Hydrodynamic Modeling of Prime Hook National Wildlife Refuge

Final Report

U.S. Fish & Wildlife Service

January 24 2014

Plan Design Enable

Table of Contents

Tables

Figures

Executive summary

Prime Hook National Wildlife Refuge (Refuge) and the adjacent water bodies are important natural features along western Delaware Bay and throughout the region; they provide critical stopover sites for migratory birds and habitat for many species of fish and wildlife. Over the past several years, large portions of the Refuge's managed impoundments have reverted to saline conditions, largely due to severe storm events that caused inland flooding, beach erosion, and several overwashes/breaches along the barrier island fronting the Refuge. Because of these breaches, the Refuge impoundments have been inundated with saltwater, resulting in loss of freshwater vegetation, oxidation of organic soils, and loss of sediments. Consequently, there has been a shift from freshwater marsh to a largely open saltwater embayment that has been slow to recover. Most recently, the slow recovery of marsh vegetation was exacerbated by Hurricane Sandy. Several new breaches have opened and the existing breaches have expanded and deepened.

As a result of the pronounced changes to the Refuge, the USFWS contracted Atkins to develop a hydrodynamic numerical model for the evaluation of circulation within the Refuge impoundments for existing conditions as well as a number of potential modifications. Water levels, salinity patterns and trends from the model will be used to guide and inform restoration decisions. The USFWS plans to restore the former impoundments to a system that will provide greater resilience to future storm damage. Our modeling effort included an examination of current and potential future hydrodynamic and salinity scenarios for various restoration alternatives. Other than the existing conditions, alternatives focused on two scenarios: 1) maintaining one breach open, and 2) closing all breaches. Flooding to adjacent communities and flood levels for roadways were also considered. Modeling results for the open connection to the Delaware Bay (open breach) indicated water elevations and salinities would essentially remain the same as existing unstable conditions. The hydrodynamic model developed for this study provided a robust, detailed tool for analyzing other potential restoration alternatives as well as the breach open scenario for the Refuge. Overall, the water levels and salinities in the model results demonstrate the following key points when analyzing possible 'breaches closed' scenarios:

- Adding a main channel connecting Slaughter Canal (and thus Mispillion Inlet) to the Broadkill River and Roosevelt Inlet (via Prime Hook Creek and Petersfield Ditch) allow for greater water exchange between the Refuge and Delaware Bay.
- The increased water exchange and flow provided by this channel lowers the water level within the Refuge by reducing the amount of water 'stacked' within the Refuge management units.
- The augmented exchange increases the average and maximum salinity levels within all four management units.
- Adding secondary finger channels to the main channel successfully distribute saline water to a larger area of the Refuge than the main channels alone.
- Closing the breaches reduces storm surge levels within the Refuge by about 1.6 feet compared to existing conditions during a Sandy-type event.

The water levels and salinities from these modeled alternatives are crucial in planning and developing any restoration activities within the Refuge.

1. Introduction

Prime Hook National Wildlife Refuge (Refuge) and adjacent water bodies are important natural features along western Delaware Bay and throughout the region: they provide critical stopover sites for migratory birds and habitat for many species of fish and wildlife. The Refuge wetlands are divided into four management units, all of which have experienced major changes over the past decade in terms of habitat, sedimentation, and water circulation. Two of these management Units, II and III, were historically salt and brackish marsh habitats that were diked and managed as freshwater impoundments starting in the early 1980s. Over the past several years, portions of these impoundments have reverted to saline conditions, largely due to recent severe storm events that caused flooding, erosion, and several overwashes/breaches along the barrier island fronting the Refuge. Because of these breaches, portions of the Refuge have been inundated with saltwater, resulting in loss of freshwater vegetation (due to toxic effects of salt) and oxidation and dispersal of organic soils (due to oxidation of organic sediments via sulfates in sea water), predominantly in Unit II. The subsequent effect in Unit II, and increasingly in Unit III, has been a shift from freshwater marsh to a largely open saltwater system that has been slow to become re-established as a saltmarsh under the altered conditions. Most recently, the Refuge (marsh and shoreline) underwent significant changes due to Hurricane Sandy. Several new breaches have opened and the existing breaches have expanded and deepened.

Figure 1 presents the location of the Refuge on the coast of Delaware Bay, highlighting the four Unit designations from north to south. Figure 2 through Figure 7 are historical aerial photographs that illustrate the changes to the Refuge over time in the vicinity of the breaches. In particular, note the changes from 2007 to 2013. In 2007, there was a single overwash fan immediately north of Fowler Beach Road. By 2009, this overwash opened into a breach, and a second overwash developed south of Fowler Beach Road. By 2011, the original breach had begun to fill in, but Hurricane Irene opened two breaches south of the road. By January 2013, the original breach had closed, but Hurricane Sandy exacerbated conditions south of the road and there were four large breaches encompassing 1500 feet in a 4,000 foot [ft] stretch of the shoreline. This is largely how the Refuge stands today.

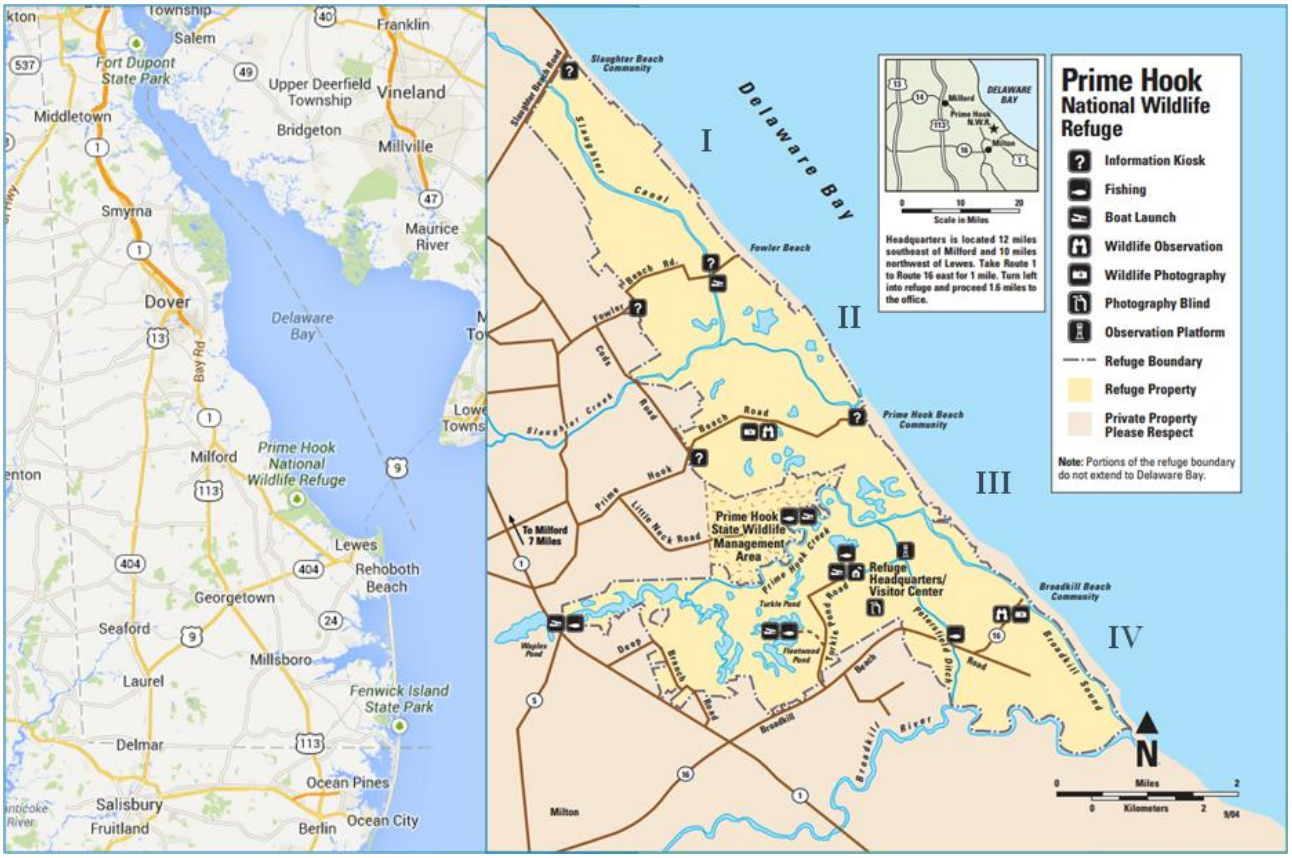

Figure 1. Location of Prime Hook NWR on Delaware Bay (left); map of the Refuge and the four management units (right).

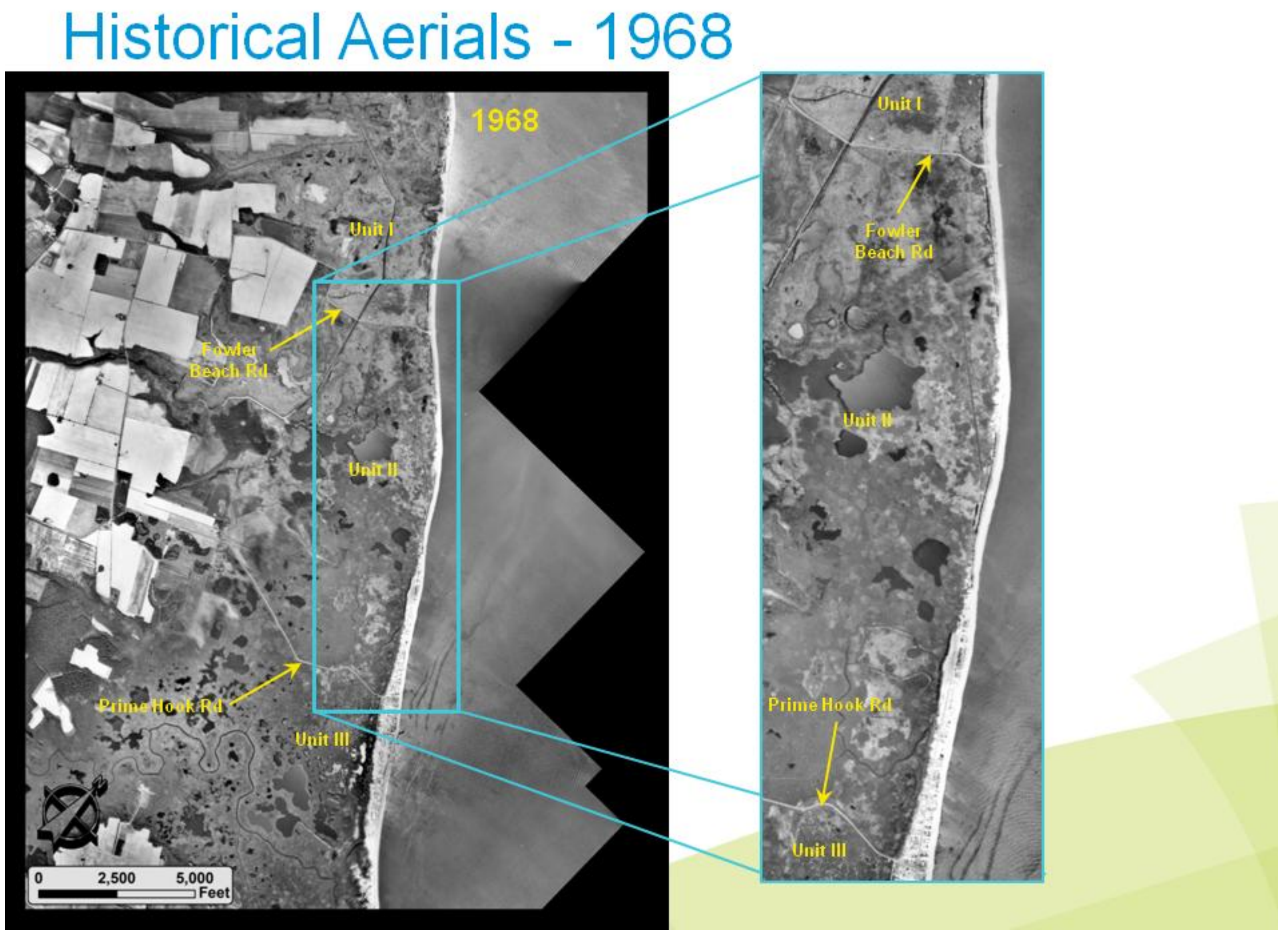

Figure 2. Historical aerial photo in the breach vicinity, 1968.

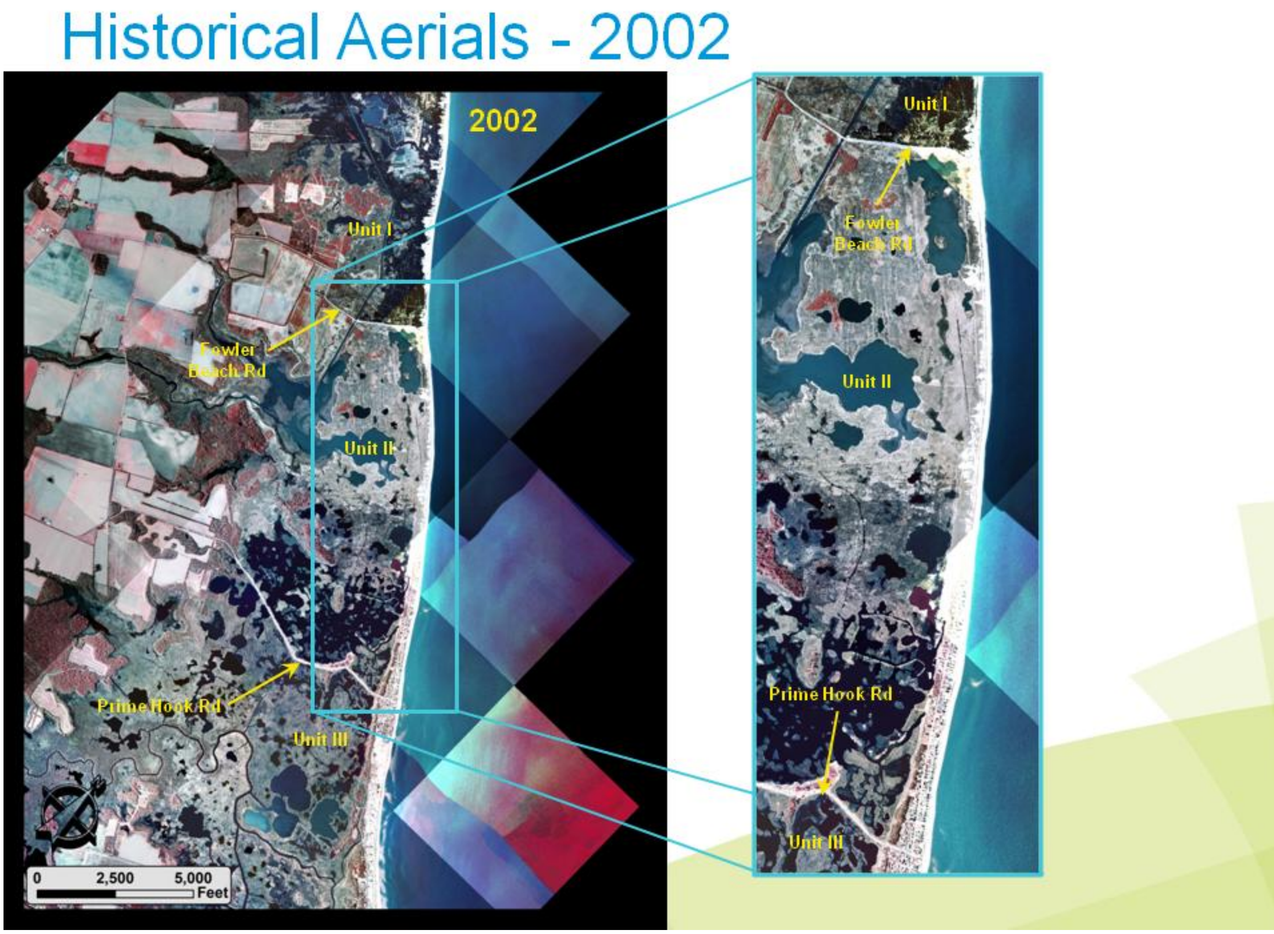

Figure 3. Historical aerial photo in the breach vicinity, 2002.

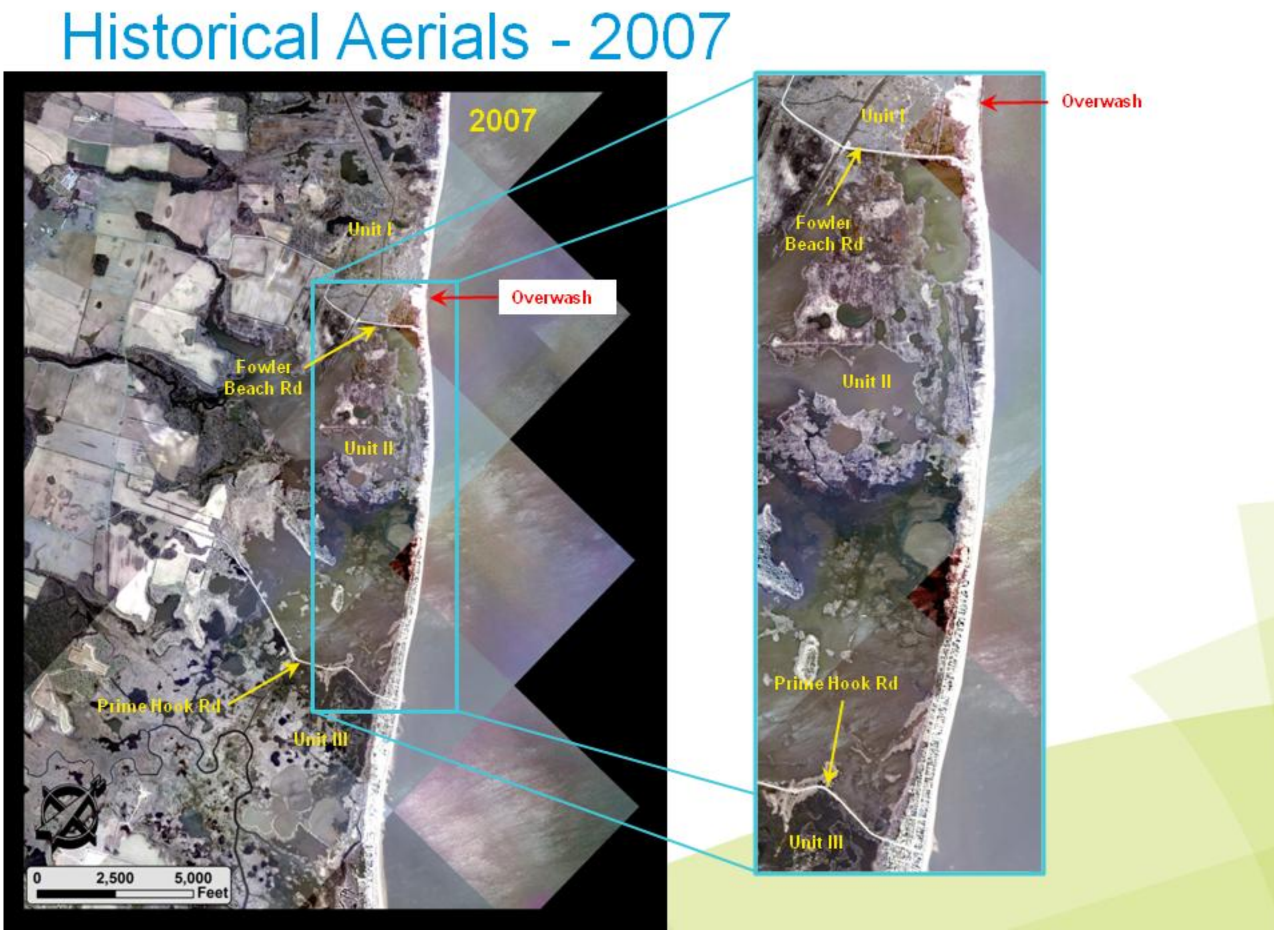

Figure 4. Historical aerial photo in the breach vicinity, 2007.

