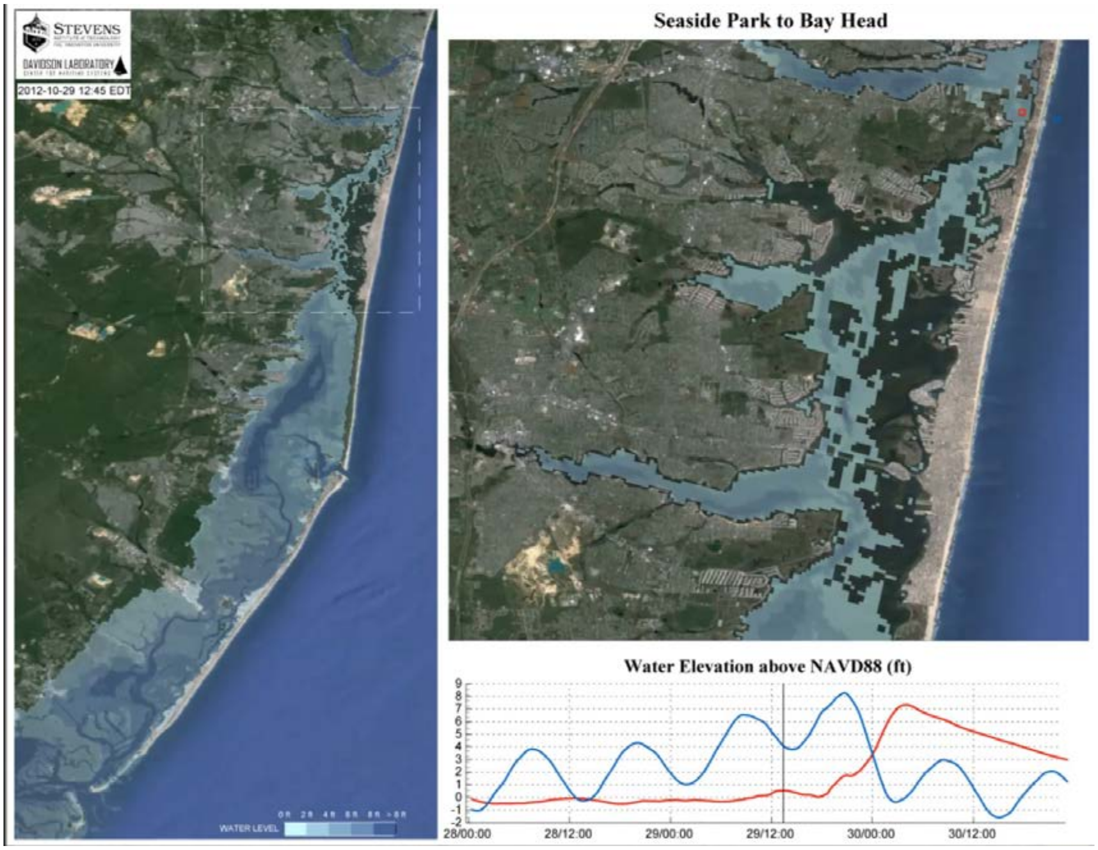

Figure 13. Water levels at morning high tide in upper Barnegat Bay on October 29, 2012.

At the oceanfront, Sandy's peak surge occurs at 20:00 EDT on October 29th, coinciding with the astronomical spring high tide there (Figure 14). Water levels reach an elevation of 8.25ft NAVD88 on the oceanfront and 1.75ft NAVD88 in the upper Bay. Looking carefully at the upper bay inset, one can see the two breaches occurring across the barrier spit in Mantoloking. Widespread flooding is evident along the southern portion of the Bay south of approximately the Route 72 Bridge into Surf City. After landfall, the offshore water levels rapidly fall on the outgoing tide. The water levels in the upper Bay continue to rise as storm tide water entering from the inlets is forced up the Bay by the strong southerly winds in the southeast quadrant of the storm (see Figure 10). Model sensitivity runs with and without wind show that the flooding might have been more destructive during Sandy because of the veering of the wind as the storm passed over the Bay. Runs without local wind forcing show water levels reaching similar peak elevations as they actually did during the storm. But the rise to these same levels without local wind would have been a near steady gradual filling of the upper bay over two to three tidal cycles, at a rate of about 0.2 vertical ft/hr. Instead, due to the shifting strong local wind forcing, the upper Bay first emptied to the south, then filled up much faster as the winds shifted, with rates closer to 1ft/hr and with resultant stronger currents and higher potential for erosion. Peak water levels in the upper Bay occur 7 hours after the peak surge on the oceanfront, and reach an elevation of 7.25ft NAVD88 (Figure 15). Widespread flooding is now evident along the entire Barnegat Bay shoreline. Water levels in the Bay slowly recede over the day on October 30th but are still above flood level by midnight on October 31st.

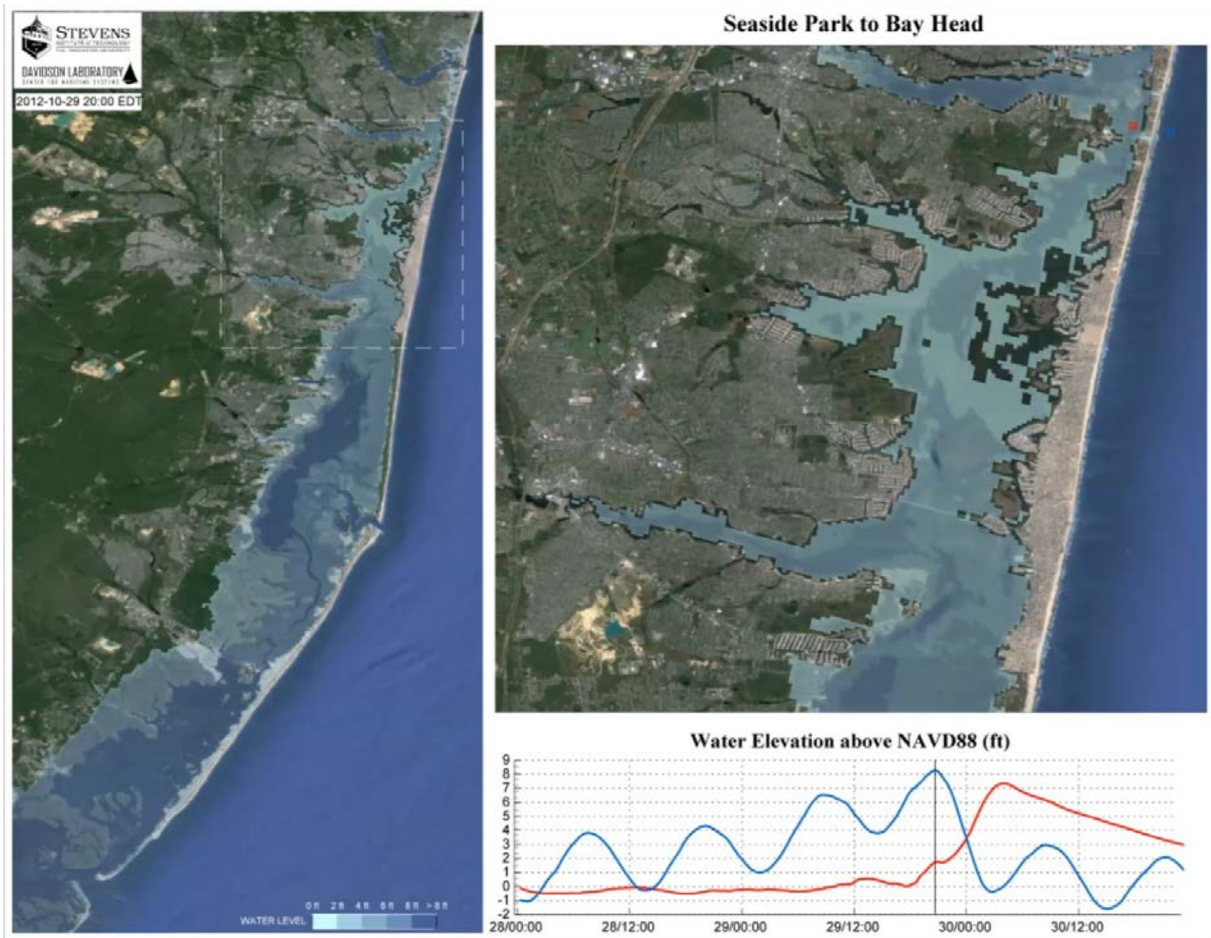

Figure 14. Water levels at time of peak surge on October 29, 2012.

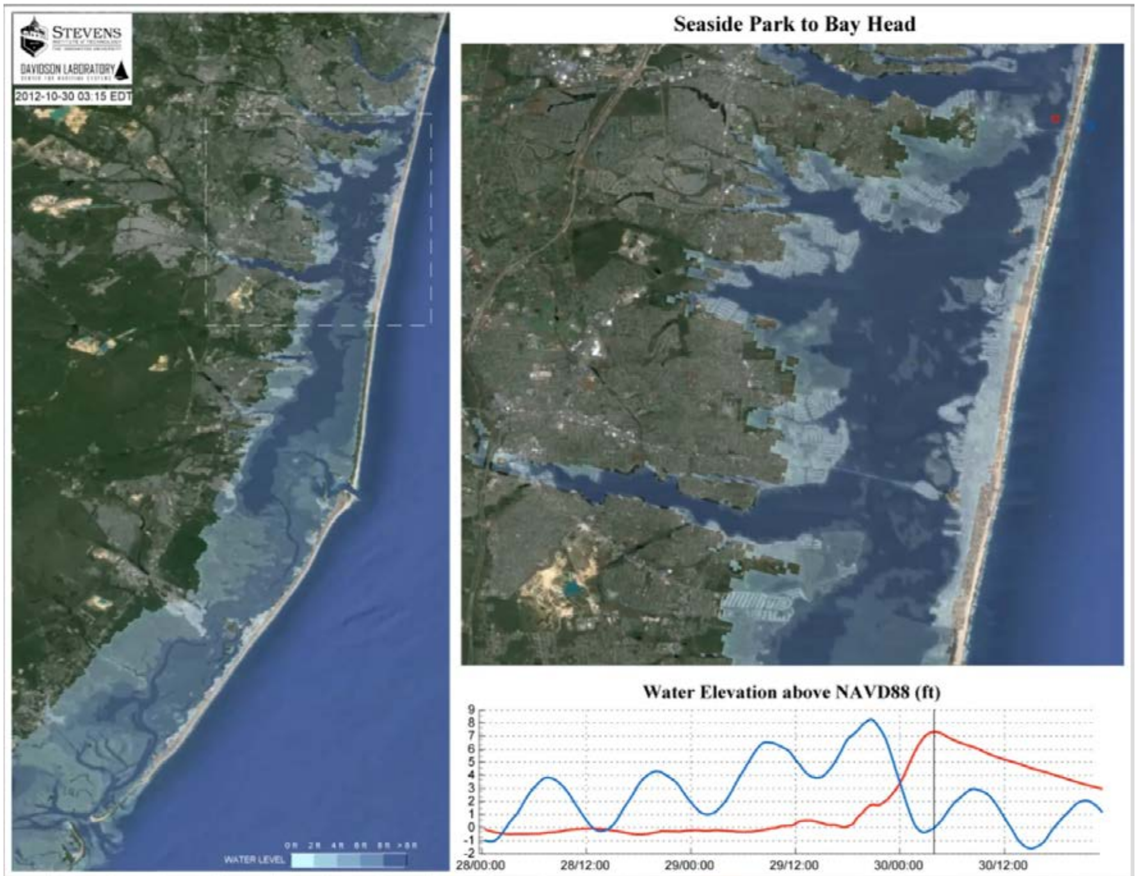

Figure 15. Water levels at time of peak surge in the upper Bay on October 30, 2012.

Model Validation

Water level time series recorded by USGS coastal tide gauges in the Barnegat Bay were used to validate the BBIMS. The USGS operates 8 real-time tide gauges in the Barnegat Bay. Two of the gauges, one in Waretown and one in Seaside Heights were destroyed during Sandy. Verified data from the six gauges that survived were used to validate the model. Meteorological data from the closest available weather station to each gauge was used to validate the atmospheric forcing. The location of each tide gauge is indicated by the light blue squares on Figure 16.

A model sensitivity analysis was conducted at each validation point in the model domain. Each validation plot presents the water level time series in the upper right and the atmospheric time series in the lower right. Each water level plot shows the observed water levels (red dots) at the tide gauge, the predicted water level without wind forcing over the bay (blue dots), the predicted water level with wind forcing (green dots), and the predicted water level with both wind and local atmospheric pressure forcing variation (black dots). Each atmospheric plot shows the modeled (black) and observed (aqua) wind vector and atmospheric pressure. The arrows on the wind vectors point in the direction toward which the wind is blowing (i.e., an arrow pointing directly up is a wind blowing from south to north).

Figure 16. Location of operational (light blue squares) and non-operational (red squares) USGS tide gauges used for model validation.

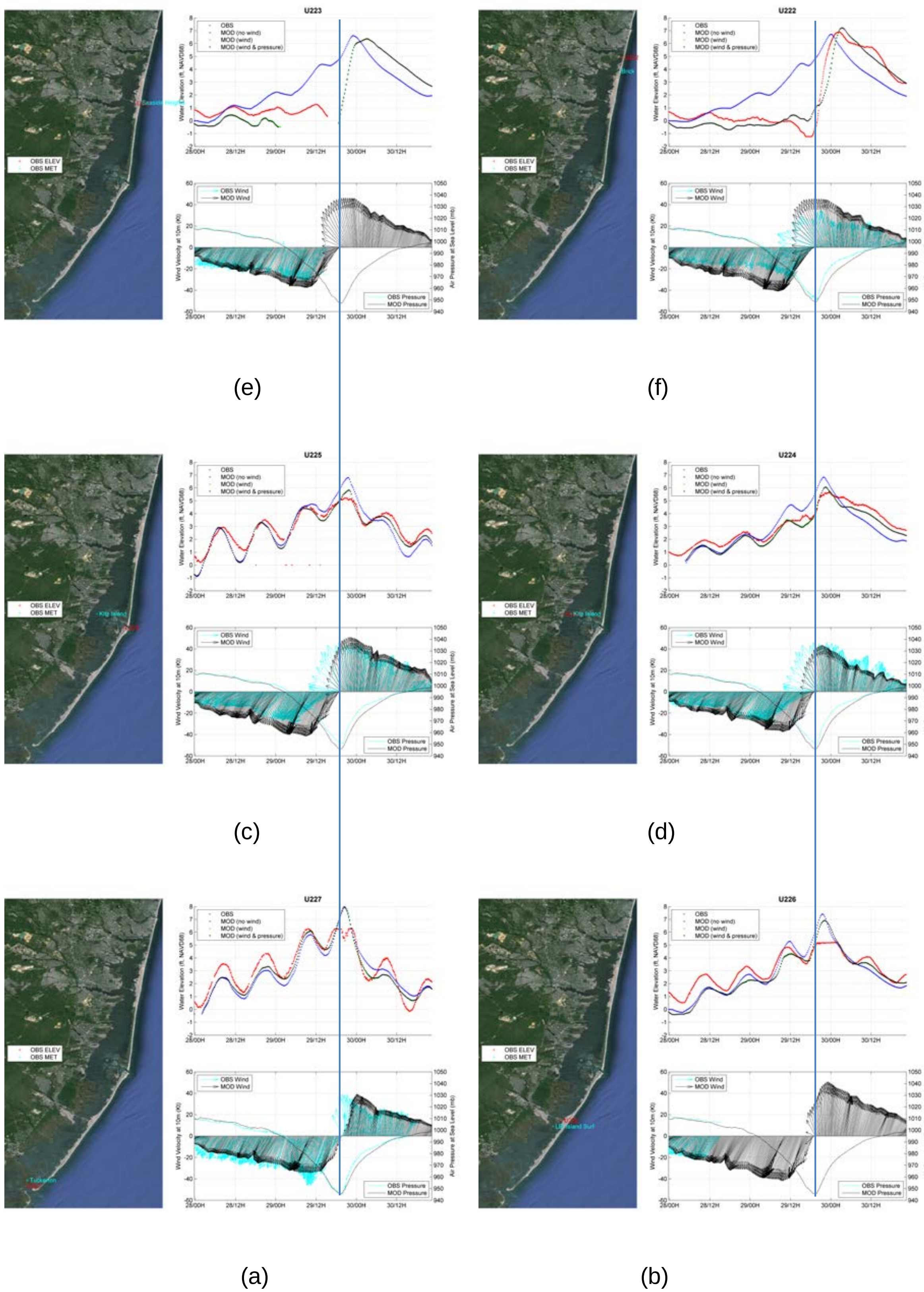

Figure 17a. Comparison of observations (before USGS corrections) and model predictions.

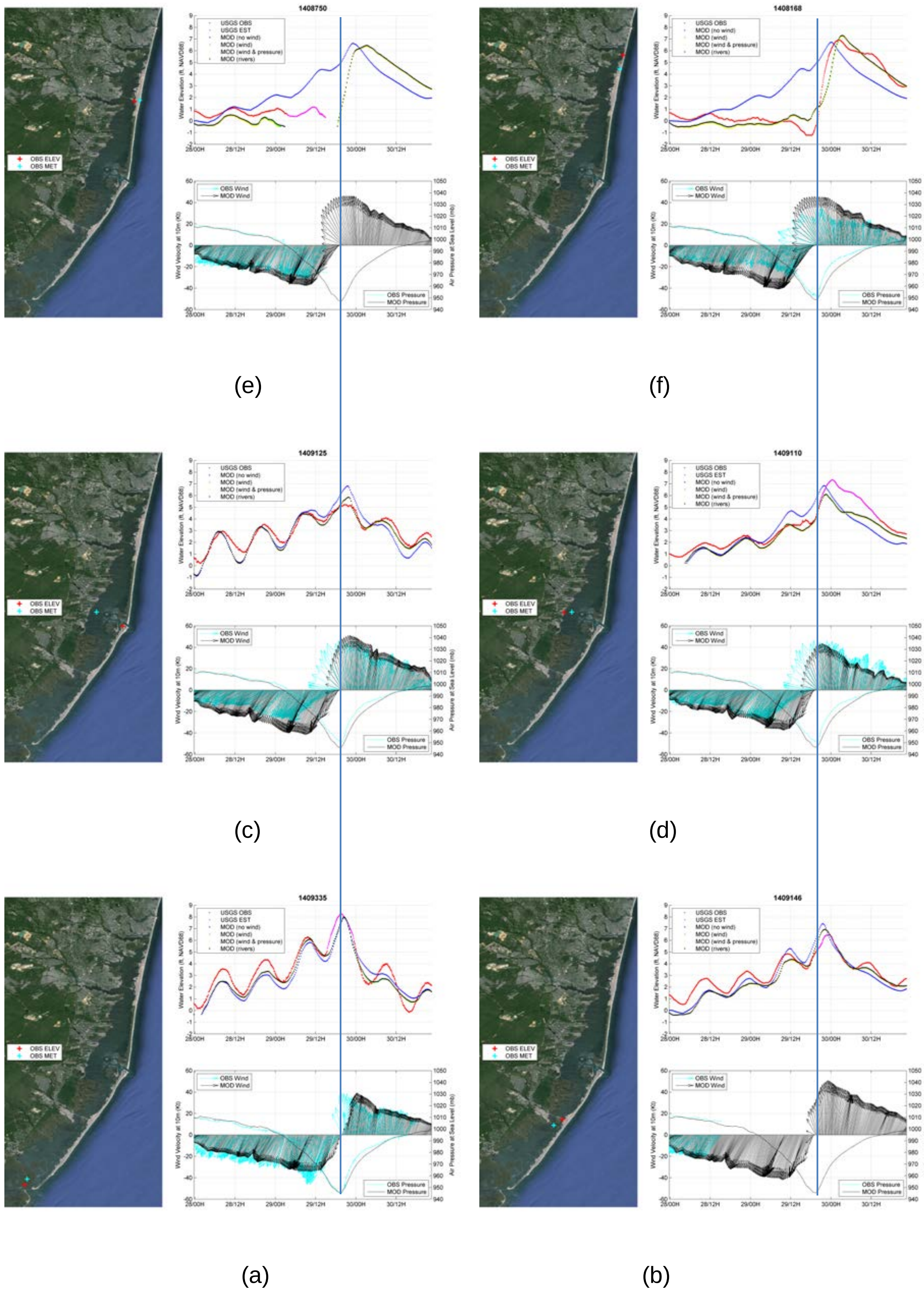

Figure 17b. Comparison of observations (after USGS corrections; pink) and model predictions.

The validation results are presented from south (a) to north (f) in Figures 17a and 17b. Figure 17a has the USGS data as originally recorded, while Figure 17b includes preliminary data revisions *estimated* by the USGS (pink dots) that add a degree of uncertainty in the observations at these points. A quick look at the observed water level shows that the southern portion of the Bay, south of Barnegat Inlet, experienced a longer duration surge event than the northern portion of the Bay. Data and model results for the southernmost tide gauge, located at the Rutgers Marine Field Station in Tuckerton, NJ, is presented in panel (a). The observations show that water began to enter the southern portion of the Bay starting on October 28th. The bay gradually filled with water on each incoming tide as Sandy approached the coast. Recorded water elevations reach 6ft NAVD88 during the morning high tide on October 29th and only receded about a foot prior to the peak surge that occurred during the next tidal cycle. Note that the gauge was unable to record the peak as the water levels exceeded the elevation at which the gauge could accurately measure water levels (Figure 18). The USGS later estimated that the peak water level was 8.26ft NAVD88 (Figure 17b). After landfall, the southern portion of the Bay began to drain but remained above the astronomic tide elevations until the morning low tide on October 30th.

Figure 18. USGS tide gauge at Tuckerton, NJ. The gauge stops recording when water levels exceed 6 ft, NAVD88.