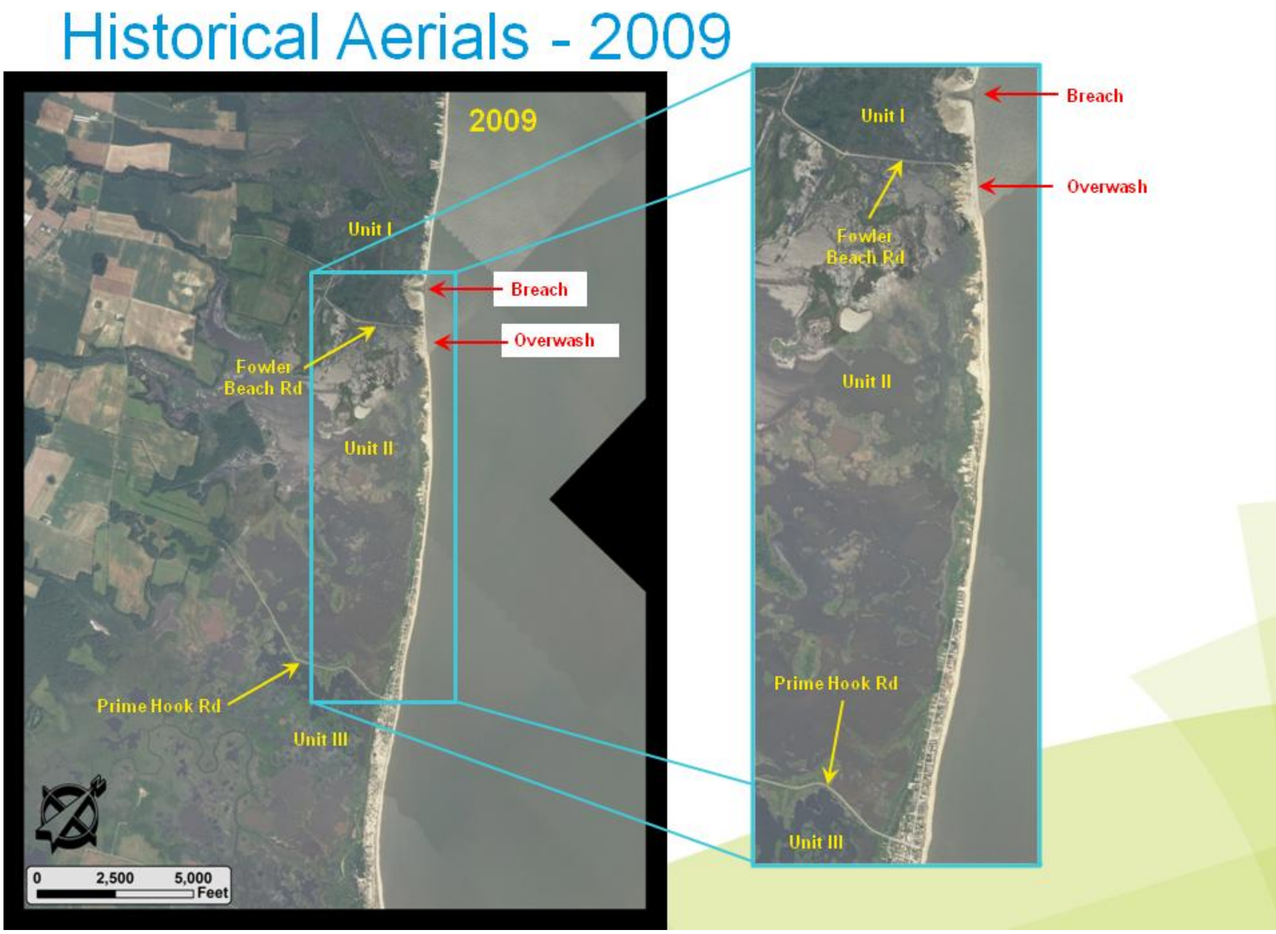

Figure 5. **Historical aerial photo in the breach vicinity, 2009.**

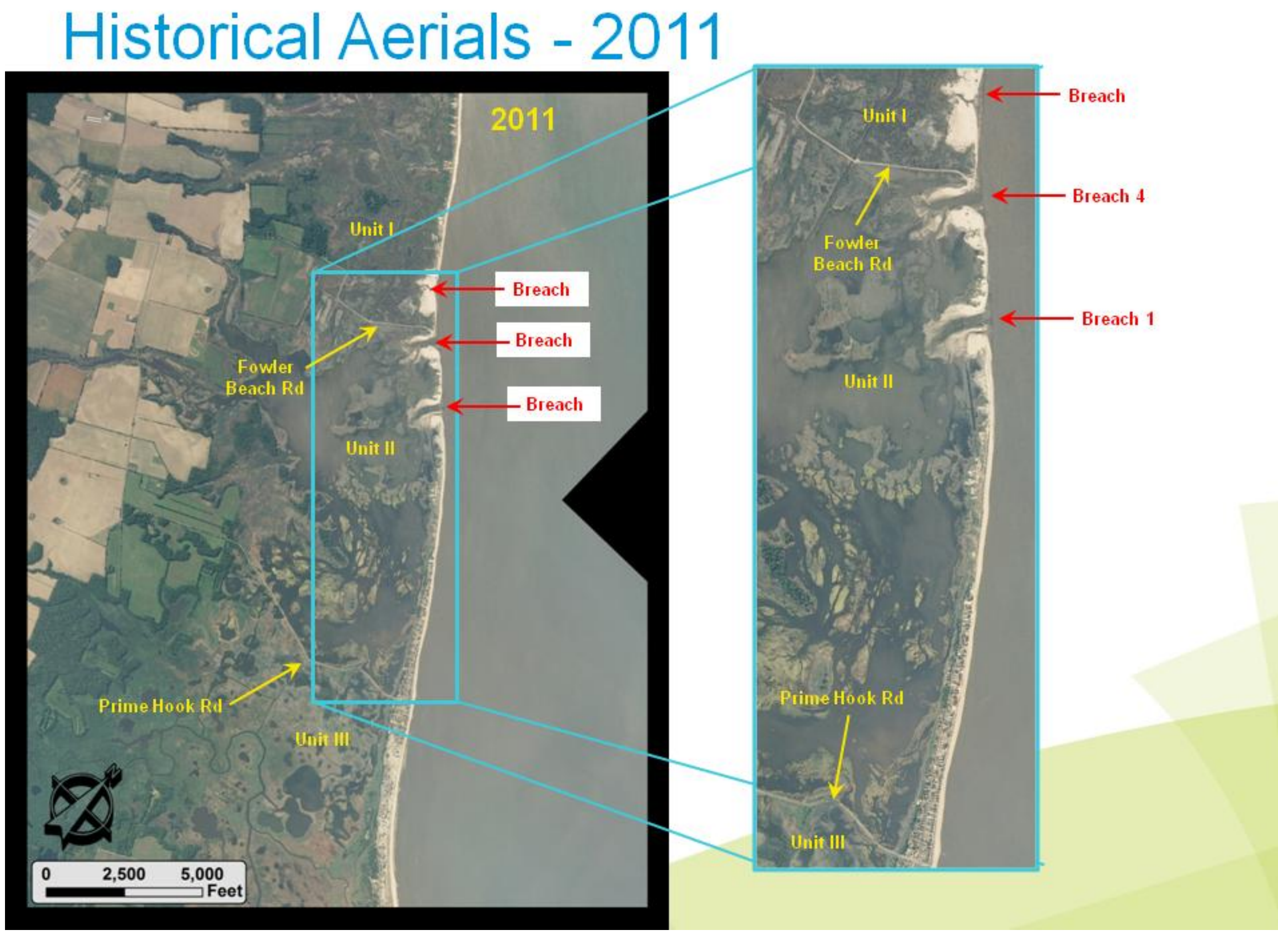

Figure 6. Historical aerial photo in the breach vicinity, 2011.

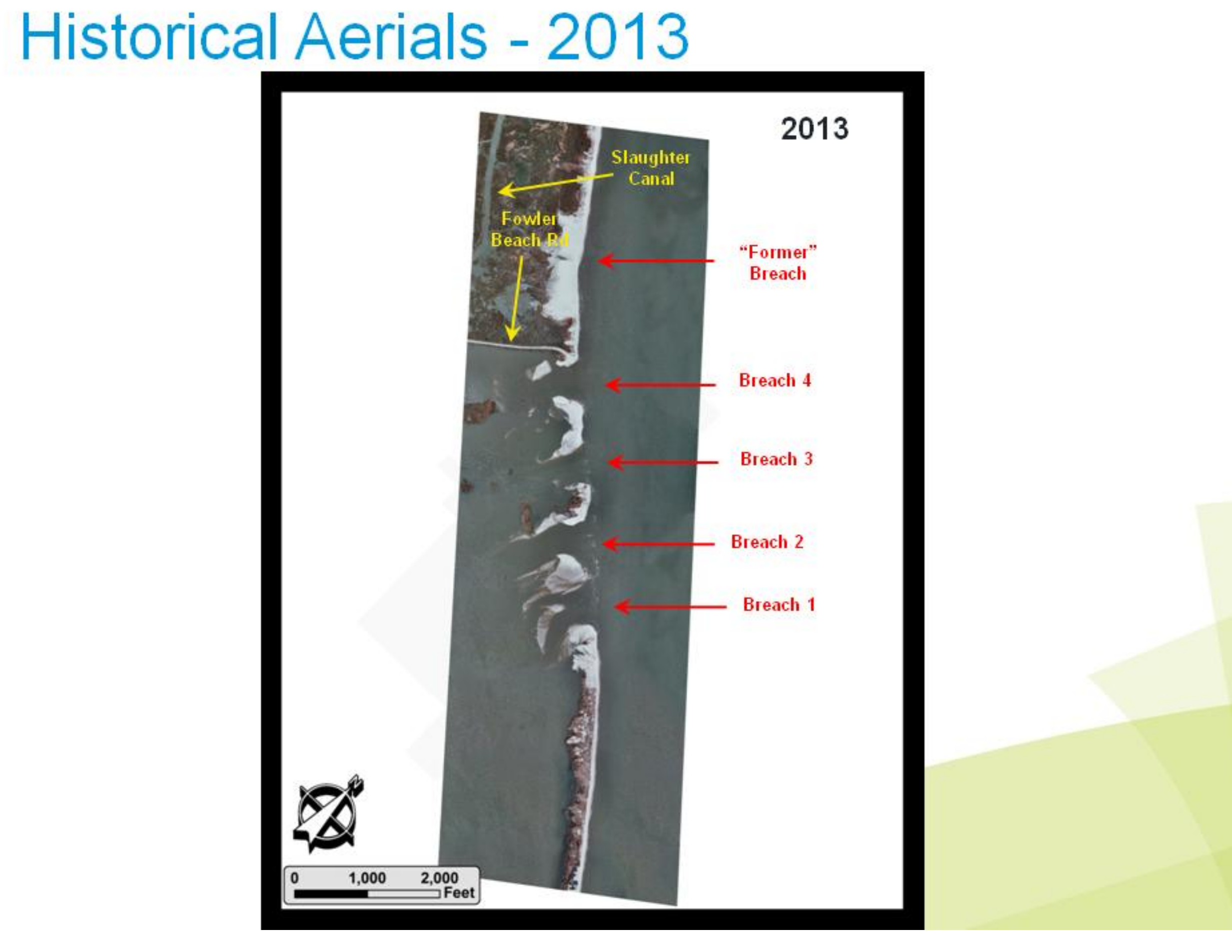

Figure 7. Historical aerial photo in the breach vicinity, 2013.

In a 2009 study produced for the Delaware Department of Natural Resources and Environmental Control (DNREC), Atkins concluded, from data analysis and a study of previous work in the region, that the shoreline of Delaware Bay is a sediment-starved beach system. In the vicinity of Prime Hook NWR, net transport is from north to south; it is likely that the original breach opening in 2009 acted as sediment sink for migrating sand and thus starved the beaches immediately south. This was, then, partially the cause of the additional breaches during subsequent storms, as the beach did not have enough sediment volume to react without failure. In the same report, a wave and circulation modeling exercise concluded that, during a storm event, the area where the breaches now exist is somewhat of a ‘hot spot’ for higher current velocities due to the hydrodynamics of the Bay and Refuge.

2. Study Purpose

As a result of the pronounced changes to the Refuge, the USFWS contracted Atkins to develop a hydrodynamic numerical model for the evaluation of circulation within the Refuge for existing conditions as well as a number of potential modifications. Water level and salinity patterns and trends from the model for a series of alternatives will be used to guide and inform restoration decisions as the USFWS prepares to transition the Refuge from an impounded freshwater marsh to a self sustaining salt/brackish marsh.

The USFWS plans to restore the former impoundments to “pre-impoundment” conditions that will provide the edaphic features needed for the development of more natural plant communities, thus providing for greater resilience to future storm damage. Our modeling effort included an examination of current and potential future hydrodynamic and salinity scenarios for various restoration alternatives. Flooding to adjacent communities and flood levels for roadways were also considered.

The main body of this report includes a condensed review of the model development performed in this study. For a more detailed discussion of the data, model development and model results, see Appendix A.

3. Existing Data

Existing measured data was used to develop the model domain and the forces that drive water circulation. The primary elements of a numerical hydrodynamic model are as follows:

- Model domain: the region of real-world space that the model encompasses.
- Model grid: a ‘mesh’ overlying the model domain that defines each point of computation. At each point on the grid, bottom elevation, water level, salinity, and any other parameters are defined.
- Model boundary: the ‘edge’ of the model domain, beyond which no computation takes place. Model boundaries can take several forms, called *boundary conditions* or *boundary forcings*. A *closed* boundary is essentially a wall, which allows no water to flow in or out of the domain. This is used at a shoreline or elevation contour to limit the size of the model domain. An *open* boundary allows the free flow of water, but must be prescribed some forcing condition to define how this flow occurs. This includes tidal and storm surge fluctuation, freshwater or saltwater inflow, and wind stress.

3.1. Bathymetry and Topography

In order to develop a numerical model that represents real-world physical conditions as accurately as possible, a detailed and up-to-date elevation data set is crucial. To this end, a number of existing bathymetric and topographic data sets were used in the model creation, in addition to survey and LiDAR data collected as part of this effort:

- A Digital Elevation Model (DEM) for Delaware Bay, created for the updated ADCIRC model for FEMA Region III (Forte, 2011)
- The Sussex County, DE topographic DEM, developed by the Delaware Geological Survey (2005)
- Point survey data collected within select water regions of the Refuge by DNREC (2012)

Survey and LiDAR data of the breaches and surrounding areas, collected by VanDemark & Lynch, Inc. (VDM) as a part of this effort (2013). These sources were merged into a single elevation data set for use in the model. Care was taken to ensure that small but important features within the Refuge, such as channels and roads, remained well-defined. Where necessary to preserve these features, elevation points were manually edited based on the best original source data.

3.2. Water Levels and Salinity

The hydrodynamic model incorporated extensive measurements of water level and salinity across a large expanse of the domain. Long-term tide gauge data pertinent to the modeling effort was available from ten sites within the Atlantic Ocean, Delaware Bay, and the Delaware River. At many of these gauges, a complete set of harmonic tidal constituents (component, amplitude, phase, and speed) were available in addition to the measured data. A harmonic constituent represents a single, periodic variation in the relative positions of the Earth, Moon, and Sun, and the combination of all harmonics at a location describes the gravitational tide in that area. These harmonic constituents are useful when a ‘synthetic’ tidal signal, free of influence from winds, inflows, and other outside factors, becomes useful.

In addition to the NOAA gauges, there were a total of nine locations within the Refuge that had recorded water levels and salinities from as early as October 2010 up through November 2012. These data were collected by USFWS and DNREC.

3.3. Wind and Freshwater Inflow

In addition to tides, wind and freshwater inflow data were also used to drive the numerical model. Measured hourly wind speed and direction is available at NOAA's NDBC station 44009, 26 nautical miles southeast of Cape May, NJ (38.461° N, 74.703° W), from 1984-present.

For Delaware Bay as a whole, the two major freshwater influences are the Delaware River itself at Trenton, NJ, the upstream limit of tidal influence, and the Schuylkill River near Philadelphia, PA. The United States Geological Survey (USGS) maintains flow gauges for each of these rivers; Station 01463500 (Delaware River at Trenton, NJ) and Station 01474500 (Schuylkill River at Philadelphia, PA).

Within the Refuge, the two main freshwater inputs are Slaughter Creek and Prime Hook Creek. The USGS Streamstats application was used to develop 'base' and 'bank full' flow rates for these creeks based on a watershed analysis. For Slaughter and Prime Hook Creeks, base flow was estimated to be 21 cubic feet per second [cfs] and 79 cfs, respectively, while bank full flow is twice that, or 42 cfs and 158 cfs, respectively.

4. Model Development

Delft3D was selected as the modeling platform for this study, based on the need for a high-resolution numerical model to estimate water levels and salinities within the Refuge for a number of different alternatives, as well as the capability to include possible sediment transport, morphology, and water quality studies in the future. Delft3D is a two- or three-dimensional hydrodynamic model that operates on rectilinear or curvilinear grids, for which hydrodynamics can be computed much more efficiently than unstructured, finite-element domains. It allows for the linkage of multiple domains, highly variable domain resolution, and sub-grid scale features. The result is a very efficient model with very little 'wasted' resolution in areas outside the location(s) of primary interest.

The model domain spans an arc in the Atlantic Ocean between Atlantic City, NJ and Ocean City, MD up Delaware Bay to Trenton, NJ, in order to be able to apply measured data at all significant forcing boundaries. A small portion of the Schuylkill River is also included. The land boundary follows the shoreline for the entirely of the model domain except for the subdomain surrounding the Refuge; here, the upland limit is the +13 ft (4 meter [m]) NAVD88 contour. The grid ranges in resolution from 2.5 miles [mi] (4 kilometers [km]) in the Atlantic to 33 ft (10 m) within the Refuge and includes approximately 2 million elements.

The merged bathymetric data set described in Section 3.1 was interpolated to the grid within the Delft3D user interface. After interpolation, important features within the Refuge such as roads and channels were manually added to the grid in locations where the interpolation process significantly smoothed and/or altered measured elevations. In this way, these features are still well-represented within the model. Culverts that cross underneath the roads at multiple locations were modeled by assigning a lower elevation to the closest grid cell so that water could flow between Refuge Units. The water control structures within the Refuge at Fowler Beach Road, Petersfield Ditch, and Prime Hook Creek were modeled as 2D weirs with their dimensions tuned to best replicate the measured water levels during the calibration period.

Figure 8 illustrates the model grid for the entire domain, while Figure 9 shows the level of grid detail within the Refuge. The bathymetric contours for the entire domain are shown in Figure 10.

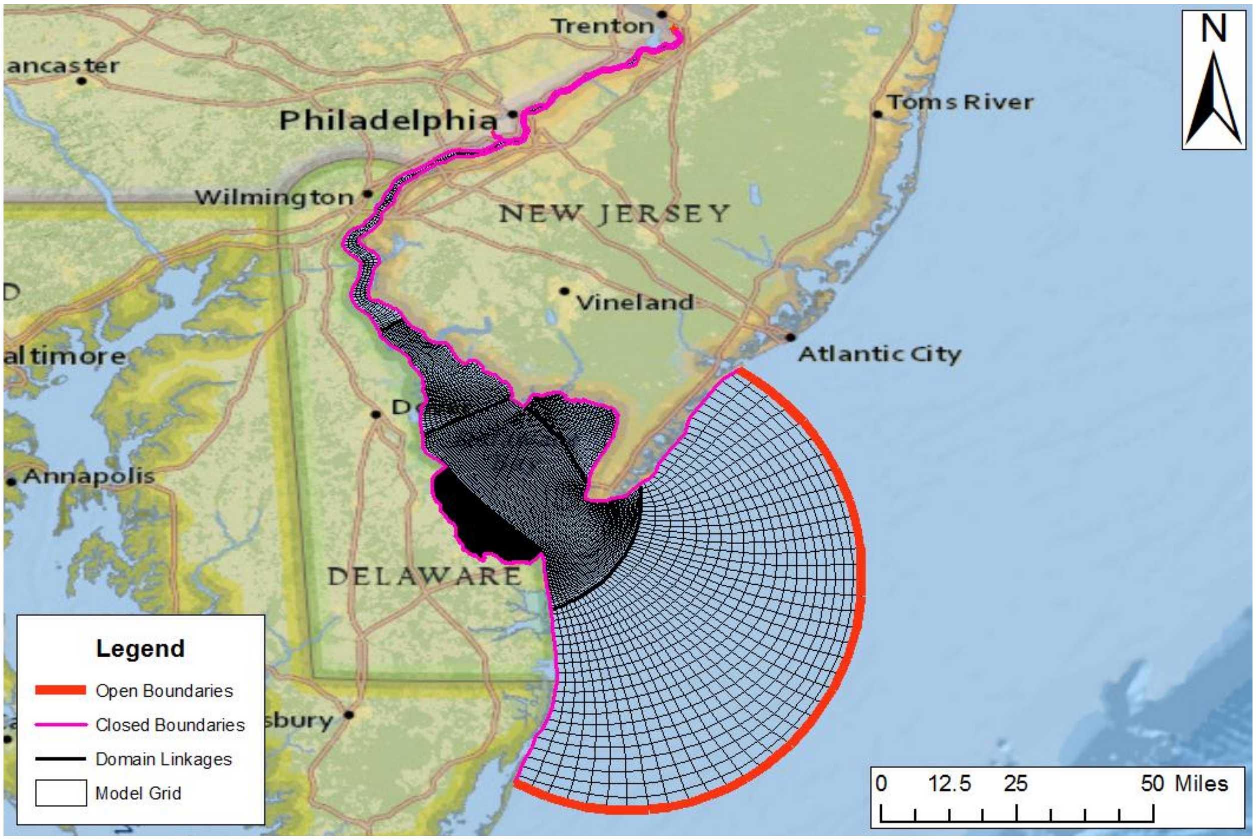

Figure 8. Model grid resolution for the entire model domain.

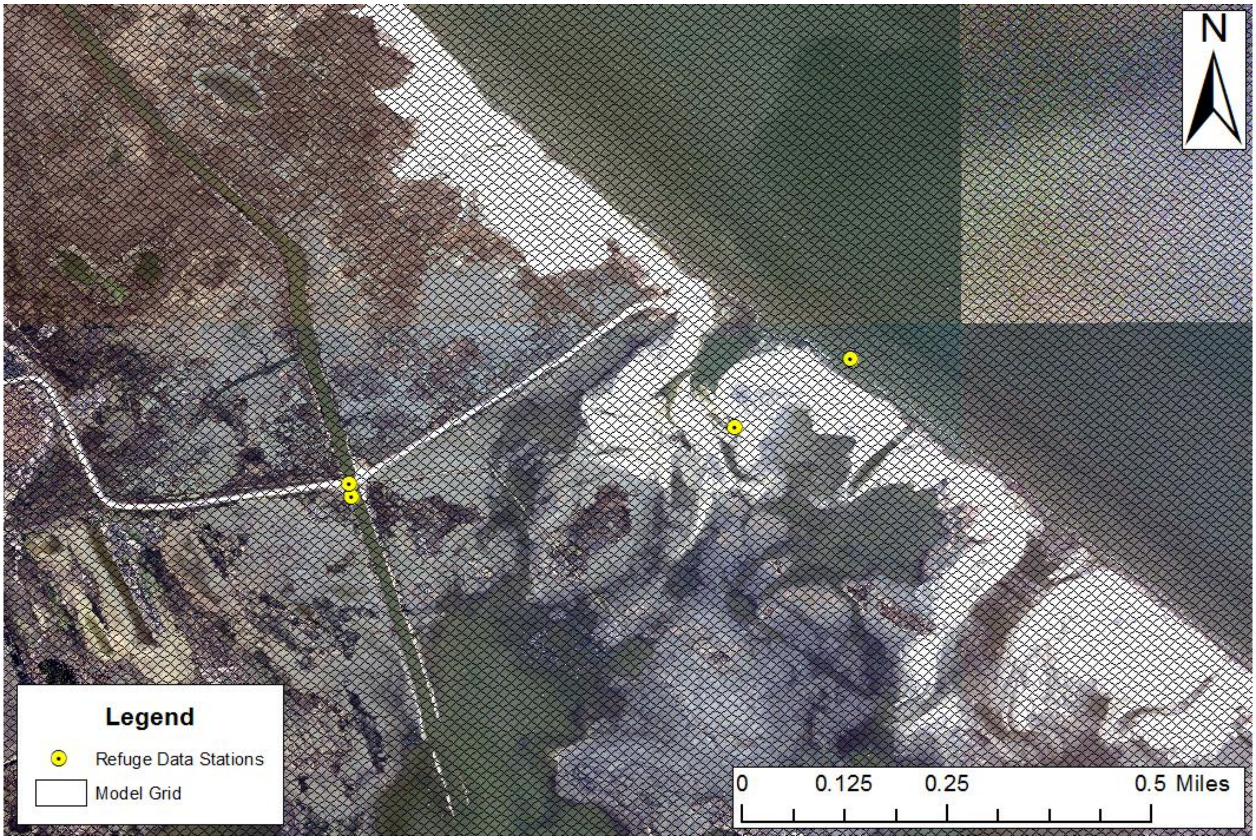

Figure 9. Model grid resolution for the Refuge.