The model water elevation prediction with and without surface wind forcing both track the observed water level well prior to landfall but underestimate the elevations by approximately 1ft. The skill of the model increases greatly on October 29th. Prior to and at landfall, the model water level prediction that includes both wind and air pressure surface forcing match the observed water level almost exactly. The model predicts a peak water level of 8ft NAVD 88 at Tuckerton, exceeding the recorded peak by 2ft (Figure 17a). The predicted value is only 0.26ft lower than the peak estimated flood height by USGS (Figure 17b). Based on the model prediction, it appears the peak water level in the southern Bay occurred within minutes of to the time Sandy made landfall. The model wind fields show a more gradual shift in wind direction from north-northeast to south than observed at Tuckerton but this does not appear to affect the predicted decrease in water levels after landfall. The model misses the high tide peaks after landfall but does capture the gradual draining of the southern portion of the Bay.

Observed and predicted water levels at Long Beach Island (LBI) are shown in panel (b). The observations at LBI also show a gradual increase in water elevation prior to landfall, similar to the data recorded at Tuckerton. The model predictions with and without wind forcing again show a trend similar to the observations but under predict the observed water levels prior to landfall. The model predictions that include wind and pressure forcing at the surface again show the greatest skill in predicting the peak water elevations; river inputs also made little difference there, though neglecting them would have introduced an overall negative bias in the model (Figure 17b). The peak water level at LBI also exceeded the elevation at which the gauge could accurately measure water levels. The model predicts a peak water elevation of approximately 7ft NAVD88 at LBI, but occurring after the time Sandy made landfall, a fact that is consistent among all back-bay stations (b, d, e, f) away from the inlets, especially in the upper bay (e and f). The revised USGS estimate for the peak water level at that gage is 0.5ft lower.

Panels (c) and (d) on Figure 17 show the observed and modeled water levels on the east and west side of the Bay inshore of Barnegat Inlet, respectively. Both tide gauges show the gradual filling of the Bay with water starting on October 28th. At these stations, the model error is reduced to between 0.25 and 0.5ft below the originally recorded water elevations. The model results with no wind forcing over predicts the peak water level in the middle of the Bay. The wind and air pressure forced simulations accurately predict the time and elevation of each high tide but somewhat under predict the observed low tide elevations. The peak water levels, occurring at about the time of landfall, are over predicted by the model at Barnegat Inlet. At the inlet, the model predicts a water elevation of 5.75ft NAVD88 while the observed water elevation peaked at 5.25ft. The USGS estimate that a peak water elevation of 7.33ft NAVD88[1] occurred at midnight on

[1] http://nwis.waterdata.usgs.gov/usa/nwis/uv/?cb_00065=on&format=gif_default&period=&begin_date=2012-10-28&end_date=2012-10-30&site_no=01409110

October 30th at Waretown, the western station. At this location, the model predicts a peak water elevation of 6ft NAVD88 at around 22:00 on October 29th. We note that the USGS-estimated and revised data at Waretown (Figure 18d) are quite different from both the originally recorded values and our model results.

The water level observations and prediction in the northern portion of the Bay are shown in panels (e) and (f) of Figure 17. It is immediately obvious from a quick look at the observed water levels that the upper Bay responded very differently than the southern and central portions. The tide gauge at Seaside Heights (e), located 12.5 miles north of Barnegat Inlet was destroyed during Sandy. Prior to its failure, the observed water levels and the fully dynamic model predictions (green dots) show a set-down in water levels in the upper bay in contrast to the observed gradual filling of the central and southern portions of the Bay prior to landfall. The predicted water elevations from the model run without wind forcing forecast a gradual filling of the Bay similar to that observed in the southern portions of the Bay. The difference between with and without wind forcing cases shows the extreme sensitivity of the northern portion of the Bay to the north-northeasterly wind field prior to landfall.

The northern most tide gauge (f) is located just south of the Mantoloking Bridge, the place with the largest breach during Sandy. The observed water levels show a gradual set-down in elevation prior to landfall. A few hours prior to landfall, the water elevations fall below the lower limit of the tide gauge (~ -1ft NAVD88). The water elevations predicted by the wind and pressure forced model forecast a near-constant water level prior to landfall followed by a slight rise and then drop in water elevations as the gauge reports a set-down in water elevation. After landfall both the observations and the model show a rapid rise in water elevation, reaching a peak approximately 7 hours after landfall. The rise in water elevations in the northern portion of the Bay is in response to the rapid switch from northerly to southerly winds following landfall; again showing the extreme sensitivity of the northern portion of Barnegat Bay to local wind forcing.

Verified High Water Marks (HWM) collected by the USGS[2] are used to assess the accuracy of the model in simulating overland peak water elevations generated by Sandy. Figure 19 presents the location of each USGS verified HWM used in the model validation. Figure 20 is a comparison plot of the observed and model-hindcast water elevations above ground. A prefect correlation between model and observation fall along the straight line plotted in the figure. The color bars represent the range of the accuracy of each measured HWM. Green bars are observations that fall within one standard deviation (0.63ft) of the model hindcast water elevations, purple bars are points that fall within less than two standard deviations and red bars are those that are greater than two standard deviations from the model hindcast elevation.

[2] See: https://water.usgs.gov/floods/events/2012/sandy/sandymapper.html

Forty-two verified HWM spanning the total length and width of Barnegat Bay were used to validate the model. Four of the validation points (9.5%) fall outside two standard deviations of the hindcast water elevations and eight (19%) fall within two standard deviations. The remaining 30 points (71%) are all within a standard deviation of the model hindcast. Two of the four larger deviations are located north of Manasquan Inlet indicating that overland flood flow along the northern boundary of the model grid may not be fully resolved in the model. A third outlier (point 33) is located at the head of a river boundary in the model. Four of the eight validation points that are within two standard deviations of the model hindcast are also located at the northern boundary of the model from Manasquan Inlet through Point Pleasant and Bay Head. This can also be seen in Figure 21, which compares the maximum flood height above ground predicted by the BIMMS model to the FEMA high-resolution storm surge extent map for Sandy. Overland flood flow across the interconnected lakes along the northern boundary of the model grid may not be fully resolved in the model. The majority of the remaining validation points throughout the Bay fall close to or along the 1:1 correlation line within one standard deviation. The close correlation between the verified HWM and the model hindcast water elevation provides a high confidence in the use of the model for overland inundation prediction.

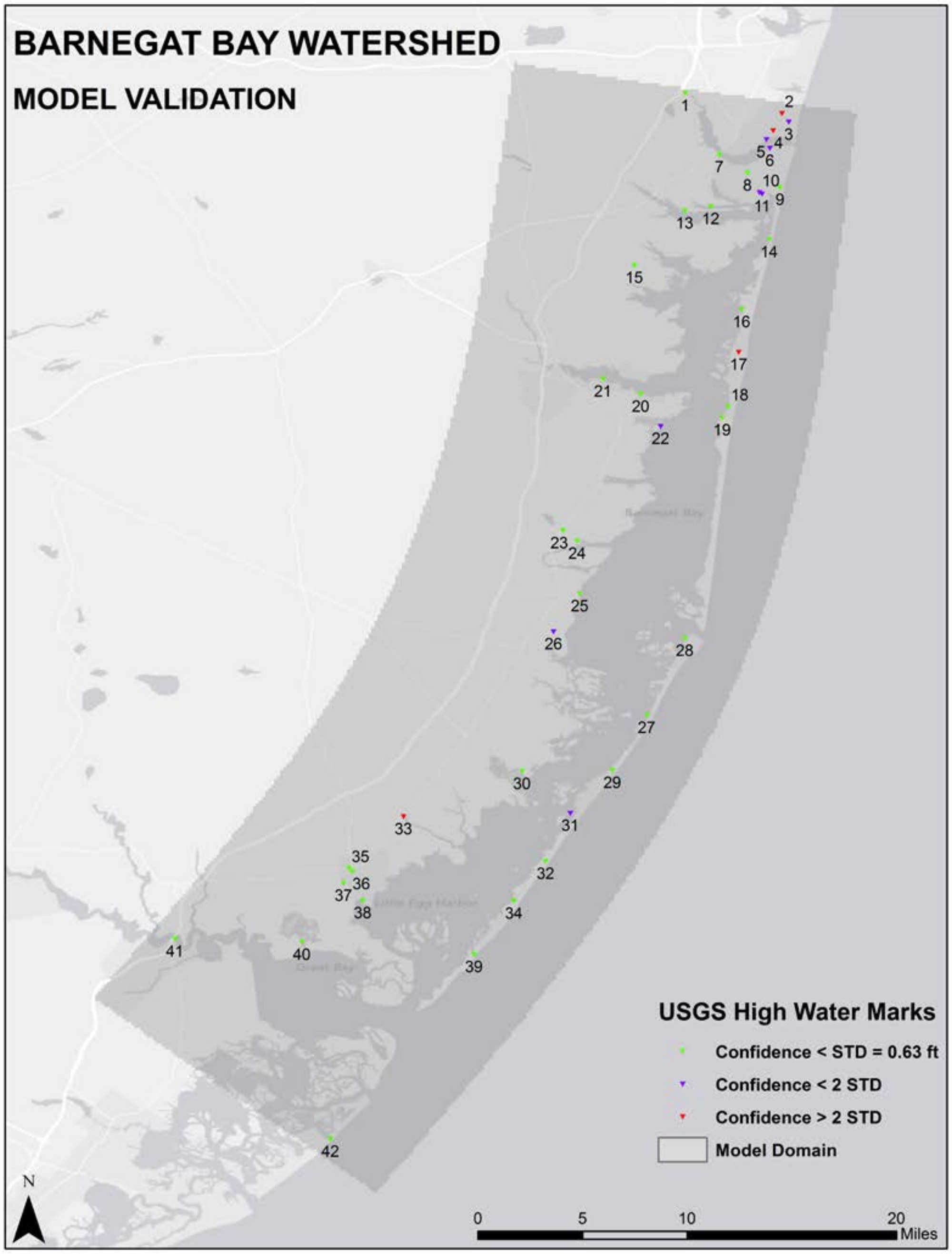

Figure 19. Location of verified High Water Marks measured by USGS used to validate model predicted overland flood depths. The colors represent the comparison with the model within 1 to 3 standard deviations shown in Figure 20 as explained in the text.