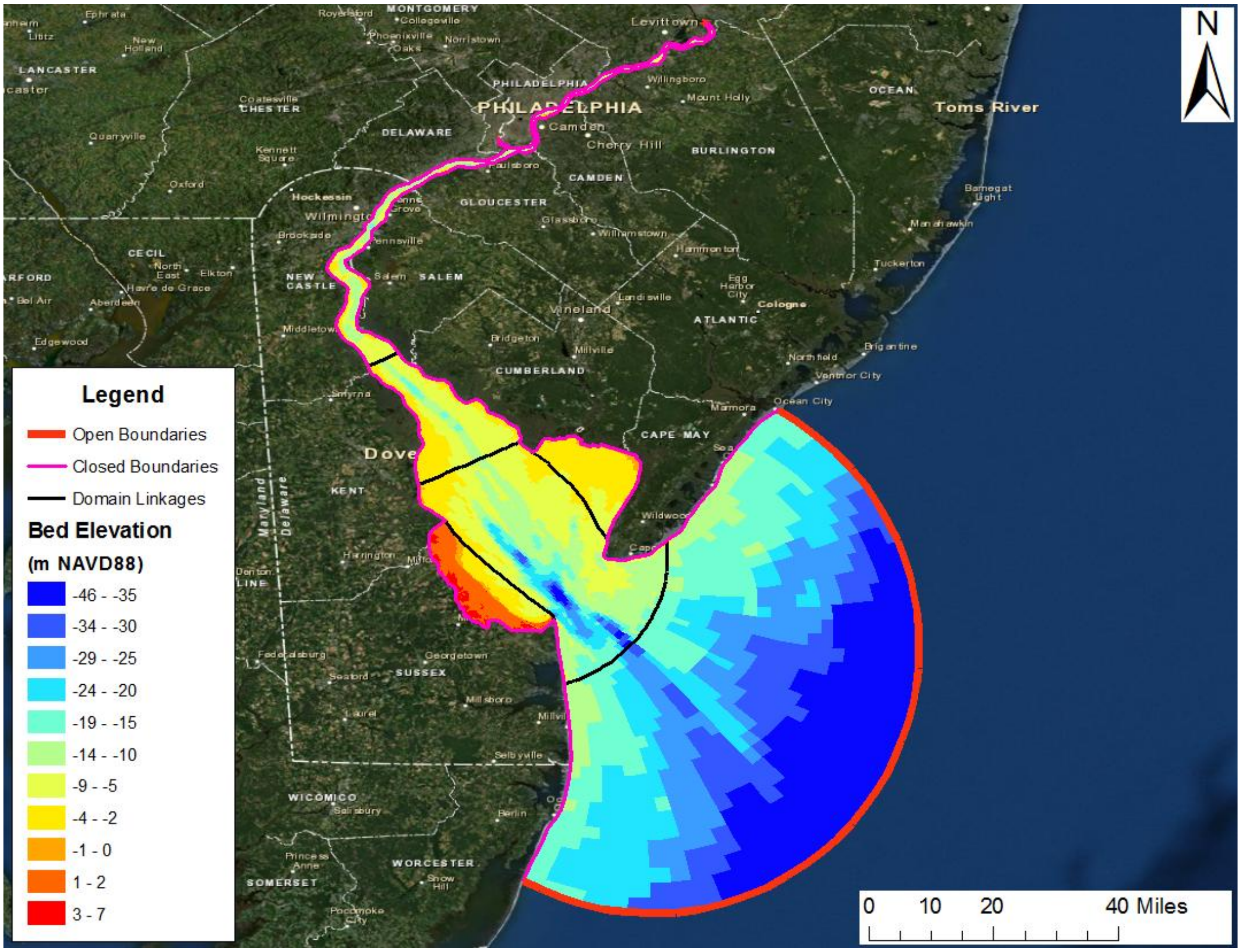

Figure 10. **Bathymetry for the entire model domain.**

5. Model Calibration and Validation

Driving factors, or variables, used to force the hydrodynamics of the model were a function of the type of model being run. During calibration and validation, the goal was to use available data to adjust model parameters to best replicate measured water levels with model results. Therefore, measured data were used to drive the model.

For calibration/validation, tidal forcing was applied along the offshore boundary of the domain by using the NOAA measured water level time series for the time period of interest at Atlantic City, NJ and Ocean City, MD and interpolating between the two time series along the arc. Freshwater inflows were applied at the two upstream limits (the Delaware and Schuylkill Rivers) using the USGS daily discharge rates as time series. A time series of wind velocity and direction from NOAA station 44009 was applied uniformly over the domain to account for wind effects.

Two primary model parameters were adjusted to obtain the best fit with measured data; first was the grid resolution, which affects the level of detail, runtime, and output file size, and second was the bottom friction formulation and value. Two time periods were examined. The grid and friction were varied while running the model for an 8-day period surrounding the peak of Hurricane Sandy until modeled water levels matched measured data to an acceptable degree. With these same parameters, the model forcing was changed to a 12-day period post-Sandy, from 11/21/12 to 12/03/12, to ensure that the calibrated model was useful for normal tidal as well as storm conditions. Measured and modeled water levels were compared at the stations located in Delaware Bay and the Refuge from NOAA, DNREC, and USFWS. The water level calibration locations in Delaware Bay and within the Refuge are mapped in Figure 11 and Figure 12, respectively.

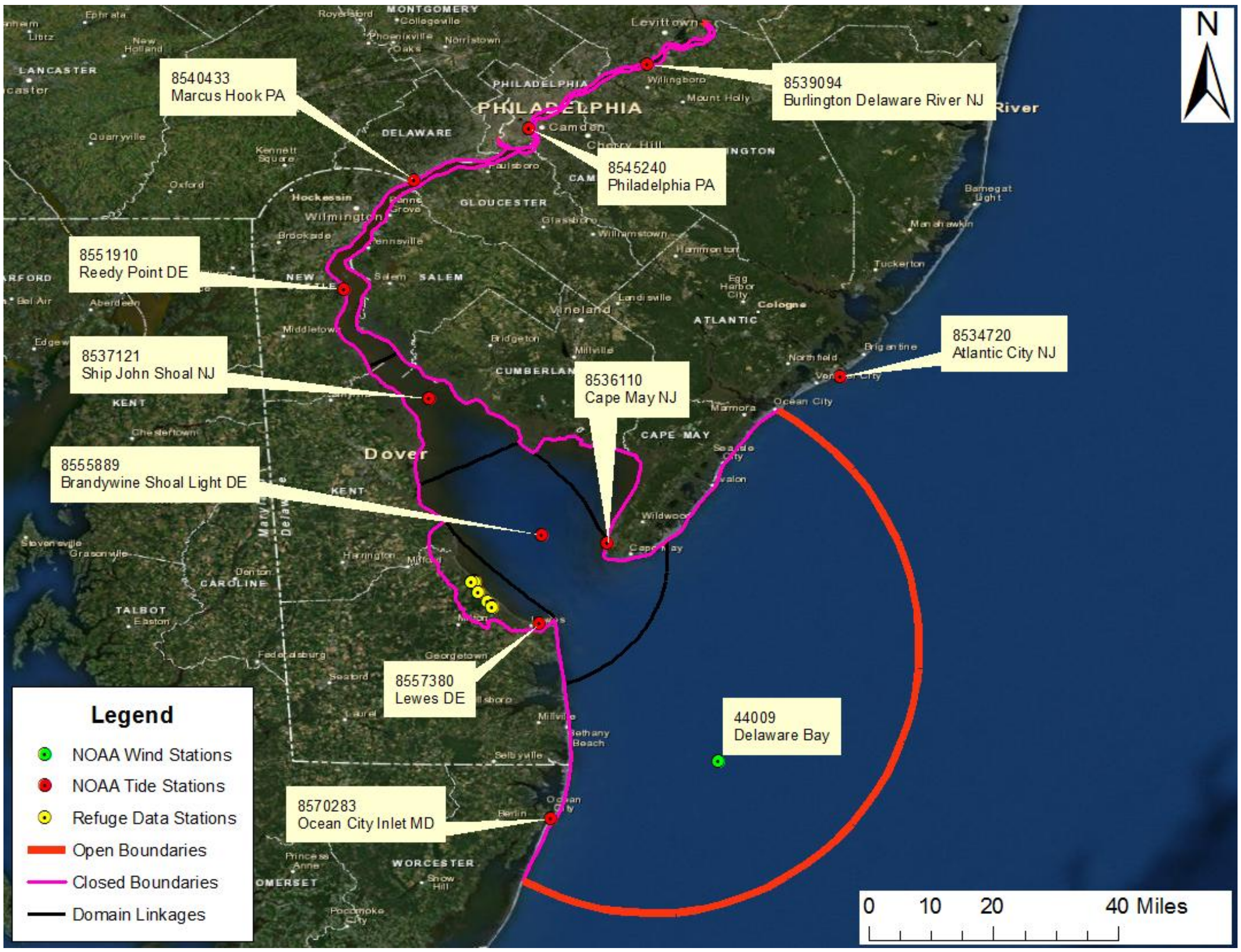

Figure 11. **Water level calibration locations within Delaware Bay.**

Figure 12. Water level and salinity calibration locations within the Refuge.

A regularly-spaced grid with a horizontal resolution of 10 m (33 ft) was chosen after testing multiple grid configurations for the Refuge domain. Elements were active or inactive based on the local water level and allowed to wet and dry as the tide and storm surge increased and decreased. For the bottom friction formulation, a spatially-uniform Manning's *n* of 0.02 led to the best results. Figure 13 illustrates the data-model water level comparison in Unit II for the finalized Hurricane Sandy simulation. Within the Refuge, the model replicates the peak storm surge elevation and matches overall trends shown in the data.

The model grid and parameters optimized during the Hurricane Sandy simulations were then applied to a 12-day period post-Sandy, from 11/21/12 to 12/03/12, to ensure that the calibrated model was useful for normal tidal as well as storm conditions. Figure 14 illustrates the water level time series for the post- Sandy simulation in Unit II. The results show that the model is accurate with regard to water levels within the Refuge for both 'normal' and storm conditions.

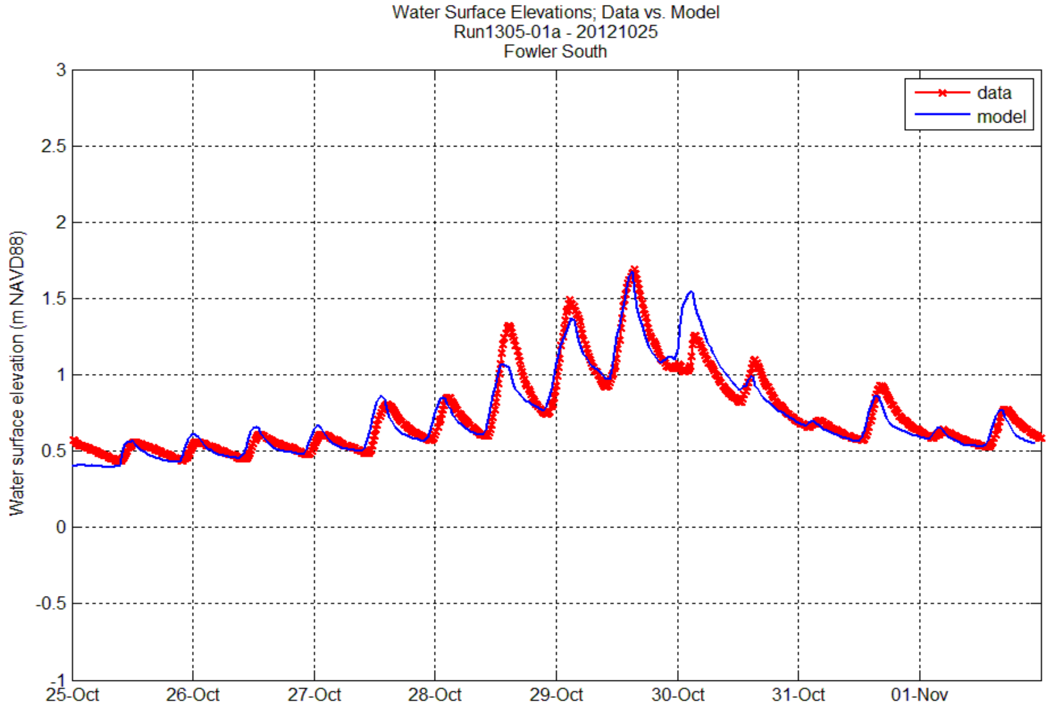

Figure 13. Measured vs. modeled water levels, Hurricane Sandy: Unit II.

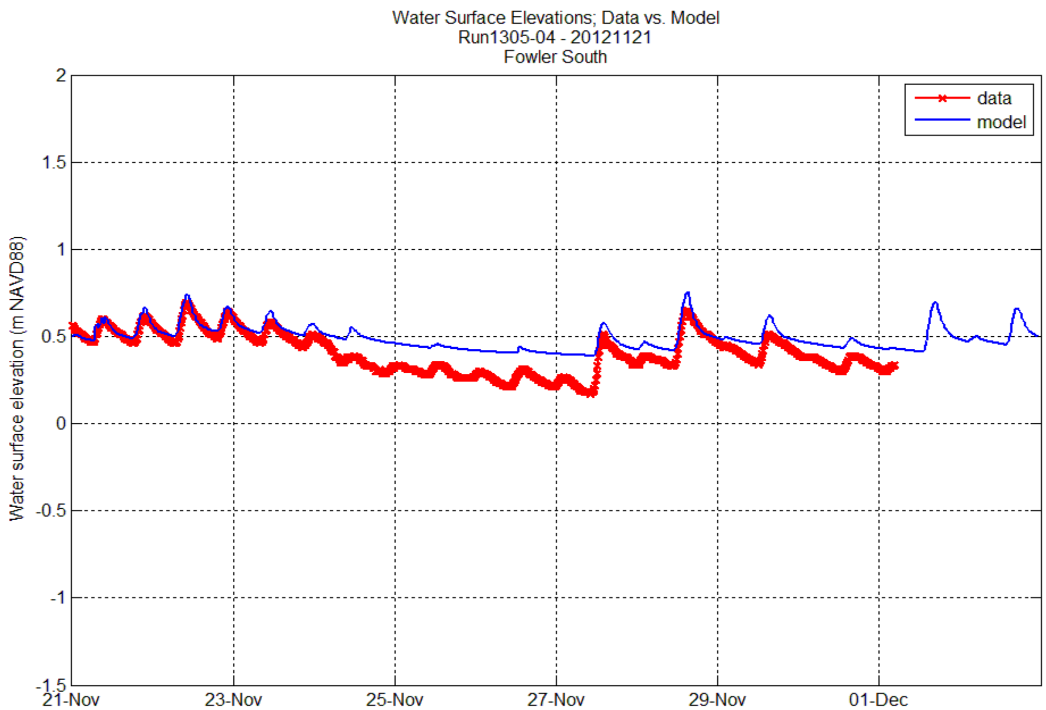

Figure 14. Measured vs. modeled water levels, post-Sandy: Unit II.

6. Alternatives Development

Management alternatives were explored once the model was refined to accurately replicate tidal conditions within the Refuge for a variety of forcing factors. These alternatives, including modifications to the breach locations, roadways, and water control structures, were examined for their effect on water levels and salinity distribution within the refuge for long-term average as well as storm conditions. In the long-term average runs, data from statistical analyses of inflow and tidal boundary conditions (detailed below) were used to drive the model so that the results were free from influence by event-based or seasonal fluctuations.

The long-term model runs were for periods of 6 months in length, based on previous results in which this was found to be the amount of time necessary for the model to 'equilibrate' into a regular pattern as the tide moved through the spring-neap cycle. Simulations were executed in 1-month time periods and driven by a reconstructed synthetic tidal time series derived from NOAA's harmonic constituents at Atlantic City, NJ and Ocean City, MD. No wind forcing was applied, nor was freshwater flow from the Delaware and Schuylkill Rivers. Constant base flow rates from USGS Streamstats were applied to the upstream boundaries of Slaughter and Prime Hook creeks and an initial salinity within the Refuge of 0 parts per thousand [ppt] was used. Figure 15 shows the modeled water levels at NOAA's Lewes, DE gauge compared to NOAA's harmonic tide for days 14-29 of a 29-day cycle; the close agreement between model and data show that the reconstructed boundary condition is accurate for modeling theoretical tides within Delaware Bay and the Refuge.

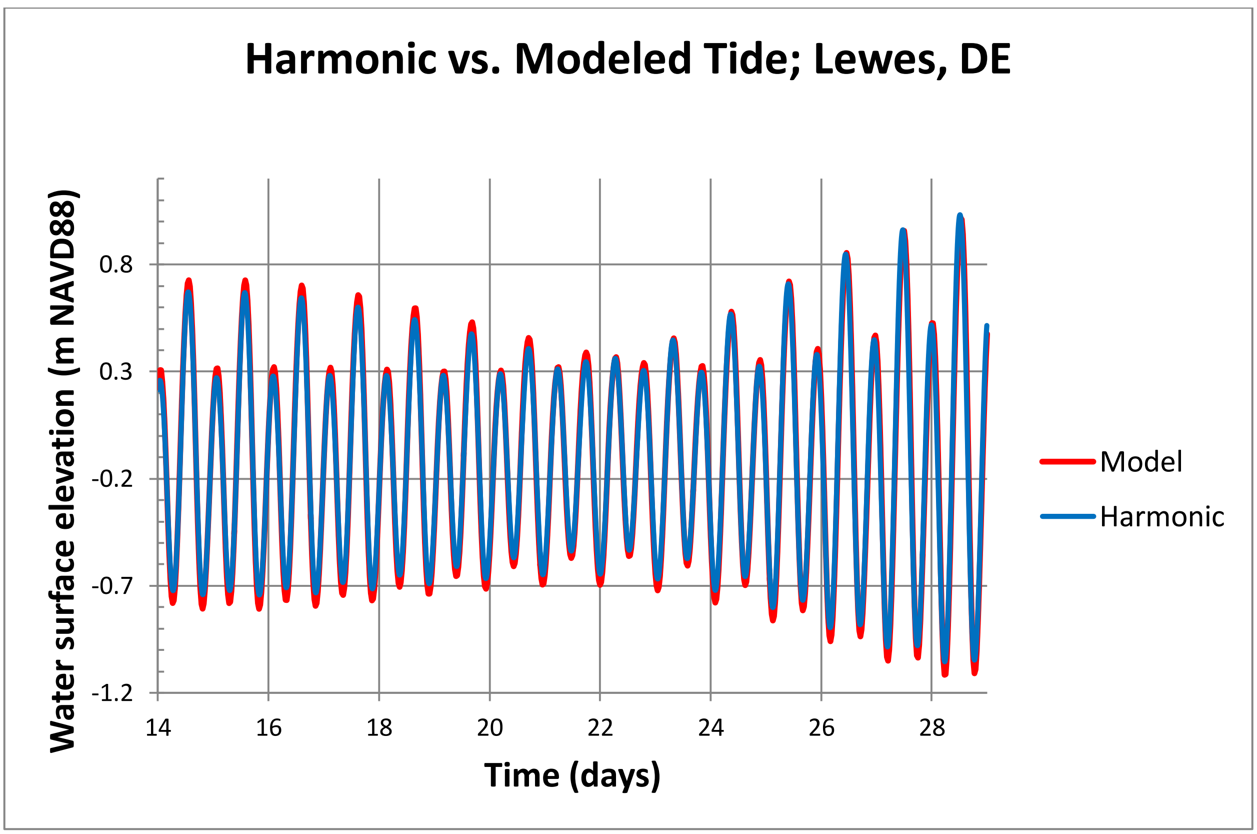

Figure 15. Comparison between NOAA harmonic constituents and modeled water level, Lewes, DE.

6.1. Initial Alternatives

Atkins worked closely with USFWS staff to develop and refine the alternatives to be modeled. Results from previous model runs provided guidance for determining future runs; in this way, the alternative development was results-driven. The first set of alternatives was characterized by variations in the breach configuration, the water control structures (WCS), and Fowler Beach Road. No modifications were made to elevations within the marsh. The model was run for: existing conditions, one breach (Breach 4) open (see Figure 7), and all breaches closed. For each of these situations, runs were performed with and without the WCS in place, and with and without the end of Fowler Beach Road (east of Slaughter Canal) intact.

The results of the initial model alternatives indicated that the breaches are the primary factors affecting the hydrodynamics within the Refuge under normal circumstances; the WCS and Fowler Beach Road have smaller effects. Further, it became apparent from the model runs with a starting salinity of 0 ppt that, over time, the Refuge can become a brackish to salt environment even with all breaches closed and tidal exchange with the Bay limited to Slaughter Canal, Petersfield Ditch, and Prime Hook Creek.

After analyzing the water elevations, salinity distribution and adverse effects of flood flows into the Refuge and adjacent communities from existing conditions, a single breach opening scenario and a complete breach closure scenario were developed and analyzed. The breach closure scenario was developed to investigate whether a resilient salt marsh could be established in Units II & III with salt water inflows primarily from Slaughter Canal and the Broadkill River. This alternative was also investigated to determine if storm surges could be dampened to reduce potential flooding impacts to additional refuge lands as well as adjacent agricultural and residential lands. Figure 16 shows the water levels over time in Unit III for each of the initial alternatives group together according to breach alternative, demonstrating that the breaches drive most of the variability in water level. Figure 17 shows the salinity over time in Unit II for a ‘breach closed’ scenario. By the fifth month, a pattern corresponding to the spring-neap tide cycle is established, and the salinity fluctuates between 4 ppt and 20 ppt, indicating potential brackish (low salinity) habitat.

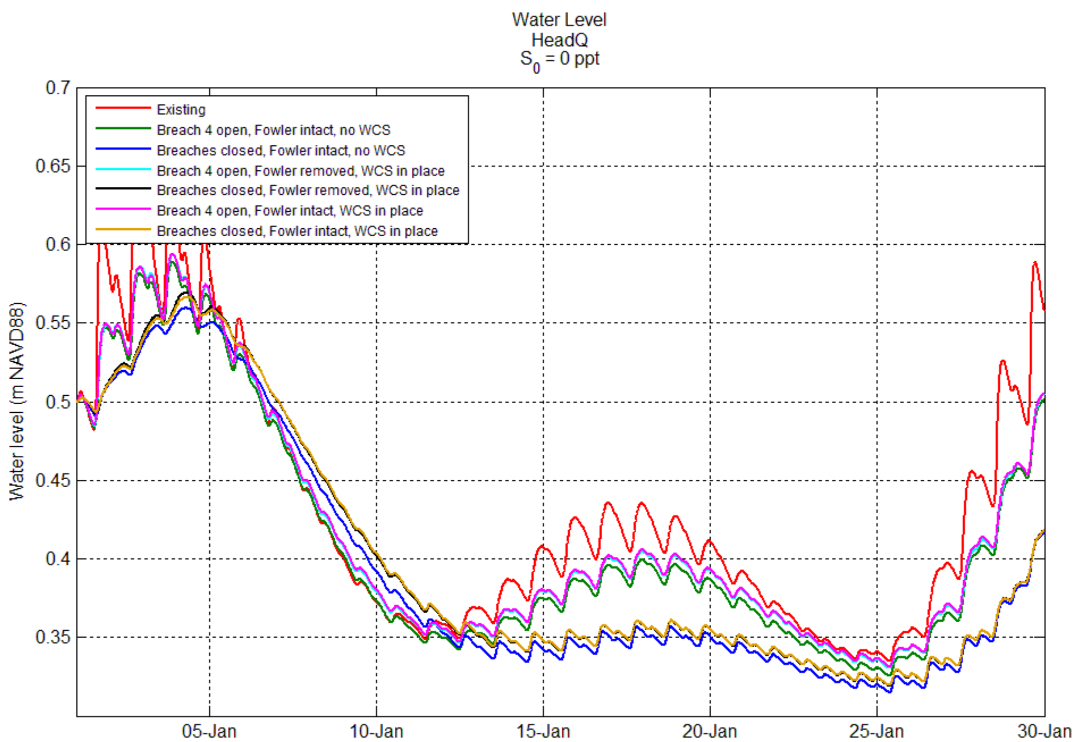

Figure 16. Water levels in Unit III for initial alternatives; note ‘grouping’ by breach configuration.