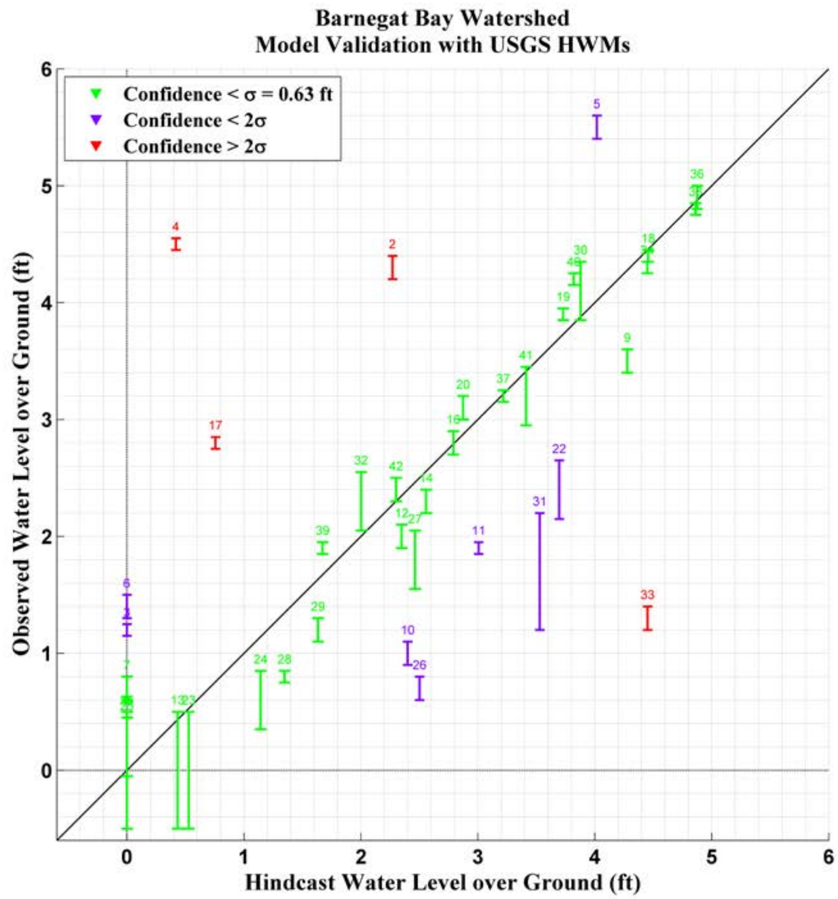

Figure 20. Comparison plot of verified High Water Marks measured by USGS and model hindcast overland flood depths. The colors represent the comparison with the model within 1 to 3 standard deviations. The numbers over each bar correspond to the numbers in Figure 19. Confidence levels are according to USGS (2013).

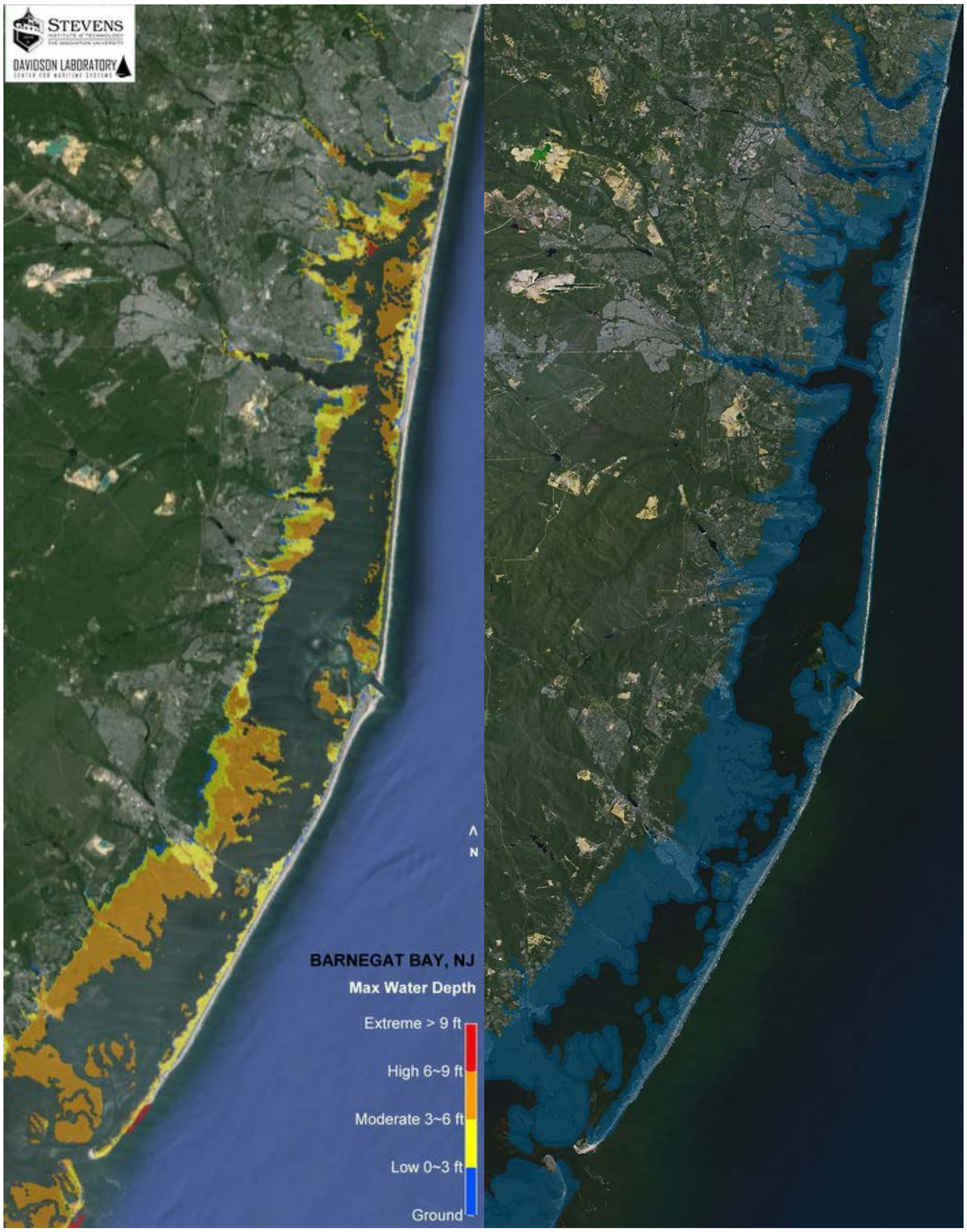

Figure 21. Comparison of Sandy storm flood extent as simulated by BBIMS (left) and as provided by FEMA (right).

In summary, the Barnegat Bay Inundation Modeling System is able to capture the spatial and temporal variation of water levels in the Bay observed during Hurricane Sandy, validating the model for use in assessing inundation mitigation options. The model shows a slight under prediction bias in water elevation which may be due to slight inaccuracies in the spatial distribution of the offshore boundary forcing. However; the validation analysis does indicate that the model can dynamically model the inundation of the land to an extent accurate enough to evaluate flood mitigation options.

Flood Mitigation Analysis

The effectiveness of both short and long-term flood mitigation options for Barnegat Bay were analyzed using the BBIMS. For each option considered, topographic and/or bathymetric elevations changes are made to represent alterations to the landforms representing the mitigation technique of interest. Each mitigation technique is evaluated under the Hurricane Sandy simulation used to calibrate and verify the model. The effectiveness of each mitigation technique is evaluated through spatial plots of water elevations differences at peak flooding. Herein we present the results of one long-term and one short-term mitigation option; a surge barrier across the Barnegat Inlet and floodwalls across breach locations in Mantoloking, respectively. A second long-term mitigation option, the restoration/creation of marsh and oyster reefs in the southern portion of the Barnegat Bay is currently under assessment in collaboration with researchers at Stockton College.

Assessment of a Surge Barrier at Barnegat Inlet

The incorporation of a surge barrier across Barnegat Inlet was achieved by creating a thin dam along the model grid elements extending 4,000 feet across the inlet and tying into the dune crest line located north and south of the inlet (Figure 22). The crest elevation of the thin dam is set above 15ft NAVD 88 to insure no overtopping of the structure occurs during the model simulation.

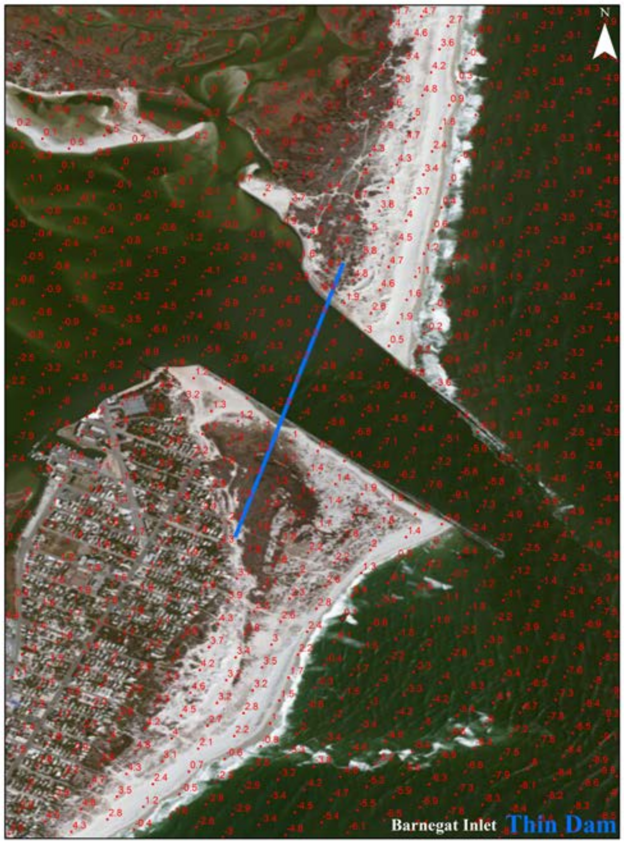

Figure 22. Location of the thin dam in the model to represent the use of a surge barrier across the Barnegat Inlet.

Figure 23 presents the peak flood water elevation changes associated with the use of a surge barrier across Barnegat Inlet. In the figure, yellow-tan colors represent no change in water elevations above ground; light green represents a decrease in water elevation of 1.0ft, aqua blue 2.0ft, dark blue 3.0ft, and purple 4.0ft. Red shades indicate an increase in water elevations of between 1.0 and 2.0ft. A quick look at the color contours indicates that the surge barrier reduces the flood elevations across a significant portion of the Barnegat Bay. North of Barnegat Inlet, flood elevations are decreased between 2 to 3 feet in the Bay and up to 4ft along portions of the shoreline. Reduction in flood water elevations of between 2 and 2.5ft extend 3.5 miles south of the inlet, and up to 1ft as far south as the Route 72 bridge into LBI. South of the bridge, up to a 0.5ft change in peak water elevation occurs along the landside but water elevations in the bay show almost no change in elevation.

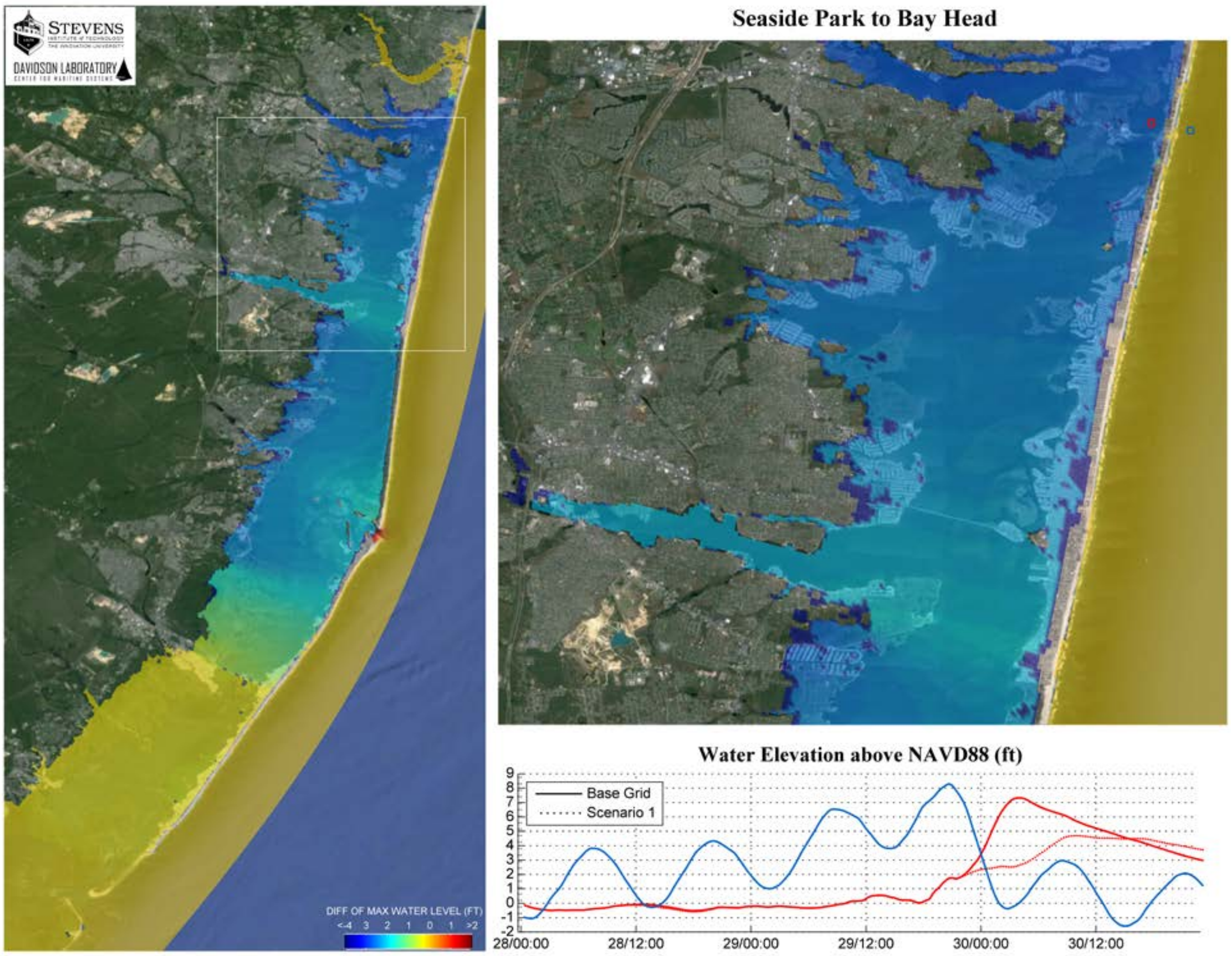

Figure 23. Peak flood water elevation difference above ground with and without a surge barrier across Barnegat Inlet.

The magnitude of the peak reduction in water elevation in the upper Bay can be seen in the time series of water elevation with (red dots) and without (red line) the surge barrier at the inlet. With the surge barrier in place, water elevations at the peak of the flooding in the upper Bay are reduced over 4.5ft from 7.25ft NAVD88 to 2.5ft NAVD88. This represents approximately a 60% reduction in the peak water elevation change in the northern portion of the Bay. The balance of the water is entering the Bay through the Manasquan Inlet to the north, Little Egg Inlet to the south and through the two breach points. The water does, however, continue to rise to slightly over 4.5ft NAVD88 approximately 5 hours after the observed peak. Figure 24 shows the water elevation change in the Inlet with the surge barrier in place. Water elevations inshore of the surge barrier are decreased 2 to 3ft in elevation and increased offshore of the barrier by 1 to 2ft. The increase in flood elevation is confined within the inlet except to the south where the model predicts about a 1ft rise in water elevation along the dune crest line a distance of approximately 50ft.

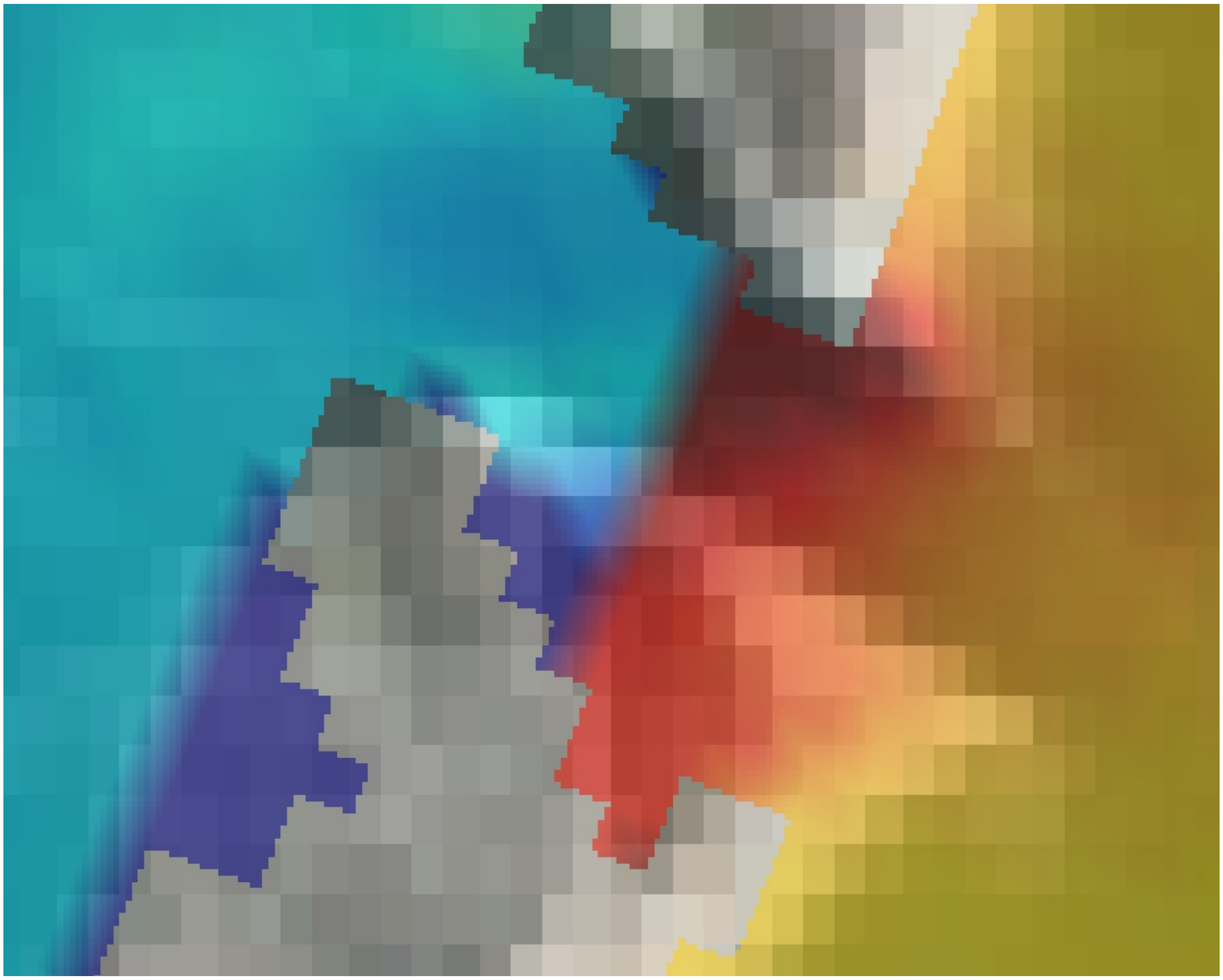

Figure 24. Peak flood water elevation difference with and without the surge barrier in place across the Barnegat Inlet.

Assessment of Floodwalls along the Northern Barrier Spit at Mantoloking

The incorporation of a floodwall in the model was achieved by creating a thin dam along the model grid elements extending 1.8 miles from Chaffey Place south to a point 400ft south of Albertson Street, along the Mantoloking oceanfront (Figure 25). The thin dam follow the six foot contour along the oceanfront and spans the breach points at Lyman St. and Herbert St. The crest elevation of the thin dam is set above 8.2ft NAVD 88 to insure no overtopping of the structure occurs during the model simulation.

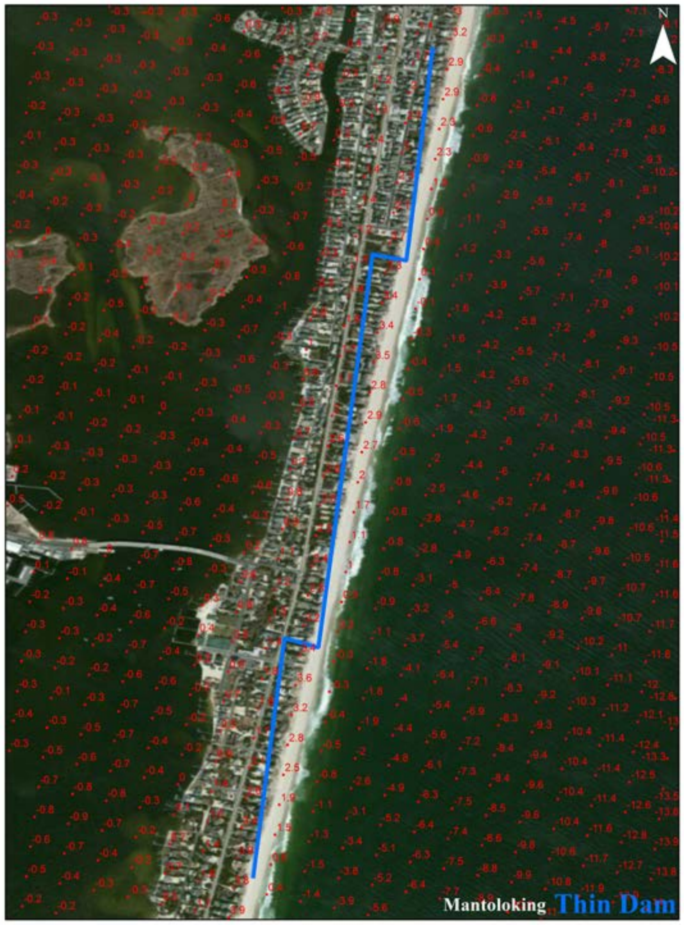

Figure 25. Location of the thin dam in the model to represent the use of a floodwall along the northern portion of the Barnegat Bay.