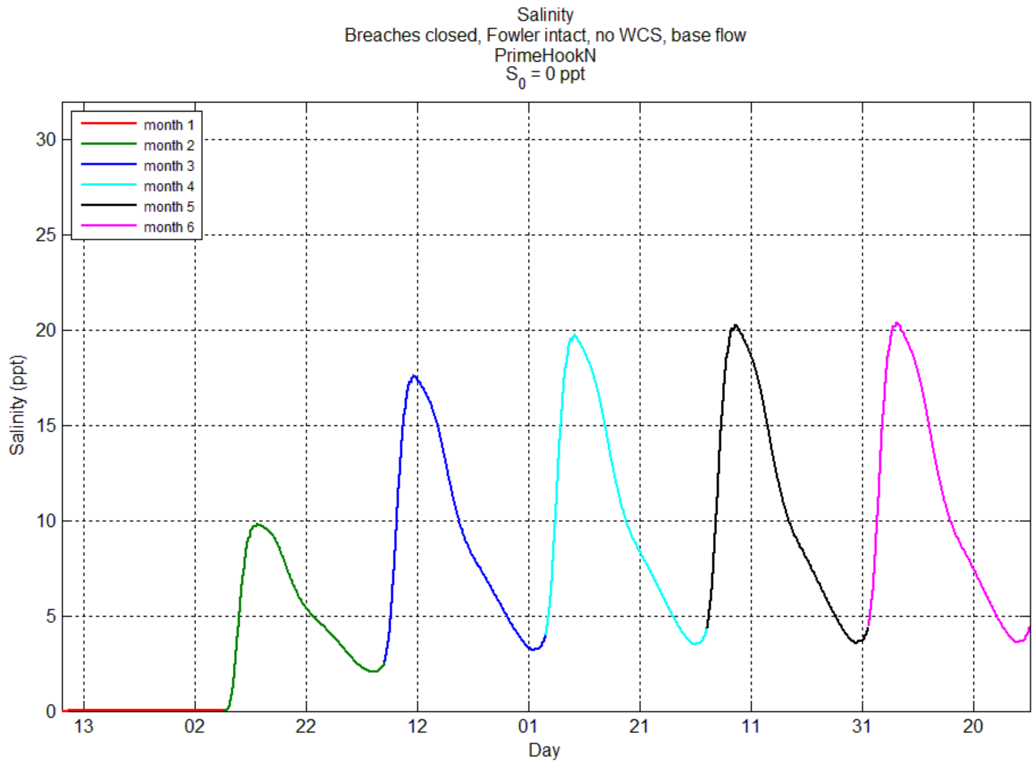

Figure 17. Long-term salinity in Unit II for a 'breaches closed' scenario.

6.2. Primary Alternatives

Results and implications of the initial model runs were discussed during meetings with Refuge and other Service staff. Once the existing conditions and future conditions with a breach opening were modeled, subsequent model runs focused on scenarios in which all of the breaches were closed so that saltmarsh restoration and flood protection could be examined. Three primary alternatives were developed to examine how changes within the Refuge could impact exchange between the Refuge and Delaware Bay with the breaches closed.

The three scenarios modeled included different channel configurations within the Refuge to increase circulation via the Mispillion Inlet and Roosevelt Inlet. Alternative 1 was simply the breaches closed with no internal channel modifications. Alternative 2 added a channel that connects Slaughter Canal (and Mispillion Inlet) in the north end of Unit I to both Prime Hook Creek and Petersfield Ditch in southern Unit III, which in turn connects to the Broadkill River and Roosevelt Inlet. The channel was approximately 40 ft in width at the bottom and sloped upward to grade 1 model cell width (30 to 40 ft) in either direction. The elevation of the channel bottom was -2.3 ft NAVD88. These dimensions, other than the side slope, are similar to the dimensions of the existing Slaughter Canal and others in the Refuge. Finally, Alternative 3 built upon Alternative 2 by adding a second conveyance channel through Prime Hook Road, between Unit II and Unit III, and added several 'finger' channels in Unit III to aid in the distribution of saline water. For all main and secondary channels, an attempt was made to follow existing channels, lower elevation areas, and historical channel paths in order to follow a natural design and minimize the amount of removed material. Precision in the channel characteristics and paths was limited by the model resolution and will be refined in the final design stages; the purpose of the modeling effort was to determine conceptually if the potential for circulation enhancement existed. Figure 18 through Figure 20, respectively, illustrate the channel paths and existing creeks/waterways within the Refuge for Alternatives 1 through 3. 'Prime Hook E' and 'Prime Hook W' denote the approximate locations where the proposed channel crosses the existing Prime Hook Road. The channel maintains its depth and width when crossing the road.

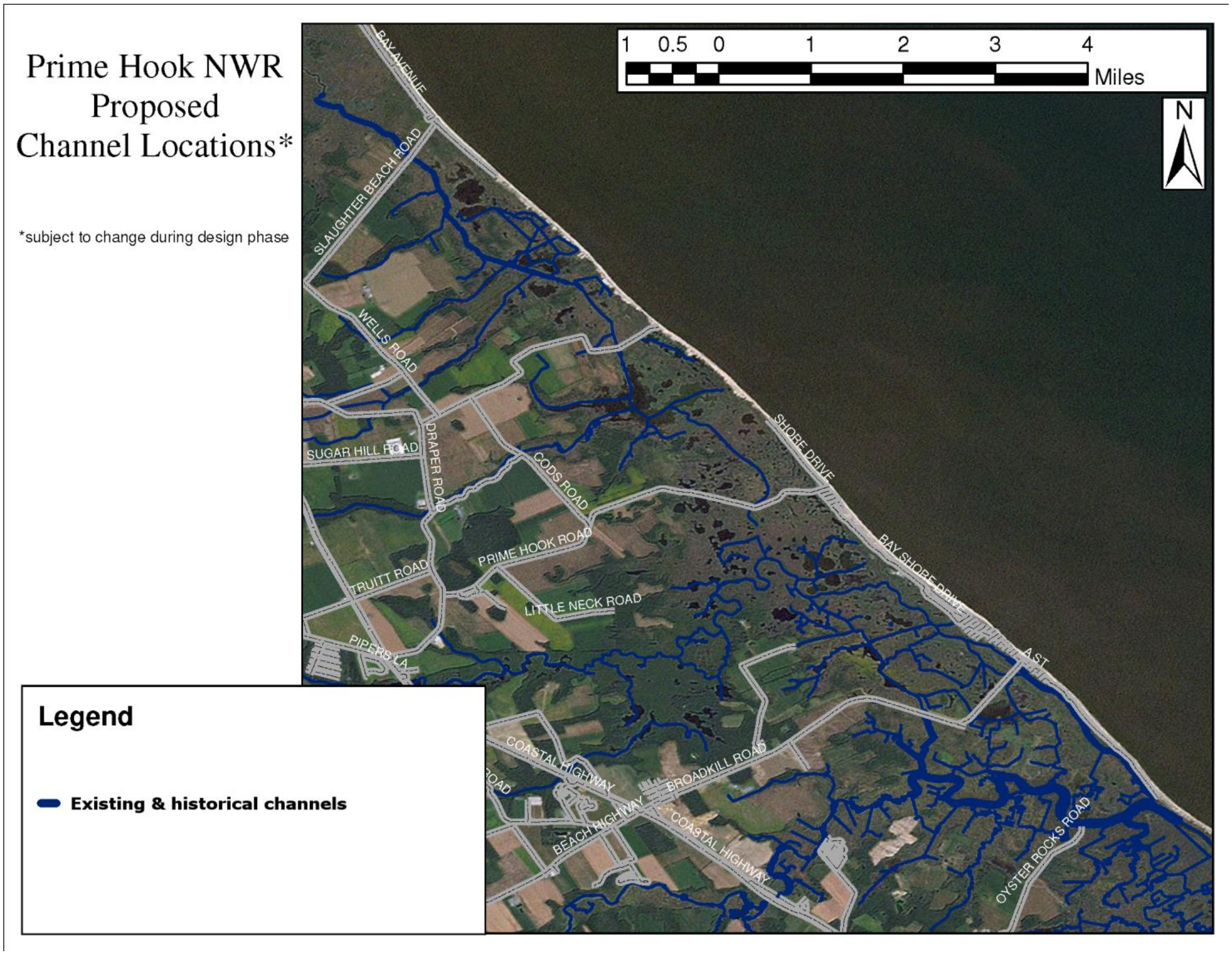

Figure 18. Channel configuration in the Refuge, Alternative 1 (no modifications).

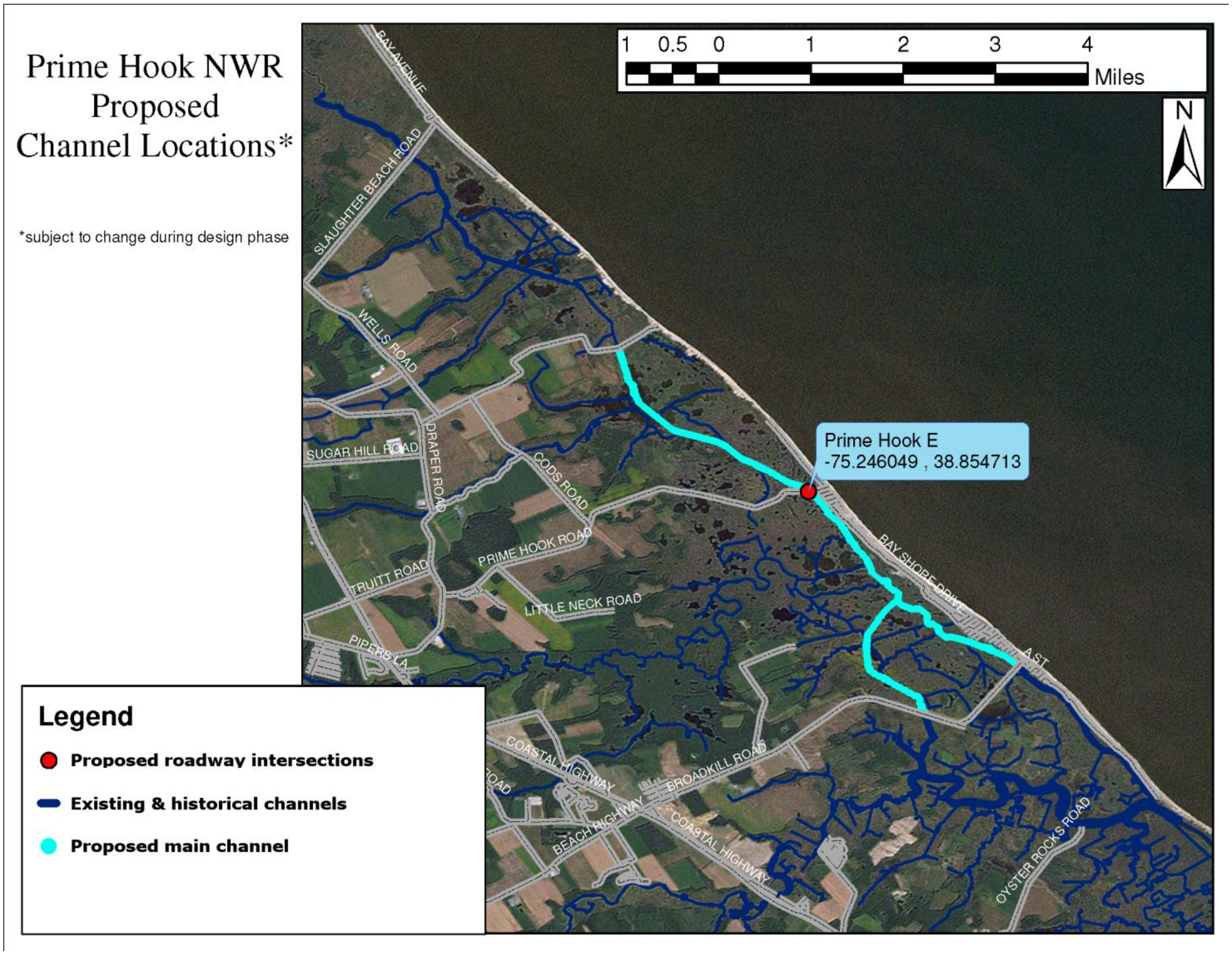

Figure 19. Channel configuration in the Refuge, Alternative 2 (main channel).

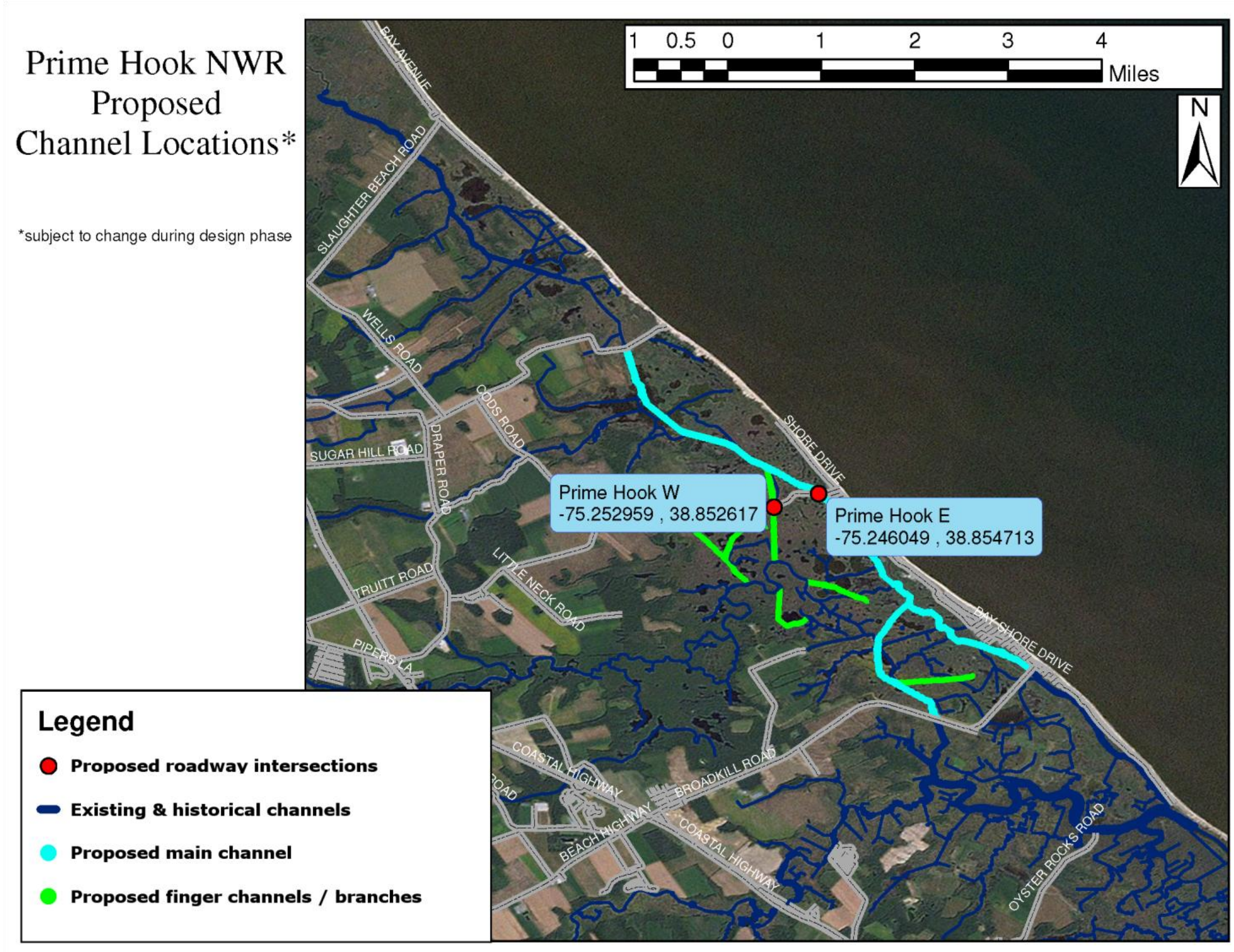

Figure 20. Channel configuration in the Refuge, Alternative 3 (main channel w/ branches).

6.2.1. Normal Tidal Conditions

Each management alternative was run for 6 consecutive, identical tidal 'months' of 29 days, allowing for conditions within the Refuge to equilibrate into a consistent pattern corresponding to the spring-neap tidal cycle. All three alternatives had the following in common:

- Harmonic-derived tidal boundary condition
- No wind forcing
- All breaches closed
- All water control structures removed
- East end of Fowler Beach Road removed
- Constant base inflow from Slaughter Creek and Prime Hook Creek (21 cfs and 79 cfs, respectively)
- Initial salinity of 0 ppt within Refuge

Conditions during month 6, representative of normal fluctuations outside of seasonal and storm effects, were used to compare water levels and salinities throughout the Refuge and help inform decisions regarding potential restoration options and further investigations.

6.2.2. Hurricane Sandy

In addition to the model runs described previously, which simulated long-term normal conditions, the three alternatives were also run using the forcing conditions for Hurricane Sandy, as detailed in the calibration and validation section of the report. The results of this 8-day storm run can be used in the planning and design of any roadway, bridge, or community improvements for flood protection, and when compared to modeled existing conditions illustrate how the breach and channel modifications have an effect on flood elevations within the Refuge during a significant storm event.

7. Model Results

Model results were used to evaluate changes in water levels and salinities in the Refuge under existing conditions and for the three restoration alternatives, and for Hurricane Sandy.

7.1. Normal Tidal Conditions

When interpreting the results of the model runs simulating normal tidal conditions, attention was focused on month 6 of these runs, after the model had equilibrated to the applied inflow and tidal boundary conditions. Figure 21 and Figure 22, respectively, present the 6-month water level time series for all alternatives in Unit II and Unit III. Figure 23 and Figure 24, respectively, present the 6-month salinity time series for all alternatives in Unit II and Unit III.

During the spring-neap tidal cycle, water levels in the Refuge have a range of about 0.4 m (1.3 ft), with overall levels decreasing slightly from north to south. This is consistent with the fact that flow through the Refuge generally enters from Slaughter Canal and flows southward, likely due to the increase in tidal range in Delaware Bay from south to north. In addition, the daily tidal influence is more prominent in the southern part of the Refuge versus the northern. When the channels are added to the system, the low water level drops by about 0.1 m (0.33 ft); this is probably because the increased throughput allowed by the channel additions let more water freely flow through rather than ‘stack up’ inside the Refuge.

The modeled salinities demonstrate that the addition of conveyance channels is a successful method of allowing more salt water to enter from Delaware Bay and increase salinity levels within the Refuge. While the low salinities remain relatively constant among alternatives, the average and peak salinities exhibit a marked increase when channels are added. For example, representative peak salinities in Unit III increase from 12-13 ppt to 19-20 ppt. In addition, Figure 24 shows that while peak salinities are unchanged when adding the finger channels in Unit III, the minimum salinity is increased, proving that the finger channels serve to distribute and hold more saline water within the Refuge. The results were subsequently mapped to provide further spatial detail of the model results.

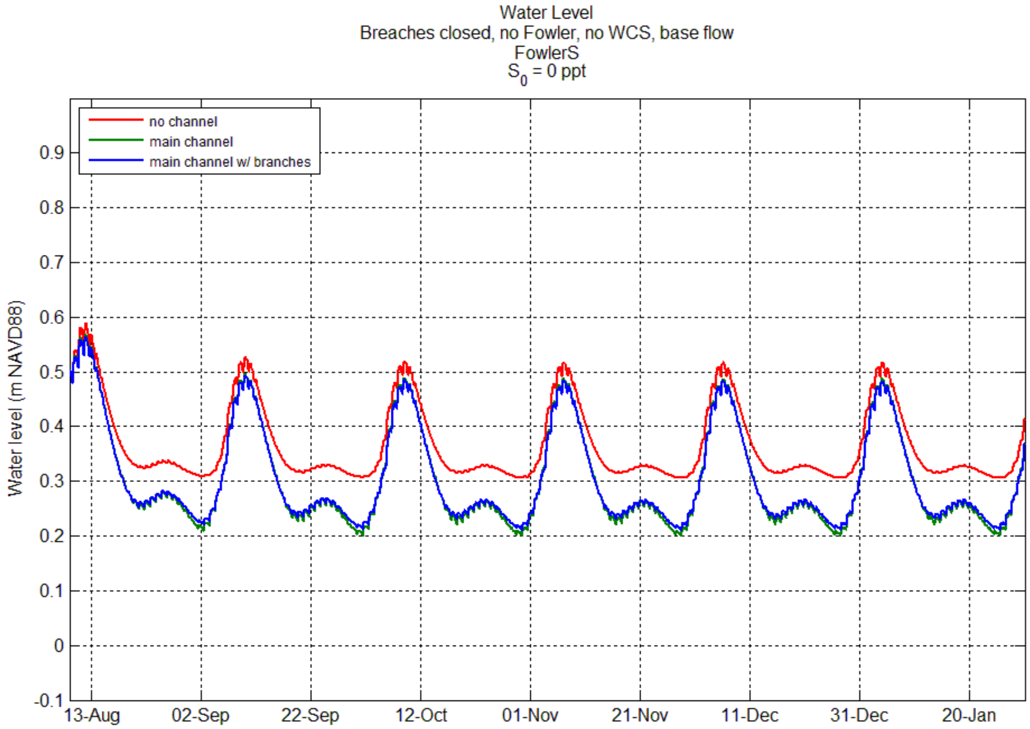

Figure 21. Water level time series for the three primary alternatives: Unit II.

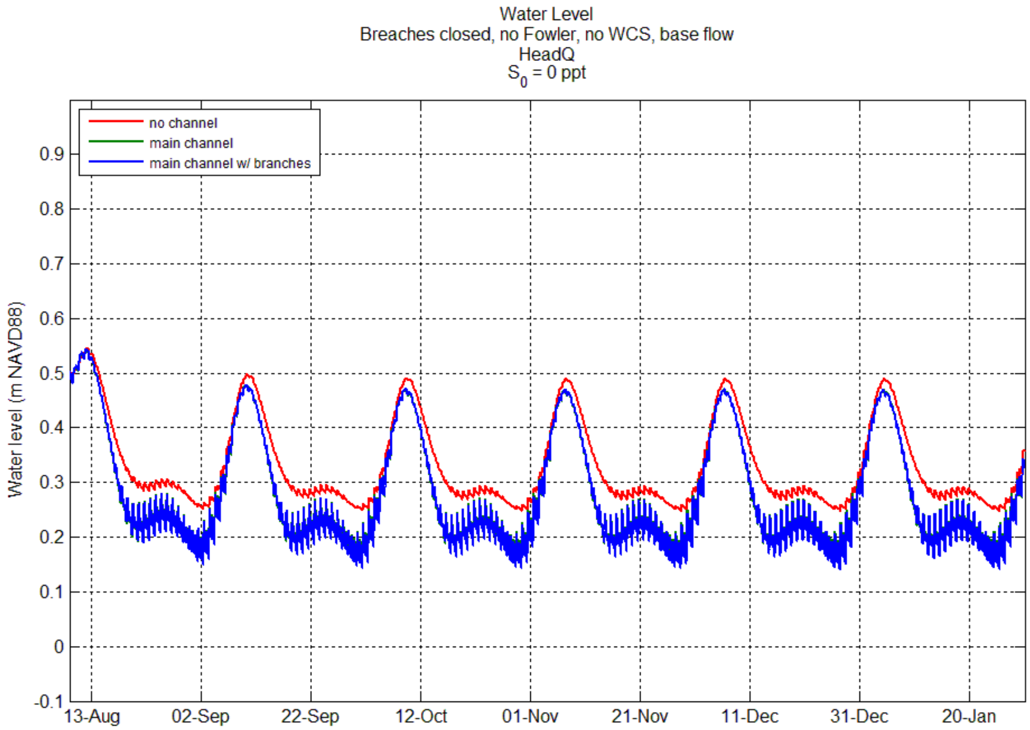

Figure 22. Water level time series for the three primary alternatives: Unit III.