The effectiveness of the floodwall in preventing large-scale flooding in the Barnegat Bay is best interpreted through the use of a spatial plot of peak flood elevation differences at each model grid point. Figure 26 presents the flood water elevation changes associated with the use of a flood wall across the two breach points in the northern portion of the Bay. The color is scaled in the figure such that, here, yellow-tan represents no change in water elevations above ground, light green represents a decrease in water elevation of 0.05ft, aqua blue 0.1ft, and dark blue 0.2ft. Red shades indicate an increase in water elevations of between 0.05 and 0.1ft. From the range of colors plotted, one can quickly determine that the floodwall does little to mitigate the large-scale flooding in the Bay. North of Island Beach State Park, the floodwall decreases the observed flood elevations by 0.05ft or about 0.7%. The remainder of the model grid shows no significant change in flood water elevations due to the 1.8 mile long floodwall. The time series of bay water elevation with (red dots) and without (red line) the floodwall is plotted in the lower right corner of Figure 26. The time series shows that water entered the Bay over a two and a half hour period around the time of Sandy's landfall. Locally, by the breaches, the water elevations are reduced approximately 0.75ft by the floodwalls.

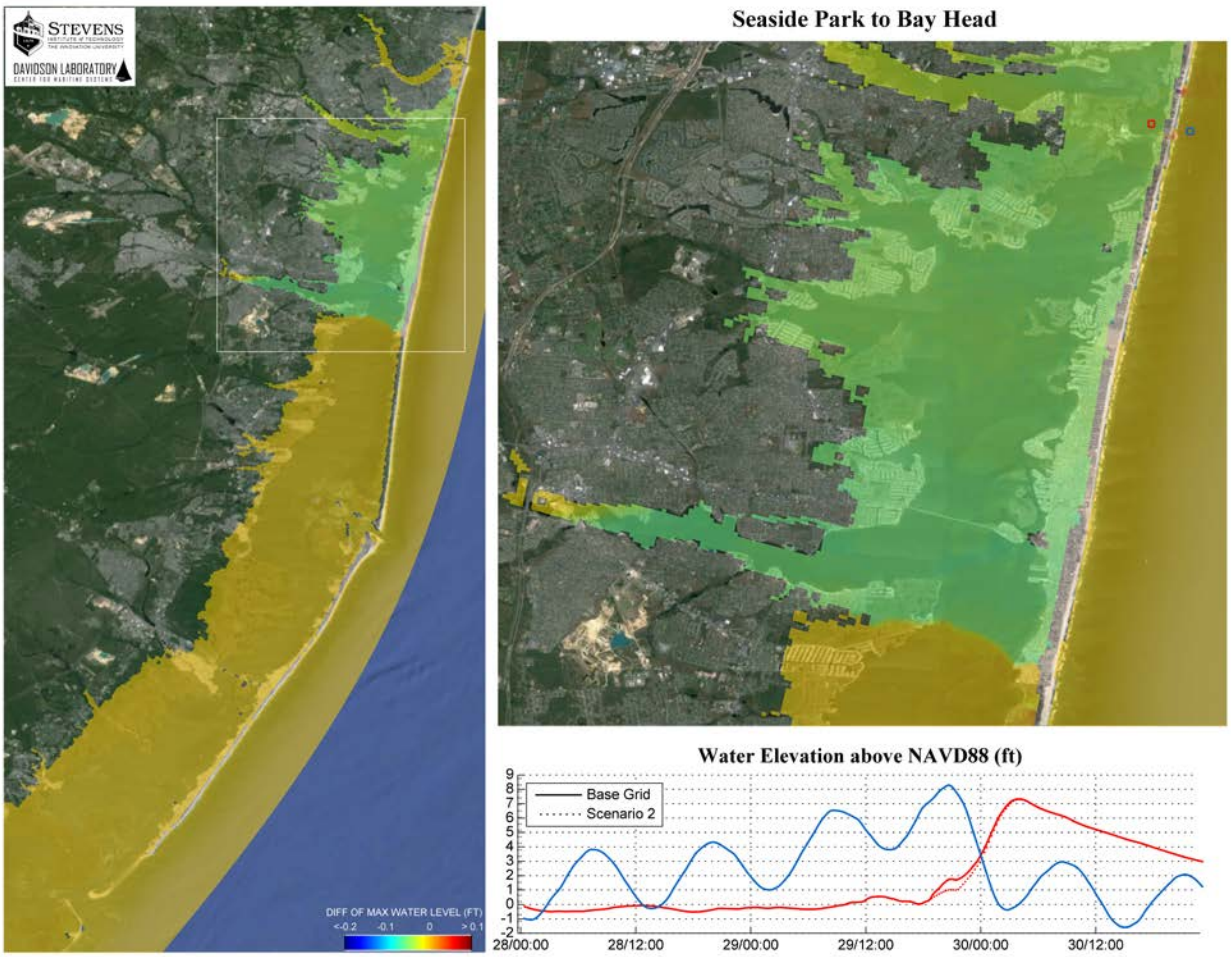

Figure 26. Peak flood water elevation difference above ground with and without a floodwall located along the northern Barnegat Bay shoreline.

Figure 27 shows a magnified view of the model grid centered on the two breach locations in Mantoloking, NJ. Within both breaches, water elevations are reduced by 0.2ft inshore of the floodwall. An increase of 0.2ft in water elevation occurs on the seaward side of the floodwall at the breach points. The increase in water level is very localized and only affects the shoreline for 100ft north and south of the breach point.

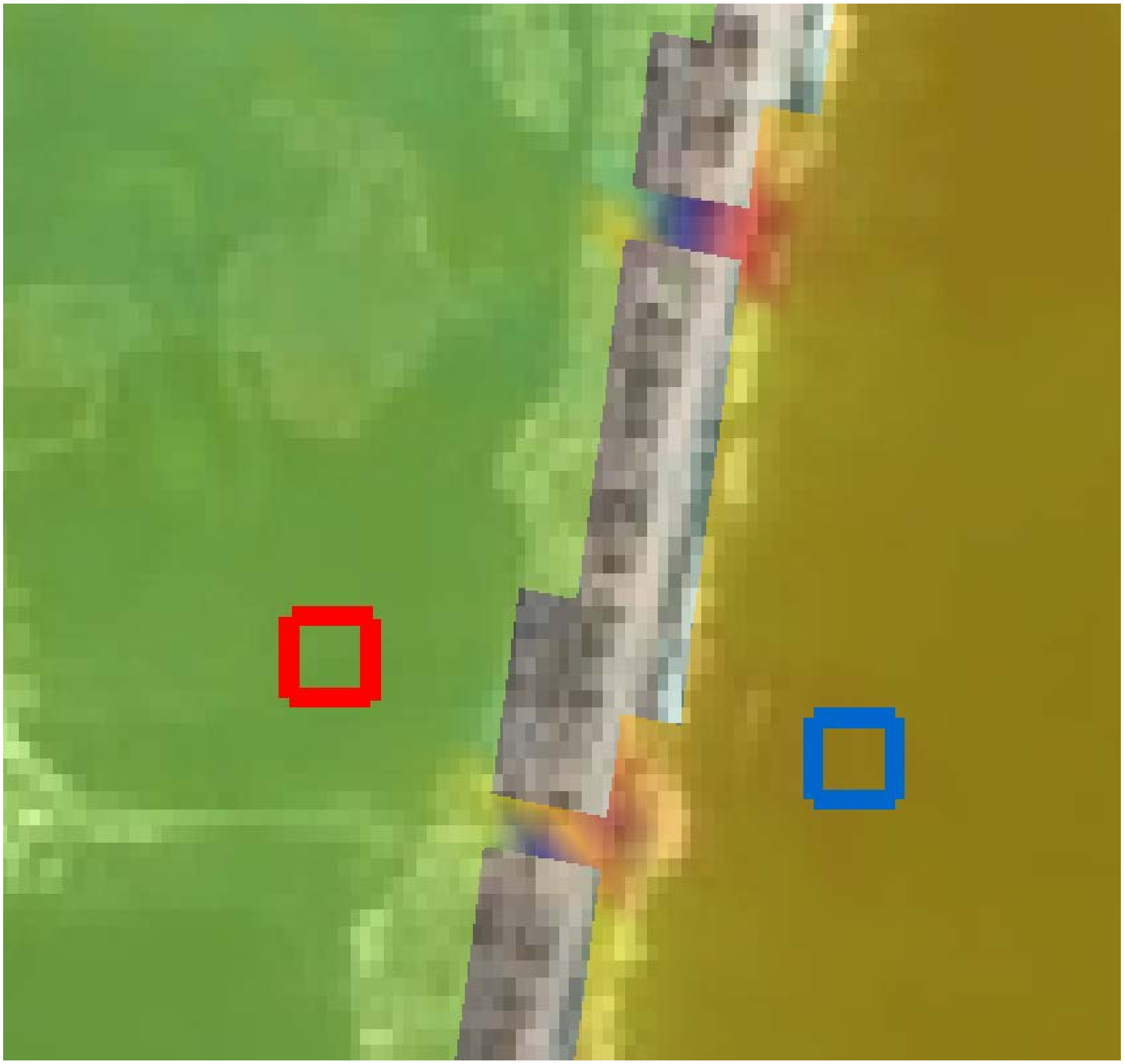

Figure 27. Flood water elevation difference with and without a floodwall at the two breach locations

The model results show that the use of a floodwall to prevent the breaching of the barrier spit at Mantoloking has a negligible effect on the water elevations and spatial extent of flooding in the Barnegat Bay due to Sandy. It is interesting to note that the 1.8 mile floodwall does reduce flood levels over approximately 20 square miles of the northern portion of Barnegat Bay.

Assessment of a Surge Barrier and Floodwall Combination

Figure 28 presents the peak flood water elevation changes associated with the use of both the surge barrier across Barnegat Inlet and the floodwall located along the Mantoloking shoreline across the breach points. In the figure, yellow-tan colors again represent no change in water elevations above ground, light green now represents a decrease in water elevation of 1.0ft, aqua blue 2.0ft, dark blue 3.0ft, and purple 4.0ft. Red shades indicate an increase in water elevations of between 1.0 and 2.0ft. In this configuration the model reduces the peak water elevations an additional 0.05ft in the northern portion of the Bay north of Island Beach State Park. The magnitude of change in peak water elevation with the combined barrier and floodwall (red dots) and just the surge barrier (red line) is presented in the lower right corner of Figure 28.

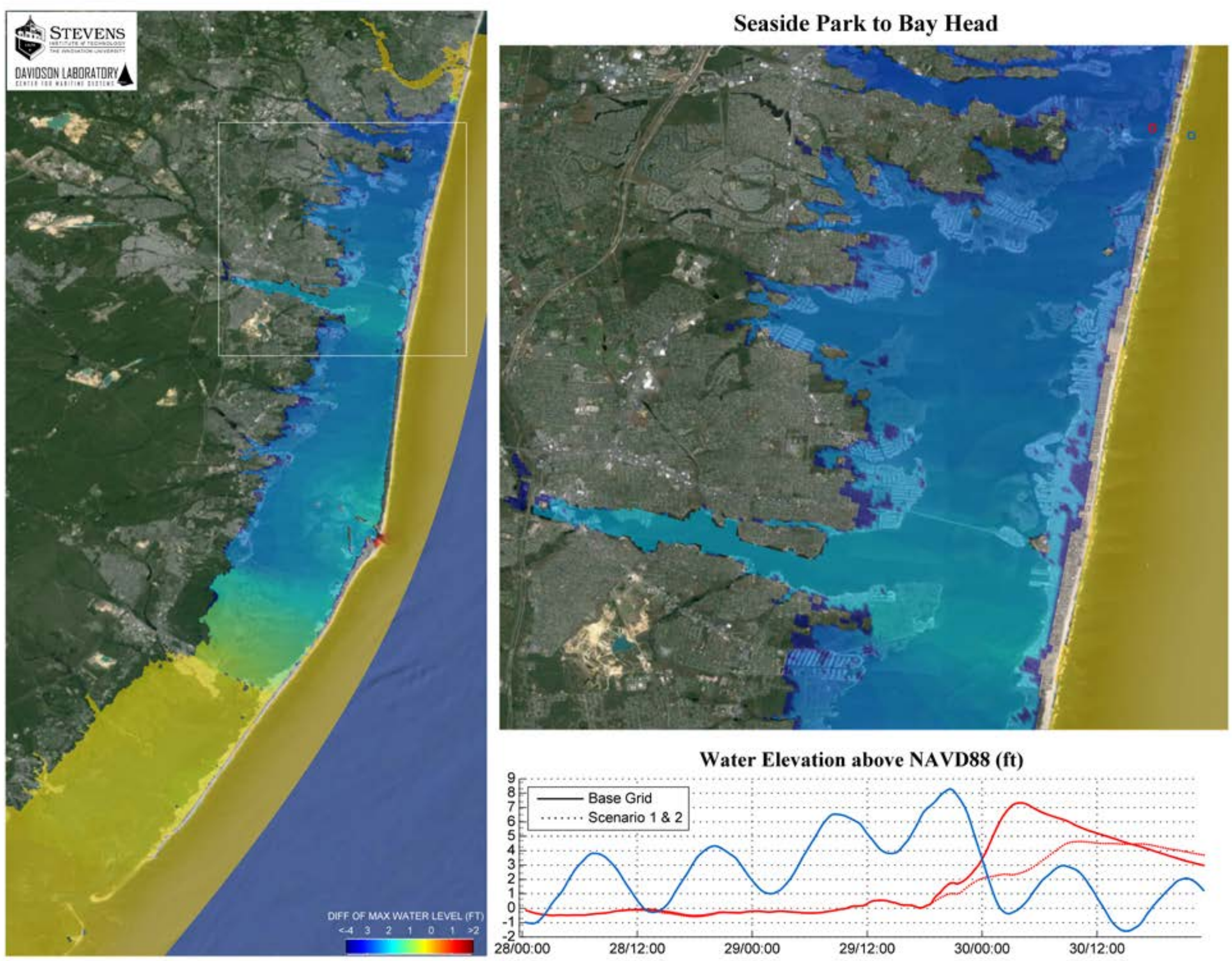

Figure 28. Peak flood water elevation difference above ground with and without a surge barrier across Barnegat Inlet and a floodwall along the Mantoloking shoreline.

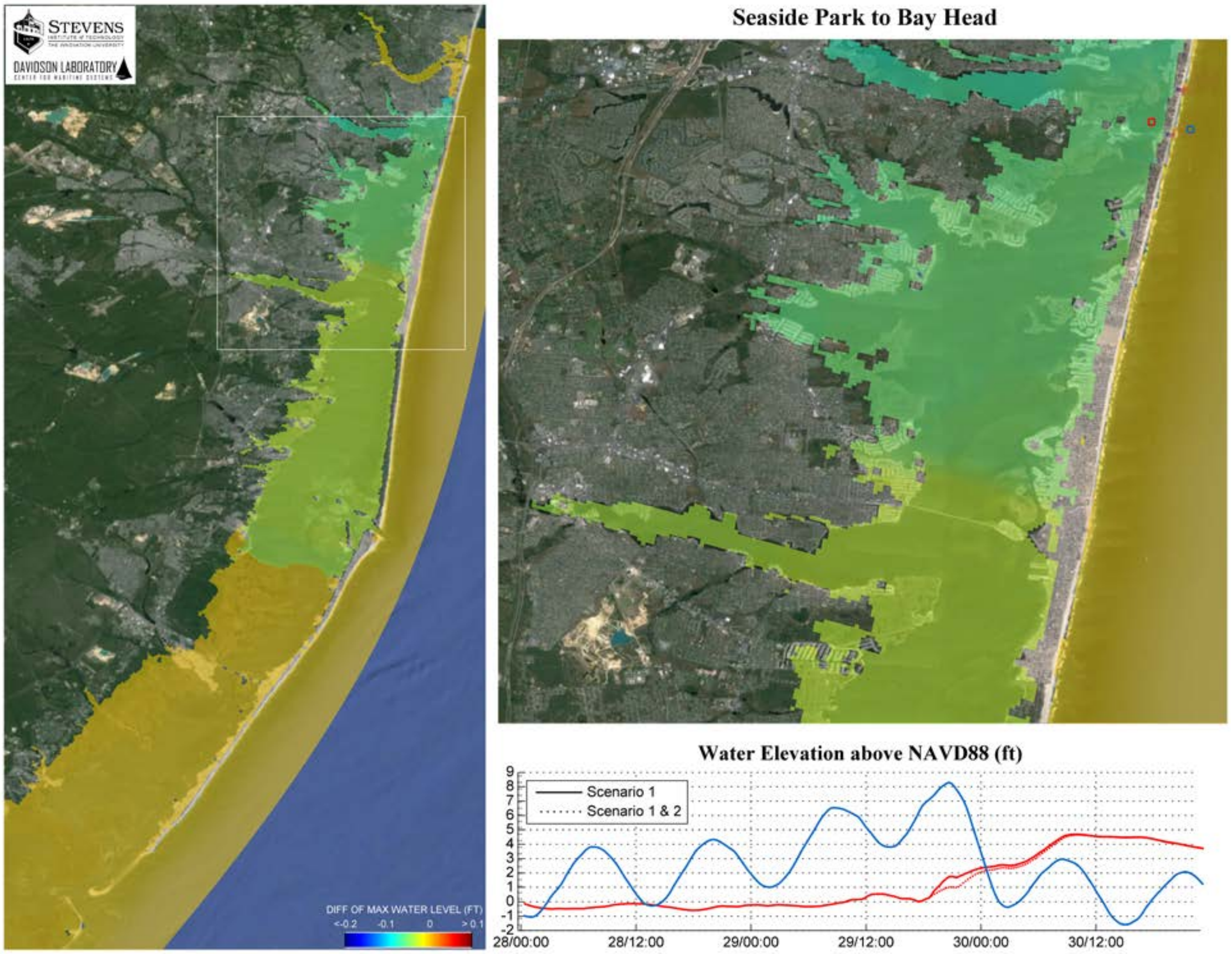

Figure 29. Comparison of the change in peak flood water elevation difference above ground with the combined surge barrier and floodwall and just the a surge barrier

A very small decrease in the rise of water occurring during the peak flood offshore of Mantoloking at landfall. The lack of floodwater entering through the breach reduces the peak Bay water elevations by approximately an additional 0.25ft, reducing the total peak by about 5 feet (Figure 28). The water level does, however, continue to rise to slightly over 4.5ft NAVD88 approximately 5 hours after the observed peak just as it did in the case with just the surge barrier alone. The combined flood mitigation does reduce peak flood elevations as compared to the surge barrier alone by 0.25 to 0.1ft from a point 3 miles south of Barnegat Inlet to the northern extent of the Bay, respectively.

Assessment of a new Mantoloking Inlet at the Mantoloking Bridge Breach

The temporary inlet created by the dune breach in Mantoloking was stabilized and filled in by the US Army Corp of Engineers (USACE) within four days from the storm. Two LiDAR missions were flown to survey topographic changes, one on November 1, 2012 by the USGS (http://coastal.er.usgs.gov/hurricanes/sandy/lidar/newjersey.php), while the new inlet was still present, and one on November 16, 2012 by USACE. As aforementioned, only a small difference in maximum flood heights was predicted by the model if a floodwall at the northern barrier spit at Mantoloking were to be constructed at the place where the new temporary inlet was created (Figures 26-27). The time series comparison in Figure 26 implies that water entered the Upper Bay from the ocean while the barrier was overtopped, as the water levels outside were higher than the ones in the Bay. As the waters rose in the bay, primarily by the water entering from the Lower Bay with only a relatively low volume entering from the Mantoloking breach, the Atlantic Ocean's waters receded towards low tide. When the falling ocean water levels dropped below the rising upper Barnegat Bay levels, some of the water exited the bay through the temporary inlet.

We have conducted a sensitivity study to determine the response of the Bay had the temporary Mantoloking inlet been present prior to the storm. Putting it another way, we seek to test what the flooding would look like if the temporary inlet was left open, and Sandy occurred again. Note however that inlet stabilization, morphodynamic evolution, and equilibration are not simulated here; Rather, post-Sandy LiDAR data were used locally to refine the model grid over the Barnegat Peninsula near Mantoloking, and the new inlet was treated as a stable 100m-wide connection of the Upper Bay to the Atlantic Ocean just north of the Mantoloking Bridge where the main breach occurred.