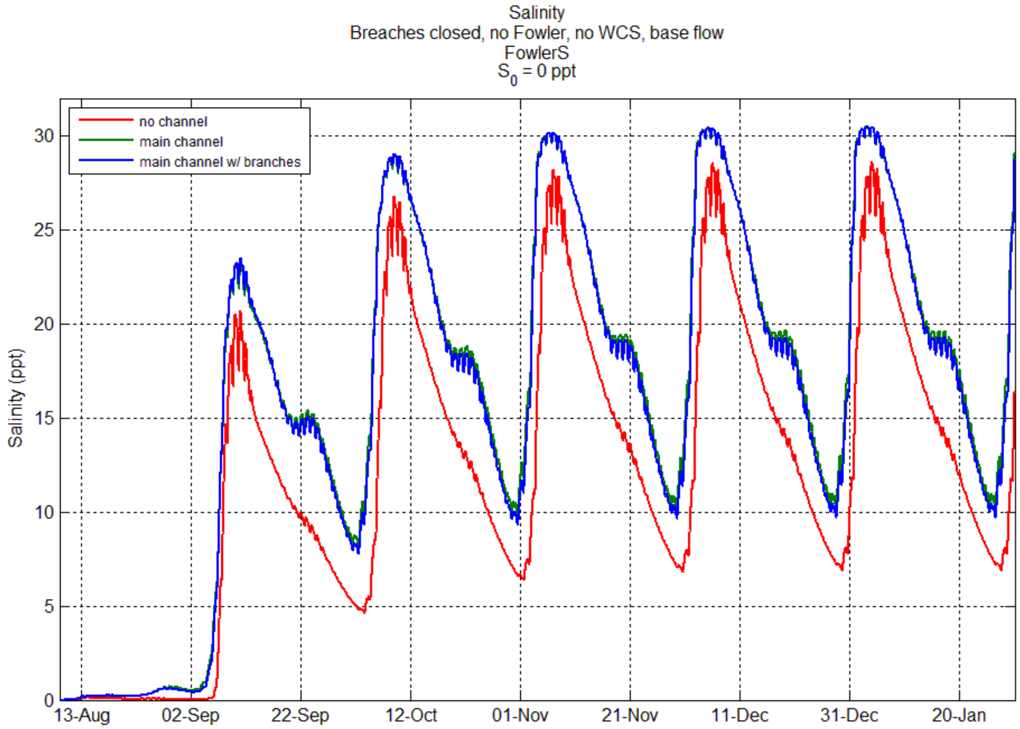

Figure 23. **Salinity time series for the three primary alternatives: Unit II.**

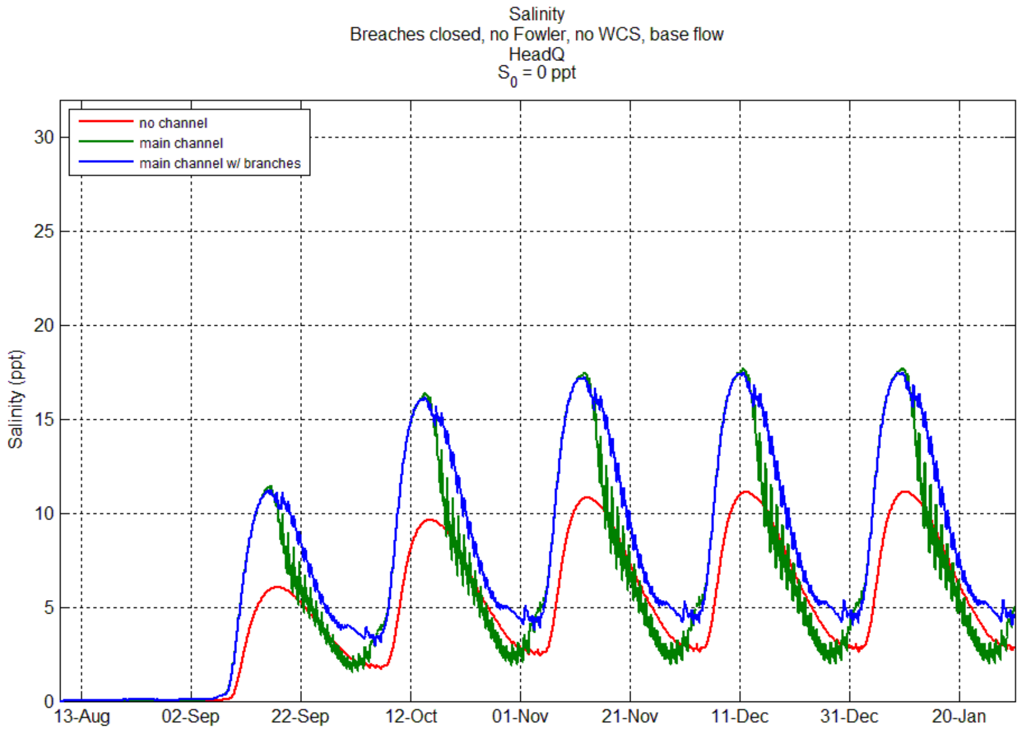

Figure 24. **Salinity time series for the three primary alternatives: Unit III.**

All mapped output is in reference to month 6 of the simulations, after the model has equilibrated. Figure 25 and Figure 26, respectively, illustrate the maximum salinities for Alternative 1 and Alternative 3. A more detailed discussion of the model results and the full set of map figures can be found in Appendix A, Figure 64 through Figure 81.

Overall, the mapped water level and salinity results demonstrate the following key points when analyzing the 'breaches closed' scenarios:

- Adding a main channel connecting Slaughter Canal (and thus Mispillion Inlet) to the Broadkill River and Roosevelt Inlet (via Prime Hook Creek and Petersfield Ditch) allow for greater exchange between Prime Hook NWR and Delaware Bay.
- The increased exchange and throughput provided by this channel system lowers the water level within the Refuge by reducing the amount of water 'stacked' within the management units.
- The augmented exchange increases the average and maximum salinity levels within all four units.
- The secondary finger channels that feed from the main channel successfully in distribute saline water to a larger area of the Refuge than the main channels alone.

The water levels and salinities from these modeled alternatives are crucial in planning and developing any restoration activities within Prime Hook NWR.

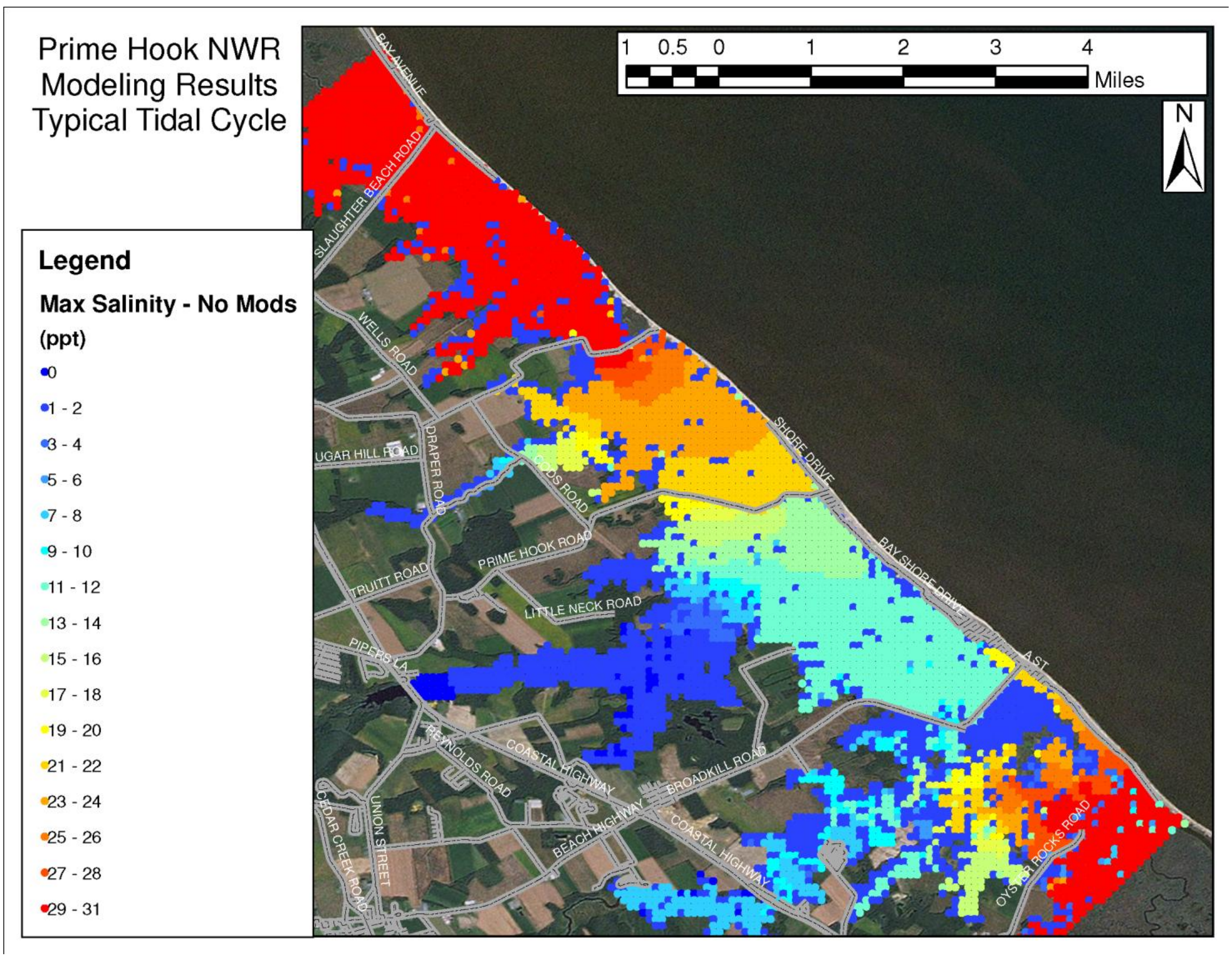

Figure 25. **Maximum salinities in Prime Hook NWR, Alternative 1 (no modifications).**

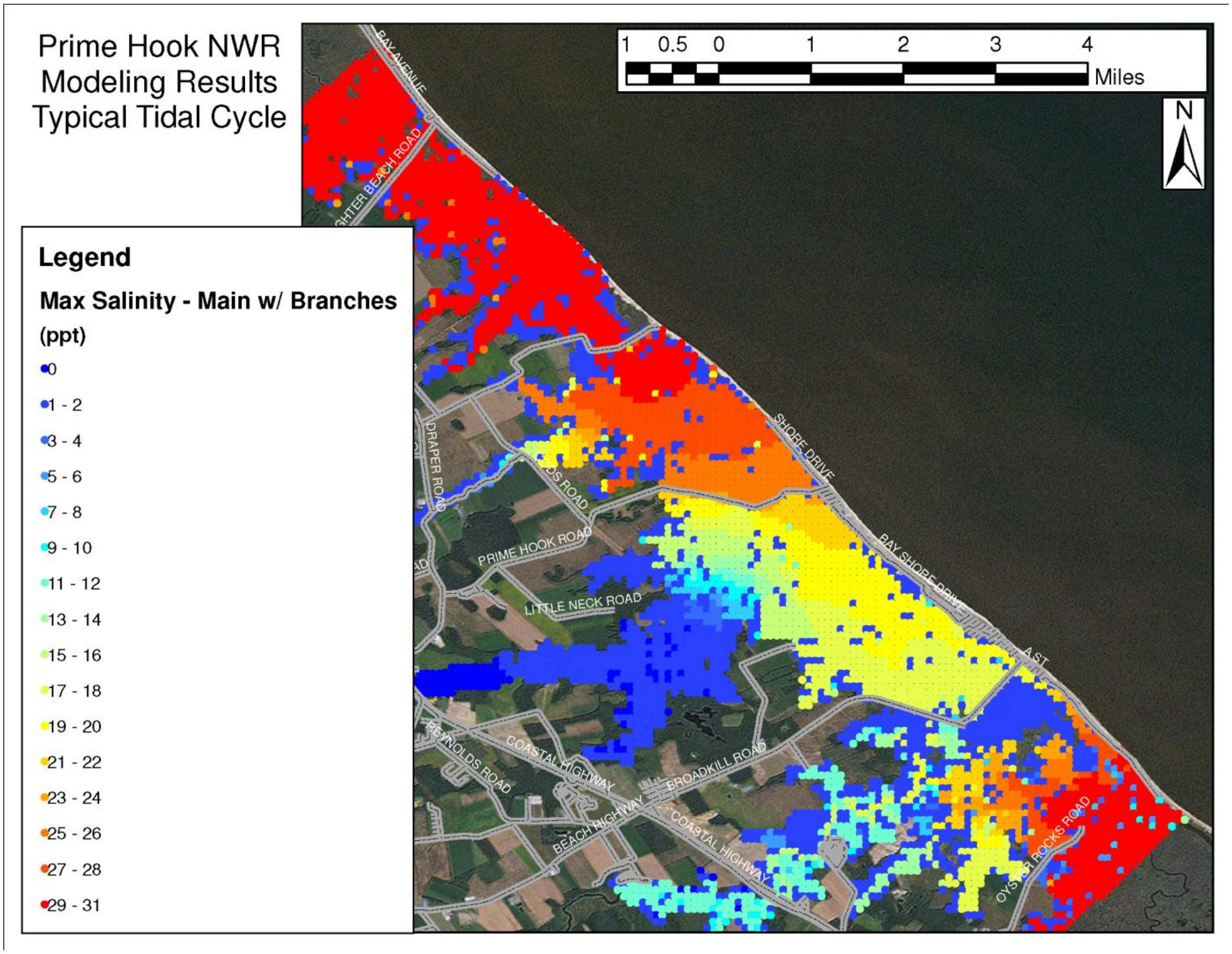

Figure 26. **Maximum salinities in Prime Hook NWR, Alternative 3 (main channel w/ branches).**

7.2. Hurricane Sandy

Figure 27 illustrates the water level time series for Hurricane Sandy in Unit II, showing water levels under existing conditions, with a single breach opening, and the three primary alternatives with the breaches closed. In each Unit, the peak storm surge in all three alternatives is reduced by about 1.6 ft (0.5 m) compared to existing conditions, from 5.9 ft (1.8 m) NAVD88 to 4.3 ft (1.3 m) NAVD88. After the peak, water levels decline at the same pace in each scenario, suggesting that water is not being trapped in the Refuge without having breaches to act as conduits.

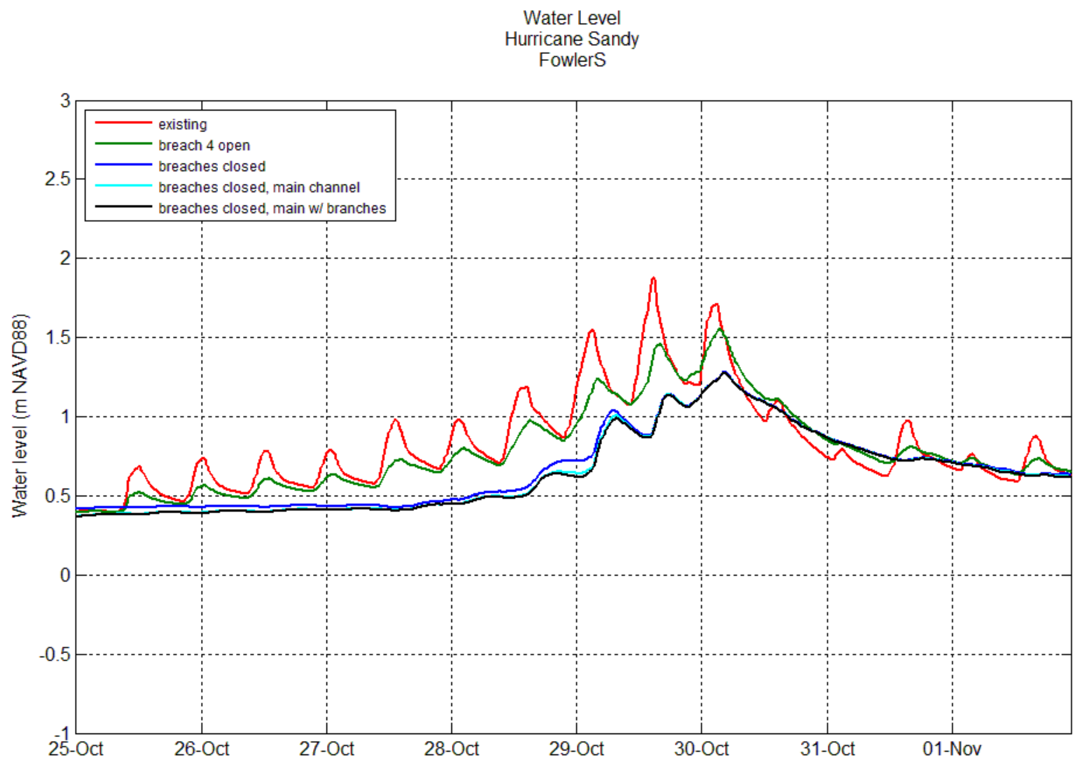

Figure 27. Hurricane Sandy water level time series for the three primary alternatives: Unit II.

8. Marsh Restoration Concepts

Shoreline breaches created during Hurricane Sandy provided openings for saltwater intrusion into the Refuge, with particularly dramatic impacts to former freshwater marshes in management Units II and III. The former freshwater wetland impoundments have shifted to include open water, saltmarsh, and areas of the invasive common reed, as a result of the reintroduction of salt water. Freshwater plants, intolerant of salt water, died, and the effect was a loss of above ground vegetation and root mass that previously helped to stabilize sediments. Freshwater organic sediments, which typically decompose very slowly because of the lack of oxygen, were oxidized with the reintroduction of salt water (via sulfates in sea water that provide an alternate electron acceptor), resulting in loss of organic sediments from the system.

Left unchecked (no action), it is expected that the transformation of marsh habitat to open water, shoreline erosion, and flooding within (and outside) the Refuge will continue and likely worsen. The first fundamental step toward restoration, then, is to re-establish saltmarsh structure and function, which includes greater stability of marsh sediments, recovery of biological components (vegetation, benthic communities, fish), and recovery of sustainable coastal habitat. To accomplish this, it is necessary to define the sediment and circulation characteristics critical to recovery of the saltmarsh system. This marsh restoration would establish the foundation for natural vegetation recruitment, set the stage for additional phases of restoration, and re-establish important ecosystem services such as wildlife habitat and attenuation (wholly or partially) of flooding in adjacent uplands.

Saltmarsh restoration efforts are anticipated to include the creation of tidal channels to deliver sea water to the marsh. A typical cross section for marsh restoration is presented in Figure 28. It is important to stress that both beach and marsh restoration need to occur. Beach restoration will provide the needed stability (and protection) to the shoreline, while the marsh will provide the foundation/platform for ecosystem recovery and sustainability. Atkins provided under a separate cover an analysis and report to fill the breaches that determined beach restoration alternatives, design configurations, fill volume estimates and associated costs (Atkins, 2013). Sea level rise is on the order of 3 to 3.5 mm/year at the Lewes tide station (NOAA, 2009). In order to create a viable and sustainable marsh system, these changes will need to be understood and accounted for in the final design process. Scientific studies have shown that as long as the relative sea level rise does not exceed 3-20 mm/year, high marsh areas maintain their levels and low marsh areas maintain or increase in elevation in relation to the water level (Morris et al, 2002). Importantly, adaptive management is a component of the restoration. If it becomes apparent that water levels are too high for the marsh restoration, it may become necessary to introduce sediments to the marsh and “build” a marsh platform. However, based on available data, elevations are high enough to provide water levels relative to sea level that are conducive to saltmarsh vegetation growth, expansion, and recovery.

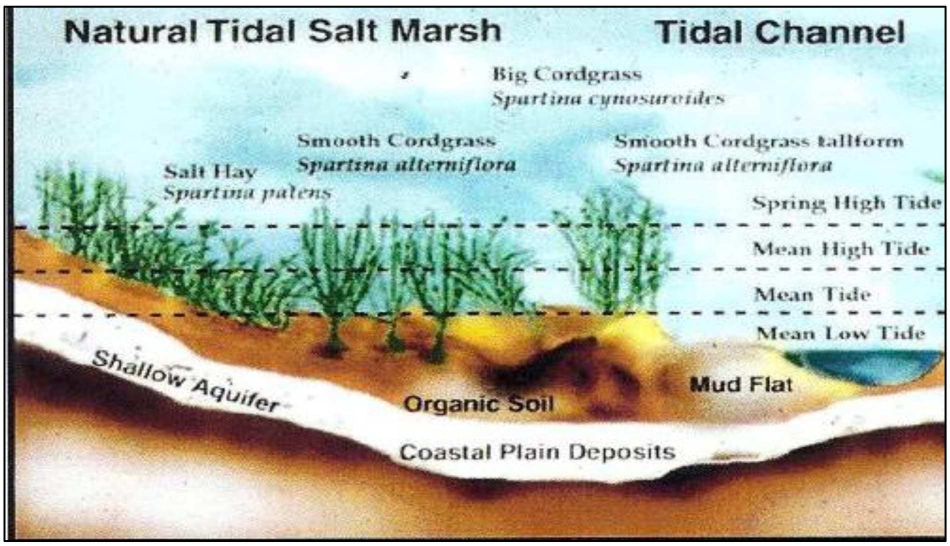

Figure 28. Typical cross section of southern marsh and tidal channel (after Weishar et al. 2005).

8.1. Importance of Saltmarsh/Dune Interaction.

Present day back-barrier marshes provide the platform on which beaches/dunes inevitably migrate. Restoring the historic saltmarsh will help to: restore the barrier system processes that control the landward dune migration, restore valuable fish and wildlife habitat, and buffer the impacts of flood waters on local (human) communities.

The beaches, dunes, and back barrier marshes of barrier systems reflect the interaction of geology, sedimentation, vegetation, winds, and other physical (and historical) factors. The role of dunes as barriers to wind and water erosion from the bay and, therefore, their role in protecting back barrier saltmarsh habitat and associated wildlife is well understood and widely accepted. For example, see Figure 29 (EPA 2012), in which the dunes ameliorate the erosion impact of the wind and provide a sediment subsidy to the marshes. The importance of coastal marshes in absorbing wave energy, reducing erosion, and buffering the effects of floodwaters is well documented (Knutson 1987, Odum et al. 1984, Rosen 1980, others) is also widely recognized. Less frequent in the restoration literature is the importance of back barrier marshes to the barrier system: the marshes slow the migration of barrier dunes and former marshes provide the platform onto which dunes may first form and/or later migrate.

Barrier system "evolution" and "geomorphology cycling" have been described predominantly by marine geologists, likely as a result of the time frame over which it typically occurs, from thousands of years to decades. For example, the Isles Dernier along the Gulf of Mexico became islands only after the back barrier marshes transitioned to open water over a period of 125 years (from 1853 to 1978). Barrier systems form over time as a result of successive overwash events, sediment inputs from the ocean side, new overwash fans over older deposits, and the creation of a shallow bayside platform onto which the barrier can migrate (simplified after Rosati et al. 2006). The bayside platform becomes vegetated, and shallow wetlands are formed, forming peat over time and stabilizing the platform further as wind-driven transport forms dunes over the new deposits. Erosion of back barrier marshes decreases island area and reduces the size of the platform available for landward migration of the barrier sand body (Reed 1989).

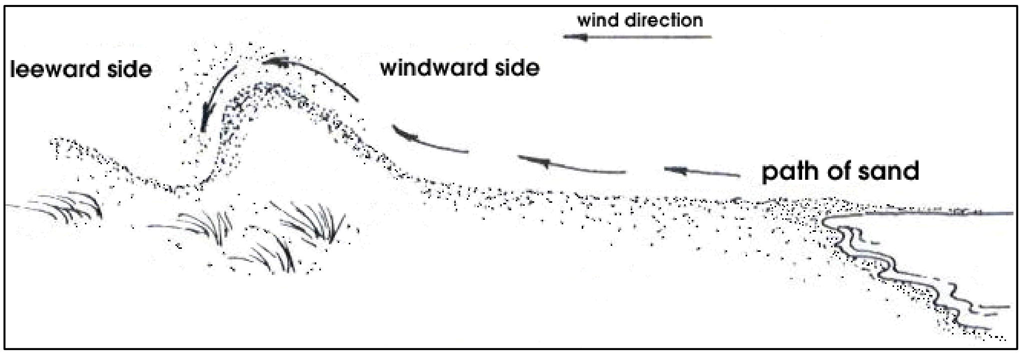

Figure 29. Barrier dunes reduce the impacts of wind and water erosion on back barrier marshes and provide sediment inputs (EPA 2012).