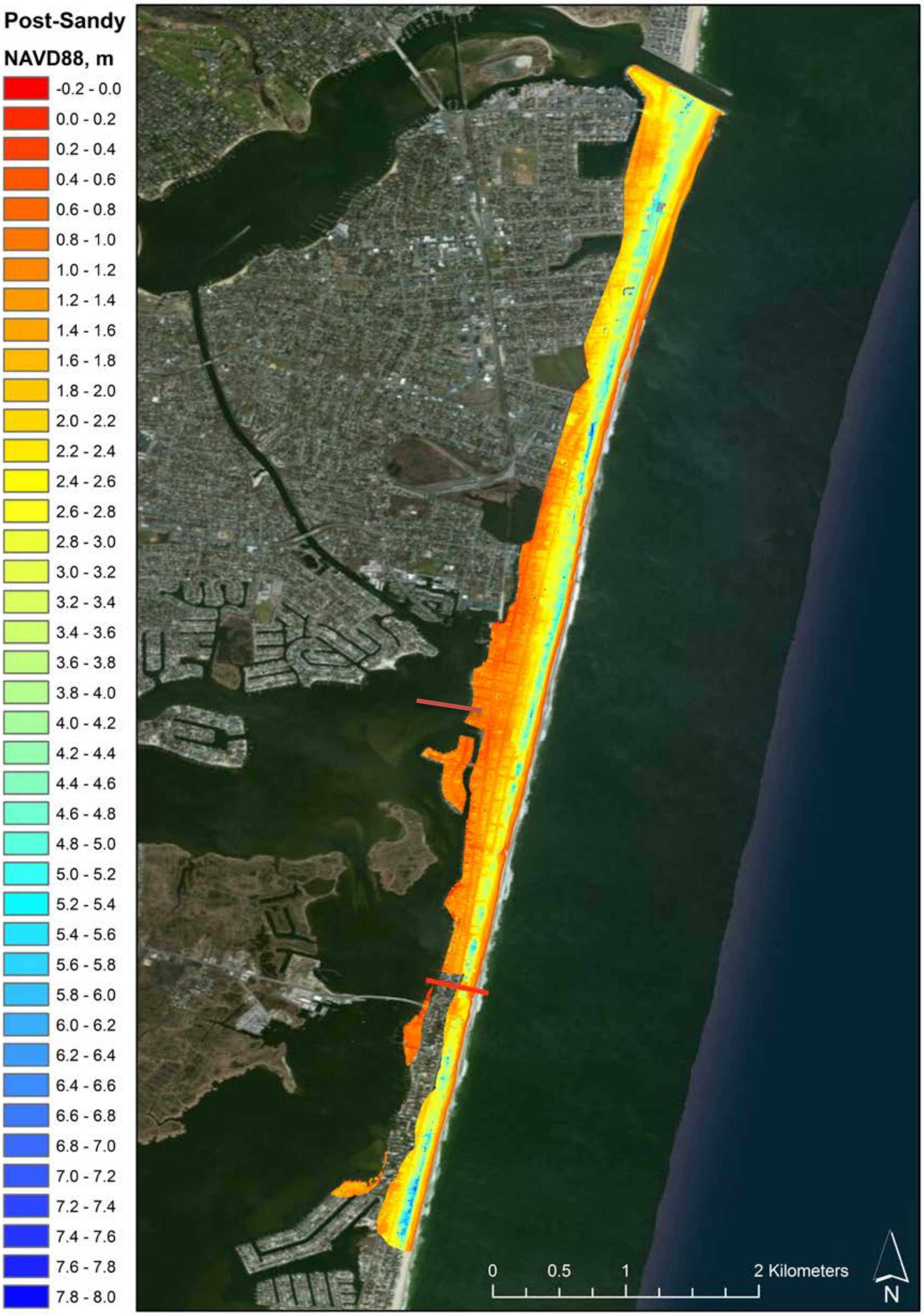

Figure 30. Part of the Post-Sandy Barnegat Peninsula topography highlighting the new inlet (red Line as modeled).

Figure 31 presents the peak flood water elevation changes associated with the presence of the new Inlet. In this figure, medium blue colors represent no change in water elevations above ground, light blue now represents an increase in water elevation of about 0.5ft, yellow 1.0ft, orange 1.5ft, and red 2.0ft or more. Dark blue shades indicate a decrease in water elevations of about 0.5ft or more. In this configuration the model increases the peak water elevations in the northern portion of the Bay between Sea Side Park and Mantoloking up to an additional 0.7ft.

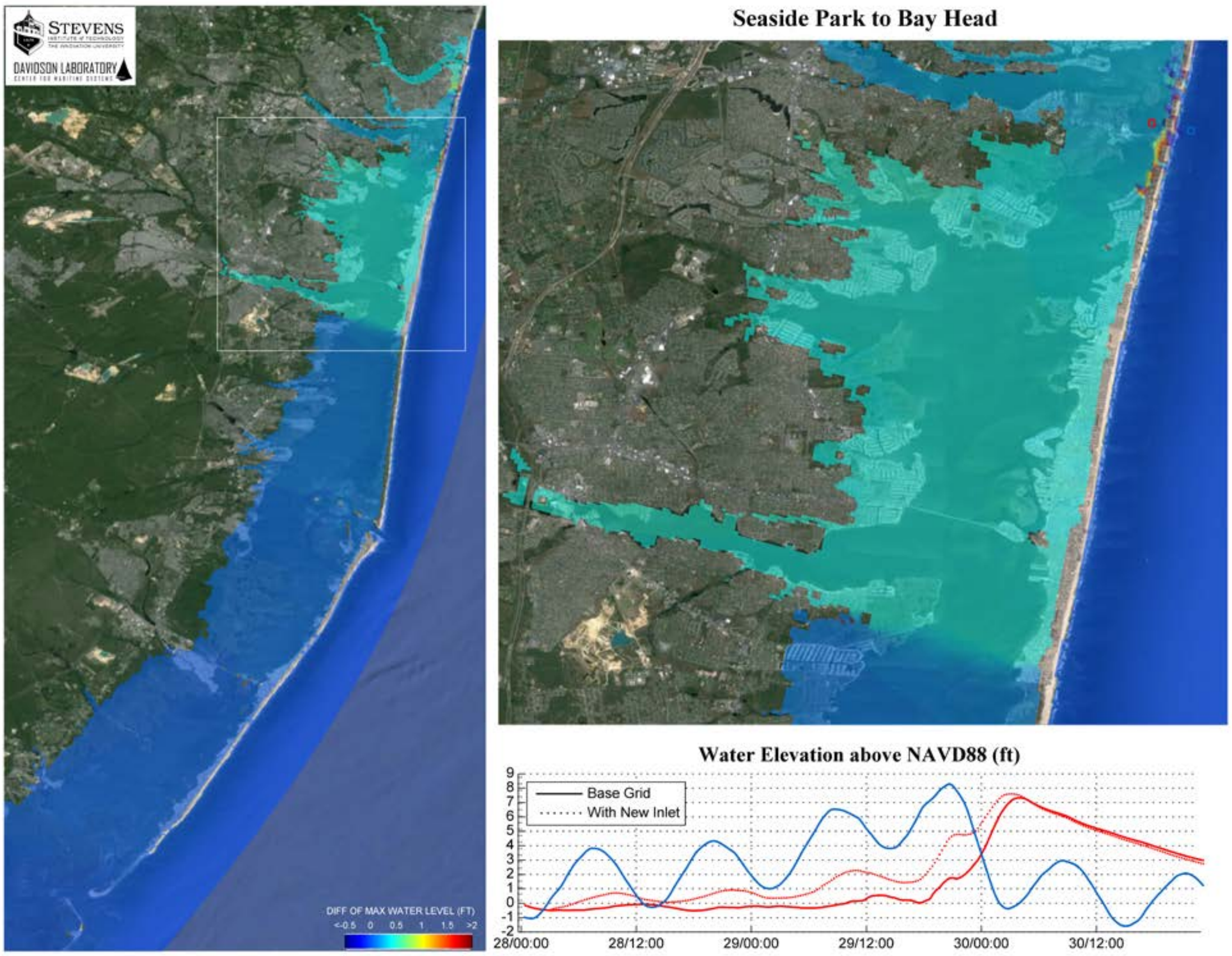

Figure 31. Peak flood water elevation difference above ground with and without an inlet in Mantoloking at the location of the main breach.

The magnitude of change in peak water elevation at Mantoloking with the new inlet (red dots) against the base case (red line) is presented in the lower right corner of Figure 31. The simulated, ever-present, direct connection of the Upper Bay to the Atlantic Ocean through the new inlet increases the tidal range in the Upper Bay, and has the net effect of pumping water into the Bay through the inlet throughout the simulation before landfall, as ocean levels (blue time series, Figure 31) are almost always higher than bay waters. After landfall, ocean levels drop below bay levels and the flow reverses through the inlet, draining some of the excess water, but with a higher peak locally by 0.4ft.

In summary, the presence of a Mantoloking Inlet would have changed the tides in the upper bay, and pumped water into it earlier, potentially creating a longer, slightly higher, but less abrupt flooding situation.

Conclusions and Recommendations

A new, high-resolution, hydrodynamic model for the Barnegat Bay estuary; including its vast intertidal areas, has been developed and validated. The Barnegat Bay Inundation Model (BBIMS) has a constant 100m resolution and is nested within the three dimensional NYHOPS model at its offshore open boundary, providing a link to upstream river flows and downstream to oceanic tidal and storm surge influences, and forced by local meteorology (surface wind and barometric pressure). Wetting and drying of land features in the model's external time step is as low as 0.1 sec in its 2D barotropic mode. This mode provides for the dynamic prediction of depth integrated flood elevations and velocities across land features during inundation events.

The BBIMS was calibrated using the NYHOPS hindcast of Hurricane Sandy. The hindcast utilized Sandy over ocean wind field and atmospheric pressure data, offshore wave and tidal boundary forcing, atmospheric heat fluxes, interior streamflow data and was validated against observed water levels and measured high water marks. A comparison against 6 water level time series measured by USGS tide gauges located in the Barnegat Bay verified that the model is able to capture the spatial and temporal variation of water levels in the Bay observed during Hurricane Sandy. A comparison against the verified high water marks found that the model is capable of hincasting overland water elevation to within one standard deviation (0.63ft) at 71% of the total water marks measured.

The verified model has been used to study flood pathways during Sandy as well as evaluate the reduction in inundation due to short-term (floodwalls in breach locations) and long-term (inlet surge barriers) flood mitigation. This analysis determined that:

1. The use of a surge barrier across Barnegat Inlet reduced peak flood elevations over approximately two-thirds of the Bay, extending 28 miles from the Route 72 bridge to the northern head of the Bay at Bay Head. North of Barnegat Inlet, peak flood elevations are decreased between 2 to 4 feet and up to 4.5ft along portions of the shoreline. Reduction in flood water elevations of between 2 and 2.5ft extend 3.5 miles south of the inlet and up to 1ft as far south as the Route 72 bridge into LBI.

2. The use of a floodwall to prevent the breaching of the barrier spit at Mantoloking has a small effect on the spatial distribution of peak water elevations in the Barnegat Bay due to Sandy. However; locally, the water elevations are reduced approximately 0.75ft by the floodwall. Sensitivity runs with the new inlet open all the time, or closed all the time, show that most of the flooding in the Upper Bay

occurred not through the breached inlet at the Mantoloking breach, but through the volume of water coming from the south parts of the Bay pushed northward by the shifting wind.

3. In combination, the inlet surge barrier and floodwall reduces the peak water elevations an additional 0.05ft in the northern portion of the Bay north of Island Beach State Park. Locally, by the breach points, the peak water elevation reduction exceeds 5ft.

Herein, we have shown BBIMS to be a valid model that can be used as a flood mitigation tool to model any desired flood mitigation option. Based on the surge barrier and floodwall model assessments preformed in this study, it is recommended that additional flood mitigation options be considered/modeled to further reduce the overland flood elevation in Barnegat Bay. It is hypothesized that a further reduction in water levels within the northern portion of the Bay could be achieved with the addition of a surge barrier at the Manasquan Inlet. Observations and the model hindcast determined that the lower third of the Barnegat Bay was flooded from water entering Little Egg Inlet. The southern end of the Bay is characterized by broad marsh areas and many small inlets and channels, excluding the use of a surge barrier as a viable flood control. Within the southern portion of the Bay, the use of wetland restoration (current research in partnership with Stockton College), oyster reefs should be evaluated to determine if the added bottom friction is effective in reducing flood elevations in the southern third of the Bay. Finally, the Barnegat Bay surge barrier model result indicates that the Route 72 Bridge constricts the flow of floodwaters form the south. The addition of a third surge barrier at the location of the bridge may provide significant flood protection for two-thirds of the Bay.

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