A generalized diagram of the barrier system in Figure 30 illustrates the layer of peat and former dunes below the present system. Slow sea level rise (SLR) allows dunes to increase in elevation and maintain a viable barrier system as migration occurs. A veneer of sand over peat remains on the shelf as the barrier (dune) migrates and inlets form, and some of this sediment may be transported back towards the beach. These interactions between barrier (dune) and back barrier (marsh) environments have also been referred to as the "co-evolution" of barrier and back barrier systems (Walters et al. 2012, referencing Godfrey 1976).

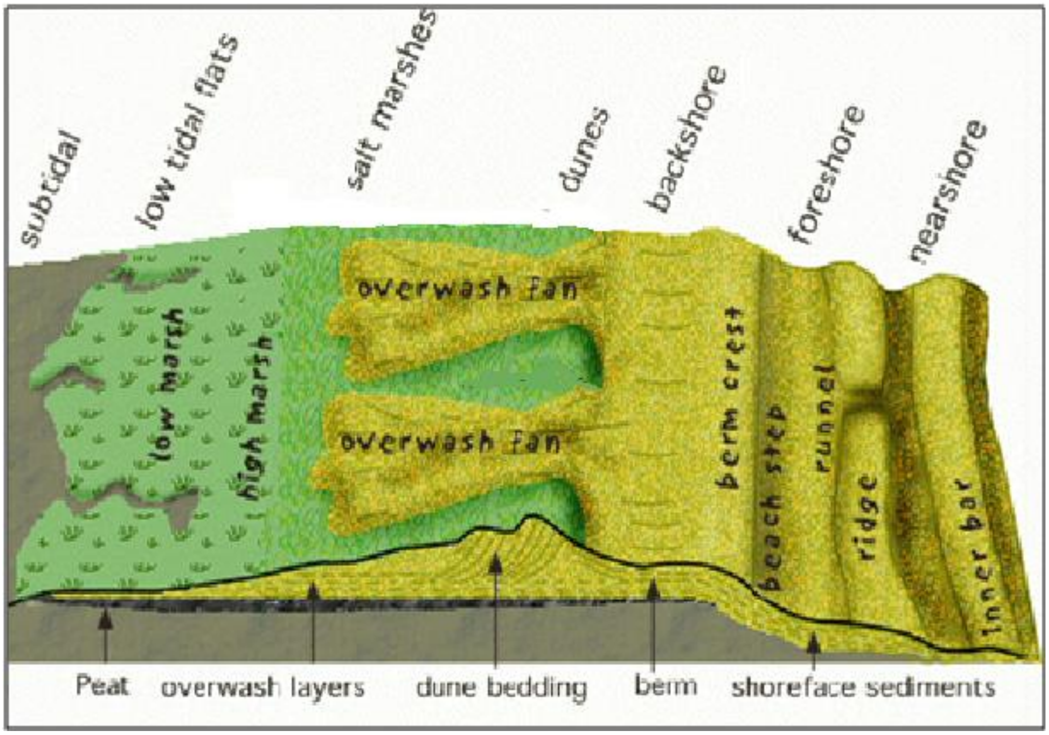

Figure 30. General diagram of dune and back barrier system, including relic peat and overwash strata beneath existing dunes (from Salem State University, redrawn from Godfrey 1976).

Much of the literature pertaining to marsh and dune restoration is an outcome of extensive restoration efforts along Louisiana's coastline. As early as 1997, the loss of barrier islands was attributed to inadequate sediment supply and lack of a stable, above-water back barrier platform upon which barrier islands migrate landward in response to SLR, reduced sediments, and storm impacts (McBride and Byrnes 1997). Under natural conditions, the system is resilient to SLR if an adequate sediment supply and an appropriate back barrier platform are present. For example, extensive erosion of the marsh platform of Chandeleur Island on the Gulf Coast has compromised the stability of the system (Sallenger et al. 2010) and migration of the shoreface will continue to erode the marsh platform (Moore et al. 2010).

Godfrey (1970), Dolan (1972a), and Leatherman (1979) suggest that storm overwash into back barrier marshes may be critical to maintaining the barrier (Goldsmith 1985). Overwashes and inlet closures maintain the width and elevation of the barriers as they migrate landward in response to SLR and saltmarshes expand and contract in kind (Godfrey 1976). Because a stationary shoreline is not anticipated with increased SLR and low sediment supply, massive sand replenishment and back barrier platform enhancement are needed to offset impacts for moderate to long-term restoration efforts (McBride and Byrnes 1997). Examples of studies that address the relationship of back barrier marshes and beaches/dunes are briefly summarized below.

- Restoration in Louisiana is focused on marshes and the relationship of dunes and back barrier marshes is well recognized. For example, Penland et al. (2004) reported that "nourishment, dune construction, and back barrier marsh creation are the only project types that built new land and reversed Gulf shoreline erosion", while Armbruster (2000) reported that "…vegetation plantings along the dune platform, Gulf side beach, barrier flat, and marsh platform to restore sustainable barrier island plant communities, foster the establishment of a primary dune system, and stabilize the surface."
- Along the coast of Virginia, the absence of back barrier marshes on southern Metompkin Island is hypothesized to increase the rate of dune migration in comparison with the northern half of the island where a substantial marsh is present (Brenner and Moore 2010).

- In Cape Cod, the “cyclic events of barrier evolution” are exhibited by the formation of saltmarshes on flood-tidal deltas, burial of the marshes by overwash, and the eventual replacement by new dunes (Leatherman and Zaremba 1986).
- Along the Delmarva barrier island chain, studies by Kraft et al. (1972) emphasize the importance of overwash deposits in terms of the total volume of barrier deposits.
- In a scenario of accelerated SLR along the east coast of the U.S., the conversion of back barrier marshes to open water is anticipated to increase tidal prisms, increase erosion of inlets, increase ebb tide delta size, and thereby reduce sand subsidies to adjacent coasts, resulting in further erosion (Fitzgerald et al. 2008).

8.2. Conceptual Marsh Restoration Design

Changes in vegetation and habitat in saltmarshes of the northeastern U.S. have often been dramatic. Historic management practices along the mid-Atlantic and specifically Delaware (Niering and Warren 1980, Roman et al. 2001, others) began with Dutch and English wetland “reclamation” practices for meadow impoundments” in the 1800s (Weinstein et al. 2000), were followed by ditching and draining for mosquito management and Open Marsh Water Management (OMWM) in the early 1900s (described by Adamowicz and Roman 2002, Adamowicz et al. 2004). More recent impacts of storms, including reduced or absent tidal influx and the loss of marsh platforms, have had equally dramatic effects.

Potential restoration scenarios for Prime Hook NWR marshes focuses on restoring the tidal channels that in turn restore hydrologic patterns; deliver salt water for saltmarsh plant species (e.g. *Spartina* spp.), and provide both the mechanism for sediment transport and the sites for processes that control the overall rate of marsh development. Because studies suggest that increasing the amount of creek edge in a tidal marsh will increase the rate at which created marshes mature (Tyler and Zieman 1999), tidal creeks are considered an important component of any marsh restoration effort in the Refuge. Consequently, aerial photography from 1956 and 1968 was used to develop a conceptual level design for a marsh restoration effort that includes tidal creeks similar to historic tidal creek patterns that reflected the local geomorphology. A conceptual design that reflects a possible creek/marsh configuration is presented in Figure 31 and is based on water level elevations predicted by the hydrodynamic model. Marsh elevations ranging from mean tidal elevation to mean high water elevation are important to the successful establishment of *Spartina alterniflora*, and, therefore, elevations surveys to confirm existing elevations would be critical prior to any restoration efforts.

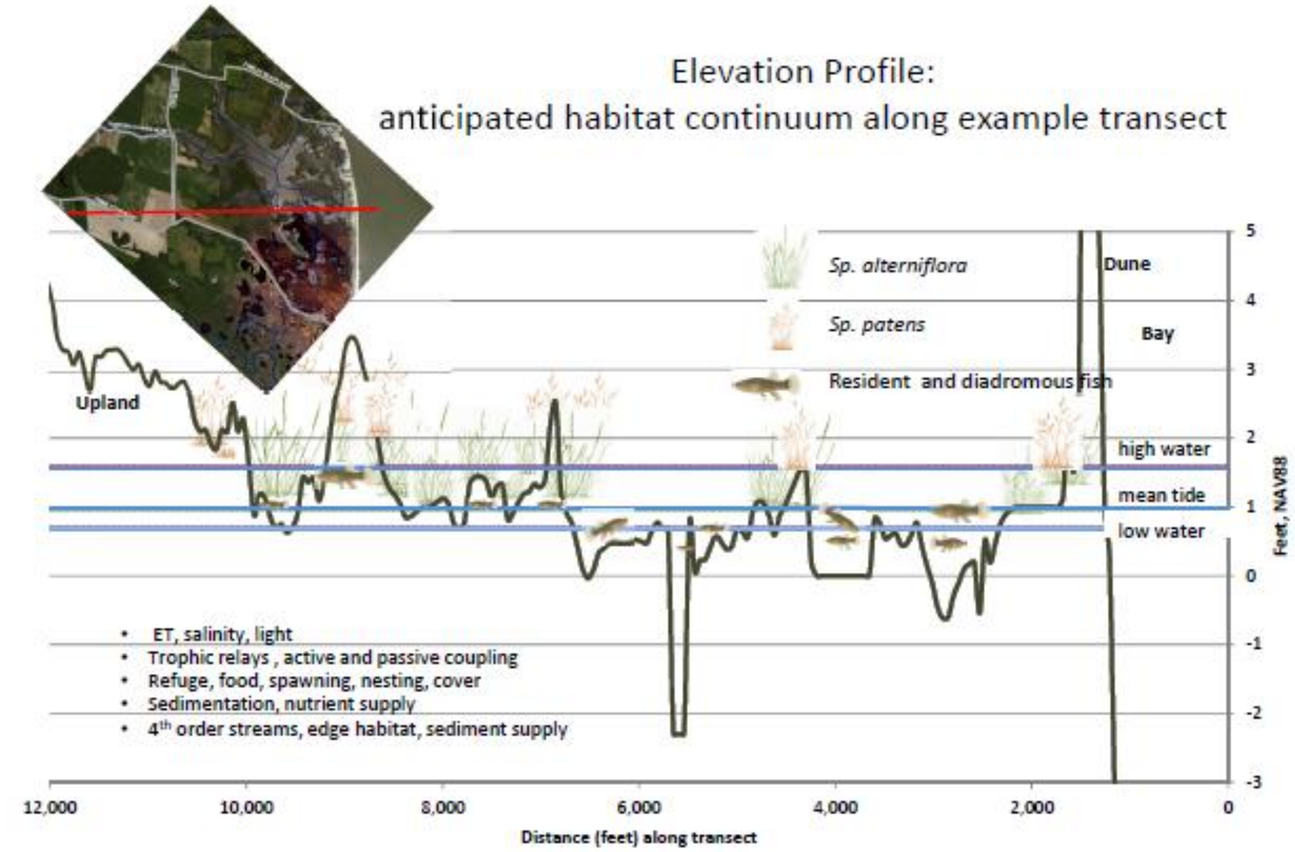

Figure 31. Example of restored marsh profile along a sample transect in management Unit II.

Marshes and associated tidal creeks provide breeding areas, prey refuge, and food (Zimmerman and Minello 1984, Boesch and Turner 1984, Kneib 1994 and 1997, Minello and Zimmerman 1991). Factors important to marshes include inundation of seawater to elevation that preclude invasion by upland species or species less tolerant of salinities. Marsh vegetation shades the soil beneath it, reduces light available for other species, and influences the salinity of the soils via evapotranspiration. Saltmarshes and tidal creeks are areas of energy exchange among biological (e.g. fish and vegetation) and physical (e.g. sediments) that occur as trophic relays and energy coupling between the water column and the sediments. The saltmarsh provides refuge, food, nesting and spawning areas, and cover for fish and wildlife.

Successful restoration/ establishment of *S. alterniflora* requires: adequate nutrients in soils, appropriate elevations (in some studies 0.2-0.5 meters above MLW), a gradual slope of 1-10 percent, adequate tidal exchange, less than 2 kilometers of fetch, and protection from herbivory and disturbance (e.g. snow geese). General conditions under which dominant, desirable, saltmarsh species are anticipated (e.g. saltmarsh cordgrass and hay), along with conditions typical of the undesirable and invasive common reed, are briefly presented in Table 1.

Based on results of the hydrodynamic model (i.e. salinity and water levels), a conceptual design of the restoration results is presented in Figure 32. The conceptual results include open water, tidal flats, and low and high marsh. This design includes restoration of flow to the marshes, which will in turn restore salinity and inundation, but does not include addition of sediments to raise the marsh surface.

Table 1. Summary of environmental conditions typical of target species for Prime Hook NWR saltmarsh restoration project.

Plant species/ community	Hydrology	Salinity	Soil/ substrate	Competition	Recovery period*
Saltmarsh cordgrass (S. alterniflora)/ low marsh	MTL-MHW, < 1' water above MHW. Optimum planting depths 1-18 in. (NRCS/USDA 2012).	0-40 ppt tolerance, typically 10-30 ppt, optimal 0-5 ppt.	Begins on younger (sandier) substrates, outcompetes *Phragmites* on sandy substrates	Outcompeted by freshwater species, including *Phragmites*, at <10 ppt. and at higher elevations	2-5 years for recovery with appropriate inundation and salinity with no planting.
Saltmeadow cordgrass (S. patens)/ high marsh	MHW – SHW, saturated soils from 10 cm below MHT to 10 to 15 cm above MHT, intolerant of regularly flooding.	1-27 ppt on Atlantic coast, Typically 2-12 ppt , 0 ppt optimal, tolerate up to 40 ppt for brief periods, < tolerant than *S. alterniflora*.	low nutrient levels, low to moderate sand coverage	Limited seaward by inundation, limited landward by competition.	Valuable for coastal restoration: rapidly establishes on dredged material, storm washover sites. Recovered from 20 cm sand cover in 2 years after simulated wash over sand accretion.
Common reed (Phragmites australis)/ low marsh	3 feet of water over rhizomes for (about) 4 months during growing season results in mortality, tolerant of seasonal flooding < 50cm.	0-20 ppt, typically intolerant of salinities >18 ppt, but up to 60 in experiments	Typically fine clays to sandy loams, < sandy than *S. alterniflora*	Invasive, outcompetes fresh or saltmarsh species once established in freshwater or low salinity wetlands	Replaced by *S. alterniflora* when hydrology restored in CT marshes Cutting and flooding reportedly effective, often associated with disturbance.

* Recovery is rapid for hydrology and vegetation and numerous invertebrates. However, soil processes may take many years to recover (see citations below).

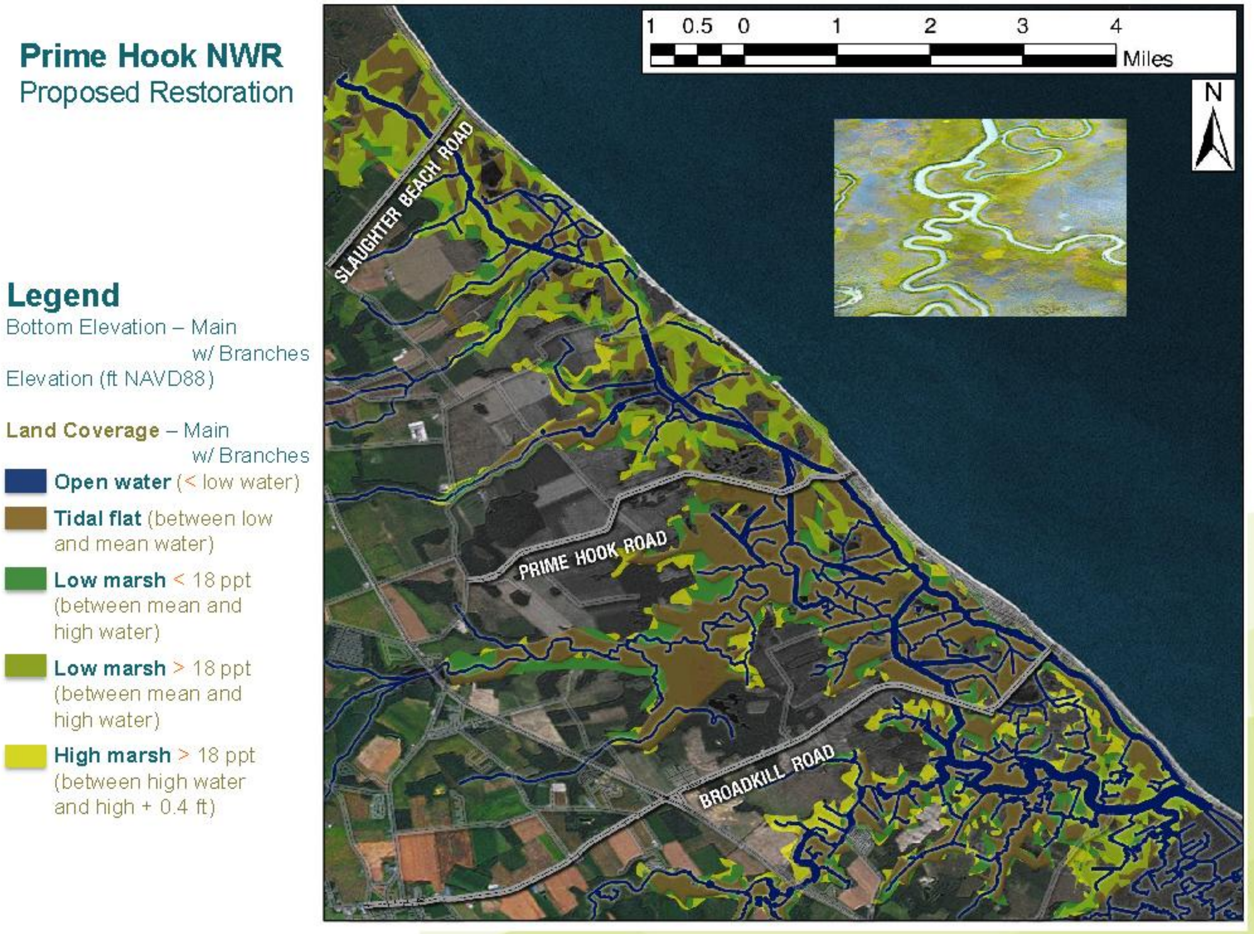

Figure 32. Conceptual diagram of proposed restoration results, based on salinity and water level modeling results.

8.3. Historical and Current Vegetation

The Delaware Natural Heritage Program (DNHP), part of the Division of Fish and Wildlife, Delaware Department of Natural Resources and Environmental Control, recently (October 2013) completed a mapping effort in which historical vegetation conditions on the Refuge were mapped using the National Vegetation Classification System (NVCS). The NVCS is a national effort by The Nature Conservancy and NatureServe to standardize the names and classification of vegetation communities in North America. Common names of the vegetation communities in Delaware are the same as those used in the NVCS. The 1937 aerial photography and corresponding vegetation communities are mapped in Figure 33 (Unit I), Figure 34 (Unit II), and Figure 35 (Unit 5). The mapping effort did not include Unit IV. These maps provided an opportunity to compare the vegetation communities anticipated under the modeled conditions (based on water levels and salinities) with the historical vegetation communities in the Refuge.

All the management units included low saltmarsh on the seaward side (lower elevations) and high saltmarsh on the landward side of the wetlands. Tidal flats occurred at even lower elevations in the marshes, with open water ponds scattered in some of the units and oldfield communities (former agricultural lands) at the landward side of the marshes.

- Historic wetland communities in Unit I were almost exclusively low saltmarsh, with some high saltmarsh at the landward edges before transitioning to oldfield communities.

- Unit II was historically characterized by low and high saltmarshes, seepage marshes (fewer tidal channels), and some small open water ponds, relatively large areas of oldfield communities. Low saltmarsh occurred on the seaward side of the Refuge where channels provided tidal exchange and mesohaline (5-18 ppt) seepage marshes occurred landward of the low saltmarsh and in the southern portion of the Refuge where there were few tidal channels, with pockets of corresponding polyhaline (18-30 ppt, associated with low saltmarsh) and mesohaline (5-18 ppt, few tidal channels) open water ponds.
- Unit III had less tidal influence and had more seepage marshes (fewer tidal channels) in the northern and central portions of the management unit, high saltmarsh landward of the seepage saltmarshes, and some low saltmarsh in the southern portion of the management unit where tidal influence (via the Broadkill River) was greater.

These vegetation community maps appear to corroborate the model results in terms of salinities and elevation and anticipated vegetation, illustrated earlier in Figure 32. Modeled elevations and salinities suggest more low marsh in Unit I when compared with the other management units, the presence of open water ponds in Unit II and Unit III.

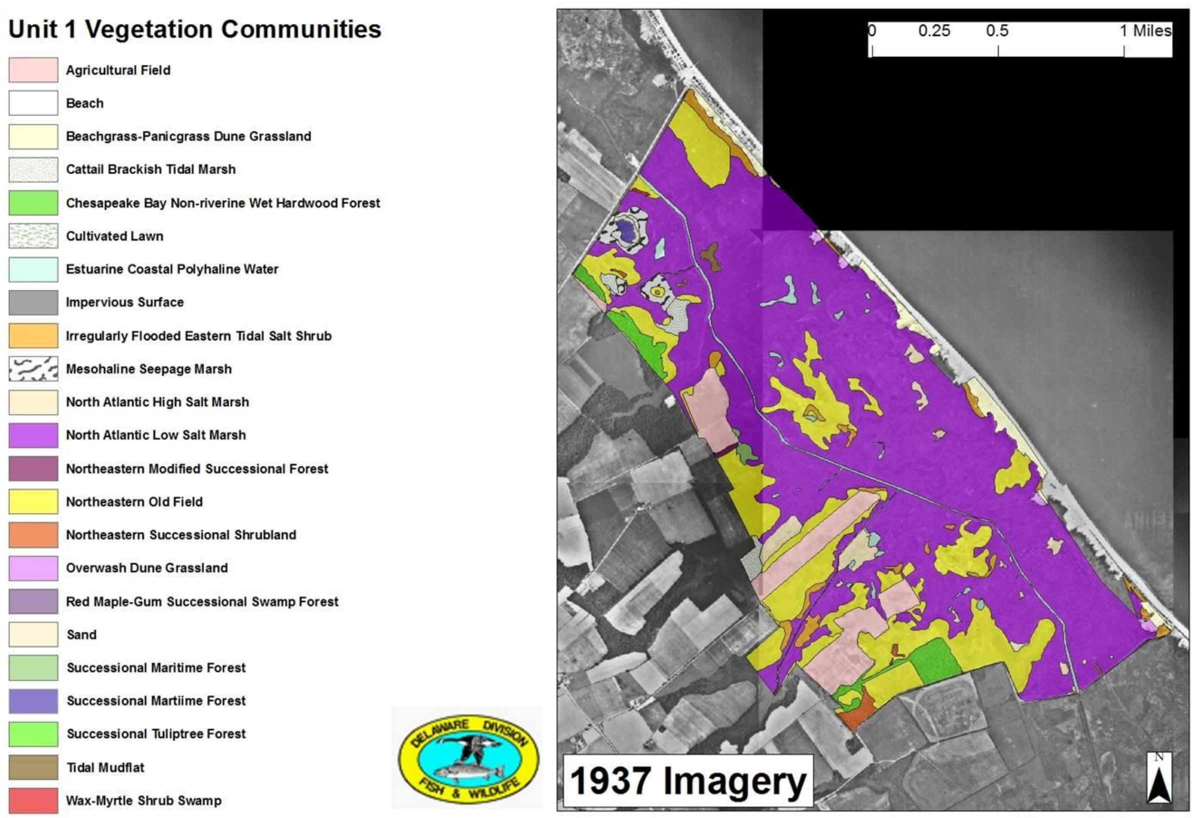

Figure 33. Historical vegetation communities in Unit I of the Refuge.

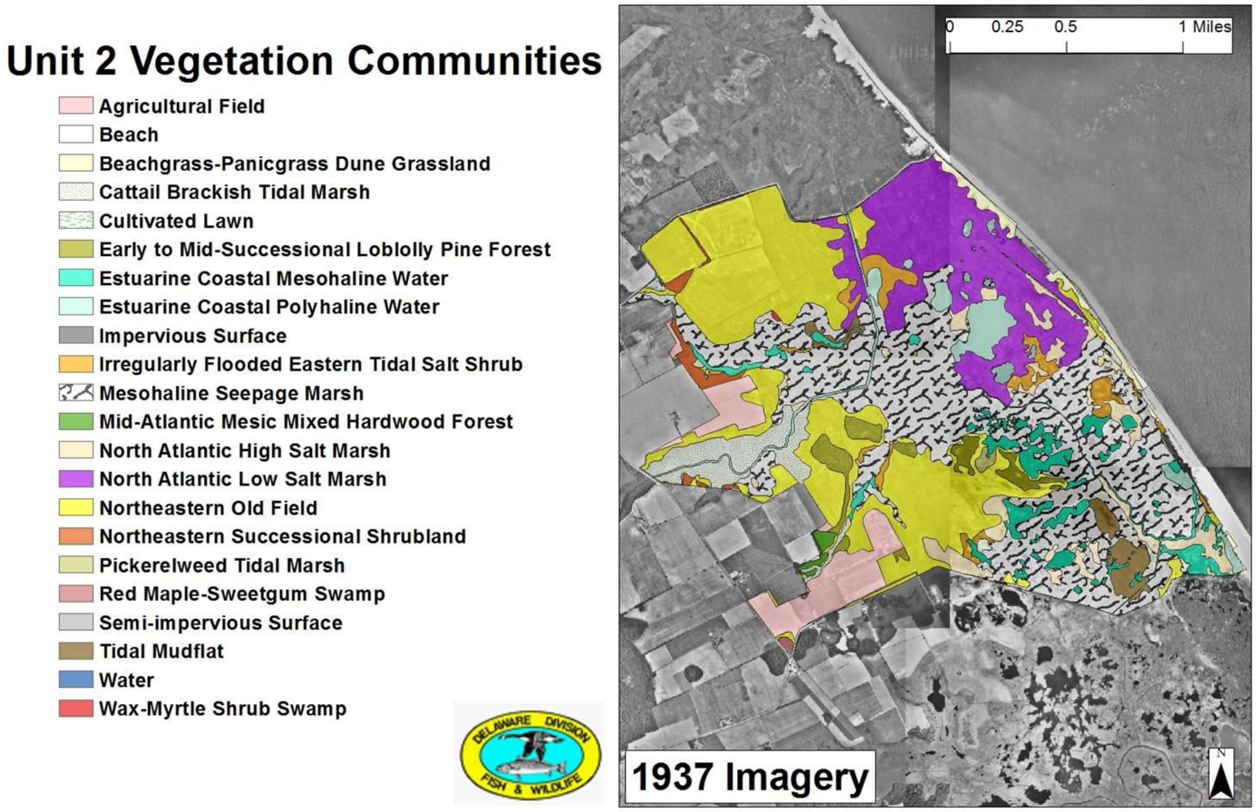

Figure 34. **Historical vegetation communities in Unit II of the Refuge.**

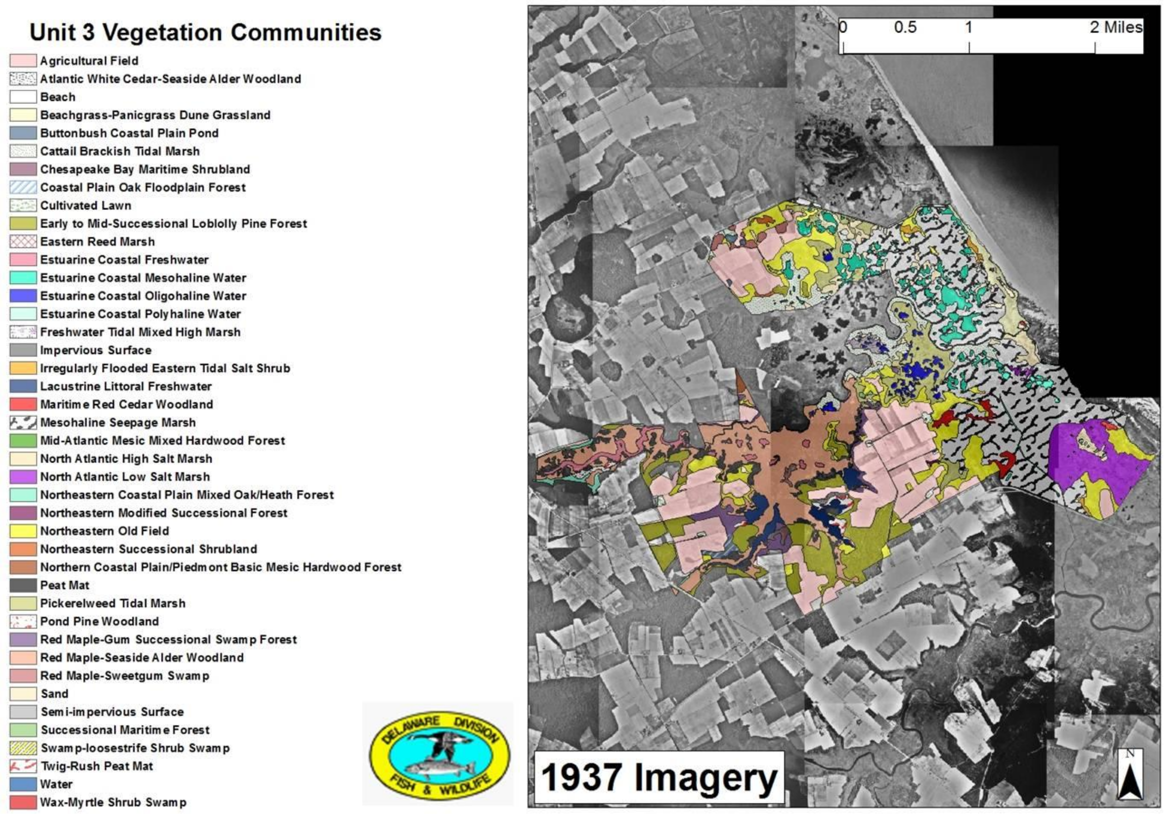

Figure 35. **Historical vegetation communities in Unit III of the Refuge.**

8.4. Timeframes

Several authors have pointed to the ability of marshes to recover very quickly with respect to vegetation, hydrology, fauna, although soils may require longer timeframe. Restoration timelines vary, but may require 2-15 years (Craft et al. 2003b, Broome et al. 1988), with vegetation recovering quickly following hydrologic restoration (Roman et al. 2001, Burdick 1997). Soils recover more slowly because of the time required to accumulate a nutrient pool. Craft et al. (2003b) describe restoration “trajectories” that illustrate/compare development of saltmarsh function development for natural and constructed wetlands (see Figure 36). In it, wetland soil development is delayed as soil organic carbon and nitrogen accumulate, while primary production due to biological processes is relatively quick when compared to natural systems.

Re-planting typically expedites restoration efforts. Techniques for seeding, planting, and transplanting *S. alternilora* have been sufficiently developed so that the establishment is highly likely when the prescribed conditions are met (Woodhouse 1979, Knutson et al. 1981, Webb and Newling 1985, Allen et al. 1986, Earhart and Garbisch 1983, Broome et al. 1988, Broome 1989, Nailon and Seidensticker 1991).

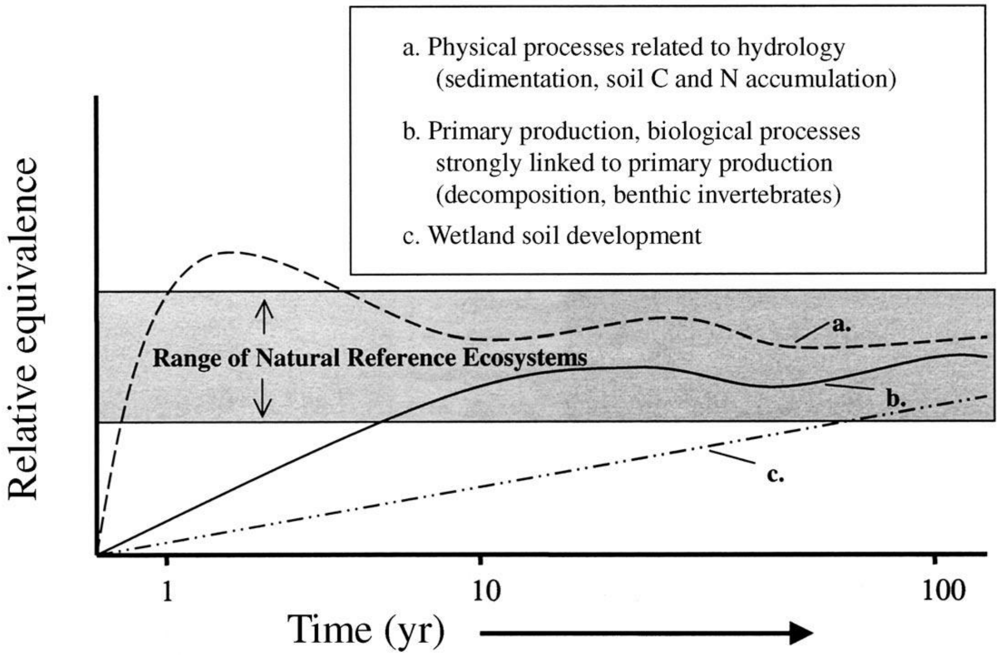

Figure 36. Time frames for restoration of physical and biological components in a saltmarsh.

9. Conclusions and Recommendations

The hydrodynamic model developed for this study provides a robust, detailed tool for analyzing potential restoration alternatives for Prime Hook NWR. Overall, the water levels and salinities in the model results demonstrate the following key points when analyzing possible 'breaches closed' scenarios:

- Adding a main channel connecting Slaughter Canal (and thus Mispillion Inlet) to the Broadkill River and Roosevelt Inlet (via Prime Hook Creek and Petersfield Ditch) allow for greater water exchange between Prime Hook NWR and Delaware Bay.
- The increased water exchange and flow provided by this channel lowers the water level within the Refuge by reducing the amount of water 'stacked' within the Refuge management units.
- The augmented exchange increases the average and maximum salinity levels within all four management units.
- Adding secondary finger channels to the main channel successfully distribute saline water to a larger area of the Refuge than the main channels alone.
- Closing the breaches reduces storm surge levels within the Refuge by about 1.6 feet compared to existing conditions during a Sandy-type event.

The water levels and salinities from these modeled alternatives are crucial in planning and developing any restoration activities within the Refuge.

10. References

Atkins (2009). *Management Plan for the Delaware Bay Beaches.* Tampa, FL. Produced for DNREC.

Atkins (2013), *Post-Storm Survey and Breach Analysis for Prime Hook*, Dover, DE. Produced for USFWS.

Adamowicz, S.C., C.T. Roman, G. Taylor, K. O'Brien, M.J. James-Pirri. 2004. Initial Ecosystem Response of Salt Marshes to Ditch Plugging and Pool Creation at Rachel Carson National Wildlife Refuge (Maine). Ecological Restoration 22:53-54.

Adamowicz, S.C. and C.T. Roman. 2002. Initial Ecosystem Response of Salt Marshes to Ditch Plugging and Pool Creation: Experiments at Rachel Carson National Wildlife Refuge (Maine). Final report to the U.S. Fish and Wildlife Service, Region 5, Newington, NH 03801.

Antonia, H. B., M. Wijte, and John L. Gallagher. Strategies *of Spartina alterniflora* and *Phragmites australis* (Poaceae). American Journal of Botany. Vol. 83, No. 10 (Oct., 1996), pp. 1337-1342.

Armbruster, C.K. 2000. Ecological Review of New Cut Dune/Marsh Restoration. CWPPRA Priority Project List 9 (State No. TE-37, Federal No. TE-11a). Database/Analysis Section, Coastal Restoration Division Louisiana Department of Natural Resources.

Bertness, M.D. 1991. Zonation of *Spartina* spp. in New England salt marshes. *Ecology* 72:138-148.

Bertness, M.D. and A.M. Ellison. 1987. Determinants of pattern in a New England salt marsh plant community. *Ecological Monographs* 57(2):129-147.

Boesch, D.F., Turner, R.E., 1984. Dependence of fishery species on salt marshes: the role of food and refuge. Estuaries 7:460–468.

Brenner, O.T. and L.J. Moore. 2010. Exploring the Importance of Back barrier Marsh Deposits in Barrier Island Response to Sea Level Rise, Virginia Coast Reserve, U.S.A. American Geophysical Union, Fall Meeting 2010, abstract #EP33B-077.

Broome, S. W. 1989. Creation and restoration of tidal wetlands of the Southeastern United States, p. 37-72 *In* Kusler, J. A. and M. E. Kentula (ed.). Wetland creation and restoration: The status of the Science. Volume I: Regional overviews. EPA/600/3-89/038. U.S. Environ. Prot. Agency, Corvallis.

Broome, W., E.D. Seneca, W.W. Woodhouse. 1988. Tidal saltmarsh restoration. Aquatic Botany 32: 1-22.

Burdick, D.M., M. Dionne, R.M. Boumans and F.T. Short. 1997. Ecological responses to tidal restorations of two northern New England salt marshes. Wetland Ecology and Management 4:129-144.

Craft, C., P. Megonigal, S. Broome, J. Stevenson, R. Freese, J. Cornell, L. Zheng, and J. Sacco 2003. The pace of ecosystem development of constructed *Spartina alterniflora* marshes. Ecological Applications 13:1417–1432. http://dx.doi.org/10.1890/02-5086

Davis, R.A. Jr.; Fitzgerald, D. M. 2004. Beaches and Coasts. Blackwell Publishing, United Kingdom. ISBN 0-632-04308-3.

Delaware Geological Survey. (2005). *2005 Delaware Coastal Program LiDAR: Sussex County.* Retrieved from http://csc.noaa.gov/htdata/lidar1_z/geoid12a/data/111/

Dolan, R., 1972. Barrier dune system along the outer banks of North Carolina: A reappraisal.

Earhart, H. G. and E. W. Garbisch Jr. Habitat development utilizing dredged material at Barren Island, Dorchester County, Maryland. "Wetlands 3 (1983): 108-1 19.

EPA. 2012. Ecosystems and their elements. http://www2.epa.gov/sites/production/files/documents/ecosystemsandtheirelements.pdf

Fitzgerald, D.M., M.S. Fenster, B.A. Argow, and I.V. Buynevich. 2008. Coastal Impacts Due to Sea-Level Rise. Annual Review of Earth and Planetary Sciences. 36:601–47.

Forte, Michael F., et al. (2011). *Coastal Storm Surge Analysis System Digital Elevation Model.* Washington, D.C. U.S. Army Corps of Engineers.

Godfrey, P. J. 1970. Oceanic Overwash and its Ecological Implications on the Outer Banks of North Carolina. U.S. Dept. of the Interior, National Park Service. 37 pages.

Godfrey, P. J. 1976. Barrier beaches of the east coast. Oceanus, v. 19, n. 5, p. 27-40.

Goldsmith, V. 1985. Coastal Dunes. Chapter 5 *In* Davis, R.A. (Ed.). Coastal Sedimentary Environments. Springer-Verlag. New York. 716 pages.

Hellings, S.E. and J.L. Gallagher. 1992. The Effects of Salinity and Flooding on *Phragmites australis*. Journal of Applied Ecology 29(1): pp. 41-49.

Kneib, R.T. 1994. Spatial pattern, spatial scale, and feeding in fishes. In: Stouder, D.J., Feller, R.J. (Eds.), Theory and Application in Fish Feeding Ecology. University of South Carolina Press, Columbia, South Carolina, pages 171–185.

Kneib, R.T. 1997. The role of tidal marshes in the ecology of estuarine nekton. Oceanography and Marine Biology. Ann. Rev. 35: 163–220.

Knutson, P.L. 1987. Role of Coastal Marshes in Energy Dissipation and Shore Protection. Pages 161-175 In The Ecology and Management of Wetlands

Kraft, J.C. 1971. Sedimentary Environment, Facies Pattern, and Geologic History of a Holocene Marine Transgression. Bulletin of the Geological Society of America, Vol. 82, 1971, pp. 2131-2158.

Leatherman, S.P. and R.E. Zaremba. 1986. Dynamics of a northern barrier beach: Nauset Spit, Cape Cod, Massachusetts. *Geological Society of America Bulletin*, January, 1986, v. 97, no. 1, p. 116-124.

Leatherman, S.P. Migration of Assateague Island, Maryland, by Inlet and Overwash Processes. Geology, Vol. 7, 1979b, pp. 104-107.

McBride, R.A.and M.R. Byrnes. 1997. Regional Variations in Shore Response along Barrier Island Systems of the Mississippi River Delta Plain: Historical Change and Future Prediction. Journal of Coastal Research. 13(3): 628-655.

Moore, L., J. H. List, S.J.Williams, K. Patsch. 2010. Barriers on the Brink? The complex intertwined roles of geologic framework, sediment availability, and seas-level rise in island evolution. Page 272-285 *In* Wang, P., J. Rosati, and T. Roberts (Ed). Proceedings of the Coastal Sediments 2011. Volume 1. World Scientific Publishing, NJ. Volume 1.

Moore, L.J., List, J.H., Williams, S.J. and Stolper, D., 2010, Complexities in barrier island response to sea-level rise: Insights from model experiments. *Journal of GeophysicalResearch-Earth Surface,* doi:10.1029/2009JF001299.

Morris, J.T., P.V. Sundareshwar, C.T. Nietch, R.N. Kjerfve, and D.R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. *Ecology,* 83(10), 2002, pp. 2869–2877.

Nailon, R. W. and E. L. Seidensticker. The effects of shoreline erosion in Galveston Bay, Texas. In: Coastal wetlands, ed. H. S. Bolton. 193-206. New York: Amer. Soc. Civil.

Niering, W. A. and Warren, R. S. 1980. Vegetation patterns and process in New England salt marshes. *Bioscience* 30:301-307.

Odum, W.E., T.J. Smith III, J.K. Hover, and C.C. McIvor. 1984. The ecology of tidal freshwater marshes of the United States east coast: a community profile. FWS/OBS-83/17. U.S. Fish and Wildlife Service. Washington DC. 177 pages.

Penland, S., P.F. Connor, Jr., and A. Beall. 2004. Changes In Louisiana's Shoreline: 1855–2002 *In* Chapter D.3. Louisiana Coastal Area (LCA), Louisiana Ecosystem Restoration Study. Appendix D - Louisiana Gulf Shoreline Restoration Report.

Reed, D. 1989. The Role of Salt Marsh Erosion in Barrier Island Evolution and Deterioration in Coastal Louisiana. Gulf Coast Association of Geological Societies Transactions Vol. 39 (1989), Pages 501-510.

Robert I. Lonard, R.I., F.W. Judd, and R. Stalter (*2010*) The Biological Flora of Coastal Dunes and Wetlands: Spartina patens (W. Aiton) G.H. Muhlenberg. Journal of Coastal Research: Volume 26, Issue 5: pp. 935 – 946.

Roman, C.T., K.B. Raposa, S.C. Adamowicz, M. James-Pirri, and J.G. Catena. 2002. Quantifying vegetation and nekton response to tidal restoration of a New England salt marsh. *Restoration Ecology* 10: 450-460.

Roman, C.T., K.B. Raposa, S.C. Adamowicz, M.J. James-Pirri, J.G. Catena. 2002. Quantifying vegetation and nekton response to tidal restoration of a New England salt marsh. Restoration Ecology 110: 450-460.

Roman, C.T., M. James-Pirri, and J.F. Heltshe. 2001. Monitoring salt marsh vegetation: a protocol for the Long-term Coastal Ecosystem Monitoring Program at Cape Cod National Seashore. Technical Report, USGS Patuxent Wildlife Research Center, Narragansett, RI.

Roman, C.T., W.A. Niering, and R.S. Warren. 1984. Salt marsh vegetation change in response to tidal restriction. *Environmental Management* 8:141-150.

Rosati, J. D., G. W. Stone, R. G. Dean, and N. C. Kraus. 2006. Restoration of barrier islands overlying poorly-consolidated sediments, south-central Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 56, p. 727-740.

Rosen, P.S. 1980. Erosion susceptibility of the Virginia Chesapeake Bay shoreline. Marine Geology 34: 45-59.

Sallenger, A.H. 2010. Hurricanes, sea level rise, and coastal change. IN Coastal Sediments, volume 1. P.Wang, J.D. Rosati, and T.M. Roberts, Editors. World Scientific Publishing, London. Pages 15-28.

Sallenger, A.H. Jr., C.W. Wright, P. Howd, K. Doran, and K. Guy. 2010. Extreme Coastal Changes on the Chandeleur Islands, Louisiana, During and After Hurricane Katrina. Chapter B of *Sand Resources, Regional Geology, and Coastal Processes of the Chandeleur Islands Coastal System: an Evaluation of the Breton National Wildlife Refuge*. Edited by Dawn Lavoie In cooperation with the U.S. Fish and Wildlife Service Scientific Investigations Report 2009–5252.

Scarborough, Robert. (2012). *Prime Hook National Wildlife Refuge Surface Elevation Surveys.* Dover, DE. Delaware Department of Natural Resources and Environmental Control.

Tyler, A.C., and J.C. Zieman. 1999. Patterns of development in the creek bank region of a barrier island *Spartina alterniflora* marsh. Marine Ecology Progress Series 180:161-177.

USGS. 2013. U.S. Department of the Interior | U.S. Geological Survey. URL: http://3dparks.wr.usgs.gov/nyc/shoreline/beaches.htm. Page Contact Information: Page Last Modified: 11-Jan-2013@16:46

Walters, D., L.J. Moore, O.D. Vinent, G. Mariotti, S. Fagherazzi. 2012. EP33B-0864: Dynamic interactions and feedbacks between barrier and back-barrier environments, and their role in barrier-marsh co-evolution. American Geophysical Union's (AGU) 45th annual Fall Meeting. San Francisco, California. December 3-7.

Webb J.W. and C.J. Newling. 1985 Comparison of natural and man-made salt marshes in Galveston Bay complex, Texas. Wetlands 4:75-86.

Weishar, L.L., J.M. Teal, and r. Hinkle. 2005. Designing large-scale wetland restoration for Delaware Bay. Ecological Engineering 25 (2005) 231–239.

Weinstein, M.P, D.A. Kreeger, M.P. (Ed.). 200). Concepts and controversies in tidal marsh ecology. Kluwer Academic/Kluwer Academic Publishers: Dordrecht. ISBN 0-7923-6019-2. xvii, 875 pages.

Woodhouse, W. W. 1979. Building salt marshes along the coasts of the continental United States. U.S. Army, Corps of Engineers Coastal Engineering Research Center Special Report Number 4. U.S. Army, Corps of Engineers, Fort Belvoir, VA.

Zimmerman, R. J. and T. J. Minello 1984. Densities of *Penaeus aztecus*, *P. setiferus* and other natant macrofauna in a Texas salt marsh. Estuaries 7: 421-433.

Appendix A. Model Details

A.1. Existing Data

A.1.1. Bathymetry and Topography

In order to develop a numerical model that represents real-world physical conditions as accurately as possible, a detailed and up-to-date elevation data set is crucial. To this end, a number of existing bathymetric and topographic data sets were used in the model creation, in addition to survey and LiDAR data collected as part of this effort:

- A Digital Elevation Model (DEM) for Delaware Bay, created for the updated ADCIRC model for FEMA Region III (Forte, 2011)
- The Sussex County, DE topographic DEM, developed by the Delaware Geological Survey (2005)
- Point survey data collected within select water regions of the Refuge by the Delaware Department of Natural Resources and Environmental Control (DNREC) (2012)
- Survey and LiDAR data of the breaches and surrounding areas, collected by VanDemark & Lynch, Inc. (VDM) as a part of this effort (2013).

All data sets were loaded as XYZ point files within the Surface Water Modeling System (SMS) and converted to geographic (decimal degrees) coordinates in the horizontal, and NAVD88 (meters) in the vertical. Triangulation of each data set was performed and extraneous border triangles were removed so that erroneous elevation interpolation was minimized; this was especially crucial in areas were the survey was simply a channel centerline. Once aligned and triangulated, the data sets were merged into a single, unified elevation set. Priority was given to data in the following order: 2013 LIDAR and survey → 2012 DNREC survey → 2005 Sussex DEM → 2011 Delaware Bay DEM. Points and triangles that fell within the triangulation bounds of a higher-priority data set were deleted in the merge. The 2005 DEM was given priority over the 2011 FEMA DEM because the 2005 DEM was much more detailed on land but contained no water points; the 2011 FEMA DEM was mainly used as elevation offshore and in regions away from the Refuge, where the highest levels of detail were not necessary.

After the merge, care was taken to ensure that small but important features within the Refuge, such as channels and roads, remained well-defined. Where necessary to preserve these features, elevation points were manually edited based on the best original source data. This final comprehensive elevation data set was used to define elevations at every grid point in the model.

A.1.2. Water Levels and Salinities

The hydrodynamic model incorporated extensive measurements of water level and salinity across a large expanse of the domain. Long-term tide gauge data pertinent to the modeling effort was available from ten sites within the Atlantic Ocean, Delaware Bay, and the Delaware River. The station locations, names, and data ranges are presented in Table 2. At many of these gauges, a complete set of harmonic tidal constituents (component, amplitude, phase, and speed) were available in addition to the measured data. A harmonic constituent represents a single, periodic variation in the relative positions of the Earth, Moon, and Sun, and the combination of all harmonics at a location describes the gravitational tide in that area. These harmonic constituents are useful when a ‘synthetic’ tidal signal, free of influence from winds, inflows, and other outside factors, becomes useful. Harmonic constituents for Atlantic City, NJ, Ocean City, MD, and Lewes, DE are shown in Table 3.

Table 2. NOAA tide gauge stations with measured data within study area.

Station ID	Station Name	Longitude (° W)	Latitude (° N)	Data Start	Data End
8534720	Atlantic City, NJ	74.4180	39.3550	1911	2012
8536110	Cape May, NJ	74.9600	38.9683	1965	2012
8537121	Ship John Shoal, NJ	75.3750	39.3050	2002	2012
8539094	Burlington, Delaware River, NJ	74.8683	40.0817	1979	2012
8540433	Marcus Hook, PA	75.4100	39.8117	1981	2012
8545240	Philadelphia, PA	75.1417	39.9333	1989	2012
8551910	Reedy Point, DE	75.5733	39.5583	1996	2012
8555889	Brandywine Shoal Light, DE	75.1133	38.9867	1984	2012
8557380	Lewes, DE	75.1200	38.7817	1957	2012
8570283	Ocean City Inlet, MD	75.0920	38.3280	1997	2012

Table 3. NOAA harmonic constituents for select gauges in model domain.

Constituent	8534720	Atlantic City, NJ		8570283	Ocean City, MD		8557380	Lewes, DE	
	Frequency (rad/s)	Amplitude (ft MSL)	Phase (rad)	Frequency (rad/s)	Amplitude (ft MSL)	Phase (rad)	Frequency (rad/s)	Amplitude (ft MSL)	Phase (rad)
M2	1.4052E-04	1.948	6.203	1.4052E-04	1.058	0.143	1.4052E-04	2.020	0.543
S2	1.4544E-04	0.381	0.311	1.4544E-04	0.189	0.534	1.4544E-04	0.355	0.991
N2	1.3788E-04	0.462	5.863	1.3788E-04	0.242	6.075	1.3788E-04	0.438	0.185
K1	7.2921E-05	0.362	3.197	7.2921E-05	0.184	3.636	7.2921E-05	0.338	3.520
M4	2.8104E-04	0.033	3.171	2.8104E-04	0.076	2.936	2.8104E-04	0.042	3.252
O1	6.7598E-05	0.246	2.899	6.7598E-05	0.176	3.484	6.7598E-05	0.273	3.292
M6	4.2156E-04	0.019	1.480	4.2156E-04	0.000	0.000	4.2156E-04	0.019	6.100
MK3	2.1344E-04	0.000	0.000	2.1344E-04	0.021	6.227	2.1344E-04	0.000	0.000
S4	2.9089E-04	0.000	0.000	2.9089E-04	0.010	3.704	2.9089E-04	0.000	0.000
MN4	2.7840E-04	0.019	2.738	2.7840E-04	0.033	2.710	2.7840E-04	0.023	3.103
NU2	1.3823E-04	0.084	5.875	1.3823E-04	0.047	6.124	1.3823E-04	0.093	0.199
S6	4.3633E-04	0.000	0.000	4.3633E-04	0.000	0.000	4.3633E-04	0.000	0.000
MU2	1.3559E-04	0.065	5.953	1.3559E-04	0.030	6.013	1.3559E-04	0.039	0.295
2N2	1.3524E-04	0.066	5.576	1.3524E-04	0.029	5.704	1.3524E-04	0.054	6.224
OO1	7.8245E-05	0.010	3.555	7.8245E-05	0.007	3.786	7.8245E-05	0.013	4.177
LAM2	1.4280E-04	0.018	0.237	1.4280E-04	0.010	0.616	1.4280E-04	0.028	0.960
S1	7.2722E-05	0.018	2.002	7.2722E-05	0.011	2.356	7.2722E-05	0.025	2.323
M1	7.0282E-05	0.014	3.742	7.0282E-05	0.012	3.557	7.0282E-05	0.012	3.864
J1	7.5560E-05	0.021	3.040	7.5560E-05	0.011	3.320	7.5560E-05	0.022	3.398
MM	2.6392E-06	0.000	0.000	2.6392E-06	0.000	0.000	2.6392E-06	0.000	0.000
SSA	3.9821E-07	0.100	0.698	3.9821E-07	0.000	0.000	3.9821E-07	0.101	0.721
SA	1.9911E-07	0.233	2.539	1.9911E-07	0.000	0.000	1.9911E-07	0.172	2.452

Constituent	8534720	Atlantic City, NJ		8570283	Ocean City, MD		8557380	Lewes, DE	
	Frequency (rad/s)	Amplitude (ft MSL)	Phase (rad)	Frequency (rad/s)	Amplitude (ft MSL)	Phase (rad)	Frequency (rad/s)	Amplitude (ft MSL)	Phase (rad)
MSF	4.9252E-06	0.000	0.000	4.9252E-06	0.000	0.000	4.9252E-06	0.000	0.000
MF	5.3234E-06	0.000	0.000	5.3234E-06	0.000	0.000	5.3234E-06	0.000	0.000
RHO	6.5312E-05	0.009	2.772	6.5312E-05	0.007	3.417	6.5312E-05	0.011	3.096
Q1	6.4958E-05	0.038	2.944	6.4958E-05	0.022	3.262	6.4958E-05	0.043	3.192
T2	1.4524E-04	0.029	0.003	1.4524E-04	0.020	0.258	1.4524E-04	0.036	0.532
R2	1.4564E-04	0.003	0.326	1.4564E-04	0.001	0.552	1.4564E-04	0.011	4.892
2Q1	6.2319E-05	0.006	2.601	6.2319E-05	0.004	3.332	6.2319E-05	0.007	3.063
P1	7.2523E-05	0.109	3.115	7.2523E-05	0.066	3.496	7.2523E-05	0.110	3.475
2SM2	1.5037E-04	0.000	0.000	1.5037E-04	0.000	0.000	1.5037E-04	0.000	0.000
M3	2.1078E-04	0.021	0.654	2.1078E-04	0.000	0.000	2.1078E-04	0.011	1.920
L2	1.4316E-04	0.063	0.110	1.4316E-04	0.027	0.236	1.4316E-04	0.065	0.838
2MK3	2.0812E-04	0.011	0.579	2.0812E-04	0.021	6.243	2.0812E-04	0.000	0.000
K2	1.4584E-04	0.103	0.326	1.4584E-04	0.050	0.494	1.4584E-04	0.099	0.906
M8	5.6208E-04	0.000	0.000	5.6208E-04	0.000	0.000	5.6208E-04	0.000	0.000
MS4	2.8596E-04	0.000	0.000	2.8596E-04	0.016	3.138	2.8596E-04	0.013	3.594

In addition to the NOAA gauges, there were a total of nine locations within the Refuge that had recorded water levels and salinities from as early as October 2010 up through November 2012. These data were collected by USFWS and DNREC. Table 4 presents the locations and names of the stations.

Table 4. Locations of water level and salinity data time series within Refuge.

Station Name	Longitude (° W)	Latitude (° N)
Bay	75.26712277	38.8794272
Breach	75.26915118	38.8782229
Fowler N	75.27593578	38.87697918
Fowler S	75.27598998	38.87720807
Prime Hook N	75.26100528	38.85395056
Prime Hook S	75.26105667	38.8537075
HQ	75.23916444	38.83305028
Broadkill N	75.22810128	38.82063688
Broadkill S	75.22783964	38.81979878

A.1.3. Wind and Freshwater Inflow

In addition to tides, wind and freshwater inflow data were also used to drive the numerical model. Measured hourly wind speed and direction is available at NOAA's NDBC station 44009, 26 nautical miles southeast of Cape May, NJ (38.461° N, 74.703° W), from 1984-present.

For Delaware Bay as a whole, the two major freshwater influences are the Delaware River itself at Trenton, NJ, the upstream limit of tidal influence, and the Schuylkill River near Philadelphia, PA. Flow from these rivers has an appreciable effect on water levels within the bay, especially during storm events. The United States Geological Survey (USGS) maintains flow gauges for each of these rivers; Station 01463500 (Delaware River at Trenton, NJ) and Station 01474500 (Schuylkill River at Philadelphia, PA). Daily discharge for the Delaware River gauge is available from 1912-present, while the Schuylkill gauge has daily data from 1967-present.

Within the Refuge, the two main freshwater inputs are Slaughter Creek and Prime Hook Creek. There is an extremely limited measured velocity data set from 2012 for these locations but not enough to determine model boundary conditions. Instead, the USGS Streamstats application was used to develop 'base' and 'bank full' flow rates for these creeks based on a watershed analysis. These flow rates cannot be used as time series boundary conditions for specific events, but are useful as general guidelines when attempting to model long-term hydrodynamics within the Refuge. For Slaughter and Prime Hook Creeks, base flow was estimated to be 21 cfs and 79 cfs, respectively, while bank full flow is twice that, or 42 cfs and 158 cfs, respectively.

A.2. Model Development

A.2.1. Delft3D Overview

Delft3D was selected as the modeling platform for this study, based on the need for a high-resolution numerical model to estimate water levels and salinities within the Refuge for a number of different alternatives, as well as the capability to include possible sediment transport, morphology, and water quality studies in the future. Delft3D is a two- or three-dimensional hydrodynamic model that operates on rectilinear or curvilinear grids, for which hydrodynamics can be computed much more efficiently than unstructured, finite-element domains. It allows for the linkage of multiple domains into one large model so that complex bathymetry and topography can be accurately represented; this also allows for highly variable domain resolution without the need for gradual transitions. Structures such as thin walls and and weirs can be modeled as sub-grid scale features. The result is a very efficient model that has very little 'wasted' resolution in areas outside the location(s) of primary interest.

A.2.2. Grid Development

The model domain spans an arc in the Atlantic Ocean between Atlantic City, NJ and Ocean City, MD up Delaware Bay to Trenton, NJ, in order to be able to apply measured data at all significant forcing boundaries. A small portion of the Schuylkill River is also included. The land boundary follows the shoreline for the entirely of the model domain except for the subdomain surrounding the Refuge; here, the upland limit is the +13 ft (4 m) NAVD88 contour. There are seven subdomains total, ranging in resolution from 2.5 mi (4 km) in the Atlantic to 33 ft (10 m) within the Refuge. The full domain includes approximately 2 million elements.

The merged bathymetric data set described in Section A.1.1 was interpolated to the grid within the Delft3D user interface. After interpolation, important features within the Refuge such as roads and channels were manually added to the grid in locations where the interpolation process significantly smoothed and/or altered measured elevations. In this way, these features are still well-represented within the model. Culverts that cross underneath the roads at multiple locations were modeled by assigning a lower elevation to the closest grid cell so that water could flow between Refuge Units. The water control structures within the Refuge at Fowler Beach Road, Petersfield Ditch, and Prime Hook Creek were modeled as 2D weirs with their dimensions tuned to best replicate the measured water levels during the calibration period.

Figure 37 and Figure 38 illustrate the model grid for the entire domain and the main portion of Delaware Bay, respectively, Figure 39 shows the level of grid detail within the Refuge, and Figure 40 pictures the model bathymetry for the entire domain.

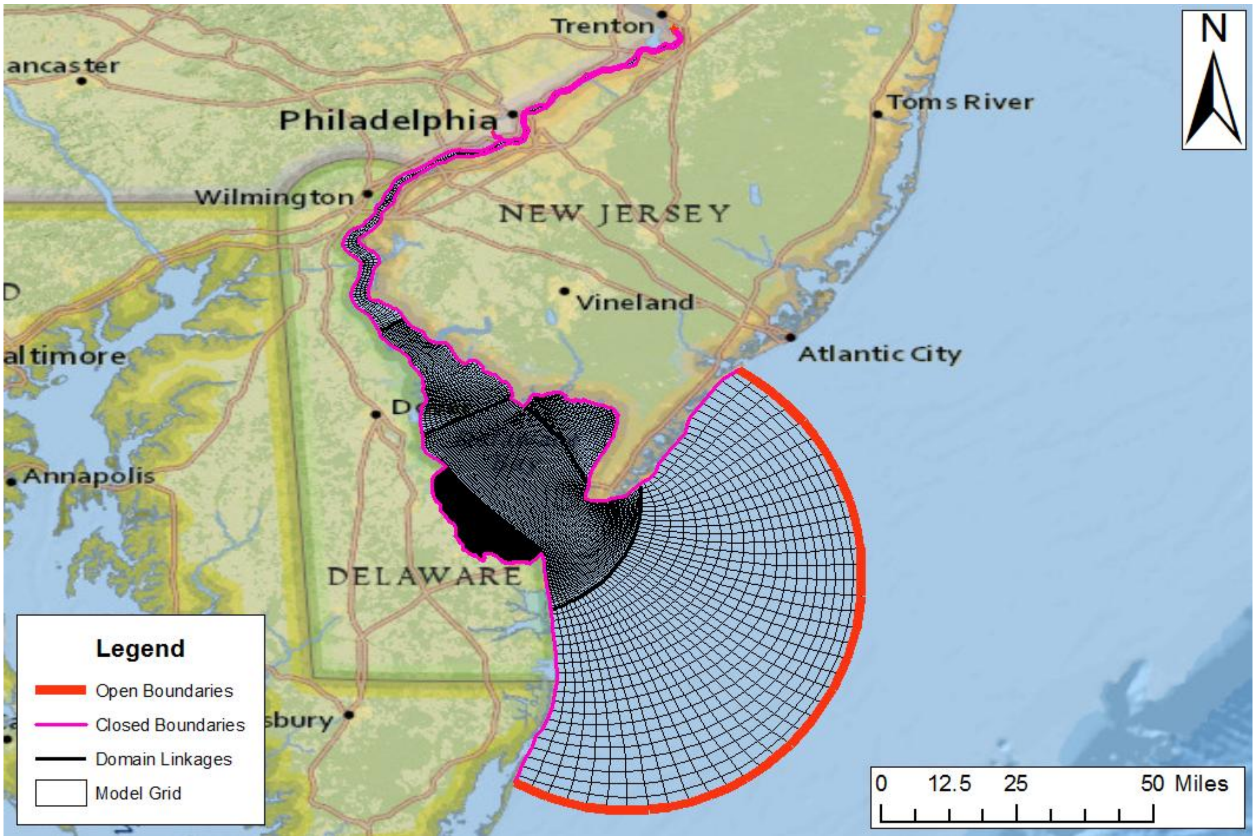

Figure 37. Model grid resolution for the entire model domain.

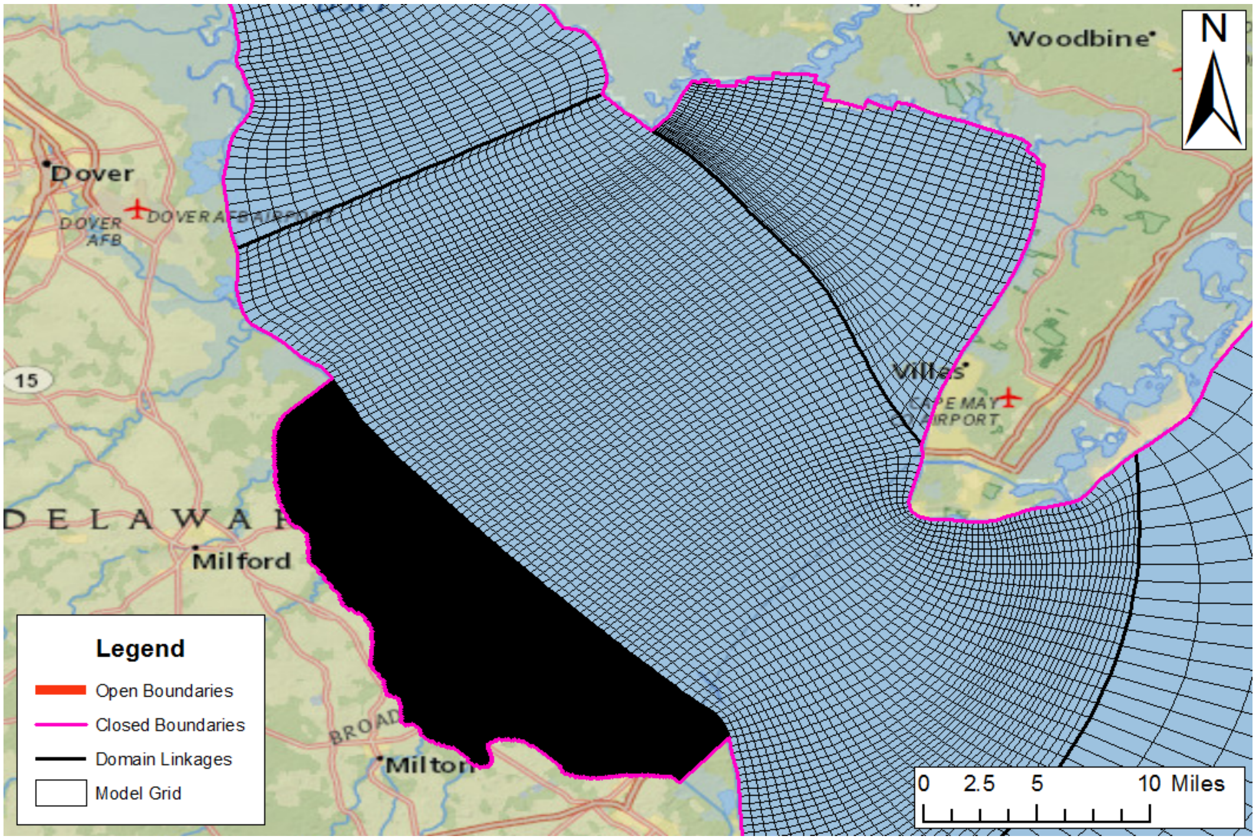

Figure 38. Model grid in the main body of Delaware Bay.

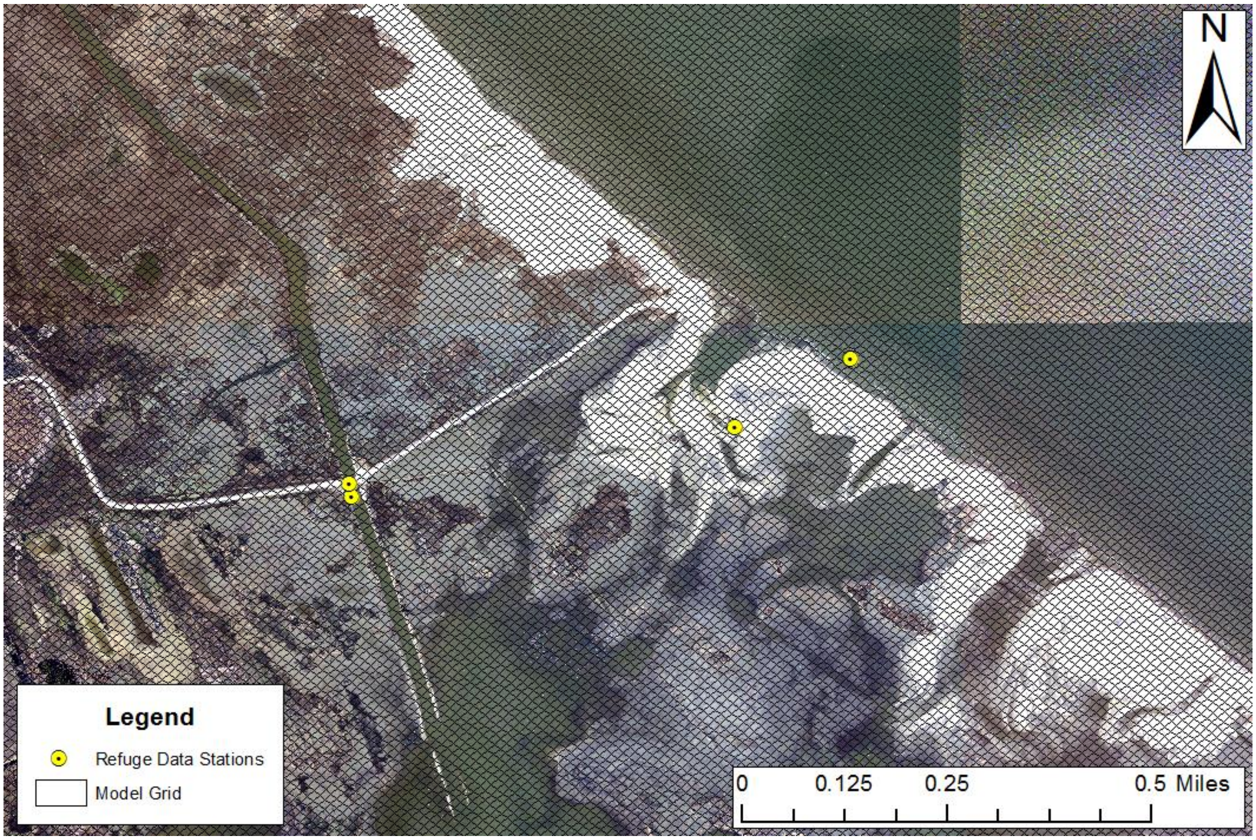

Figure 39. Model grid resolution for the Refuge.

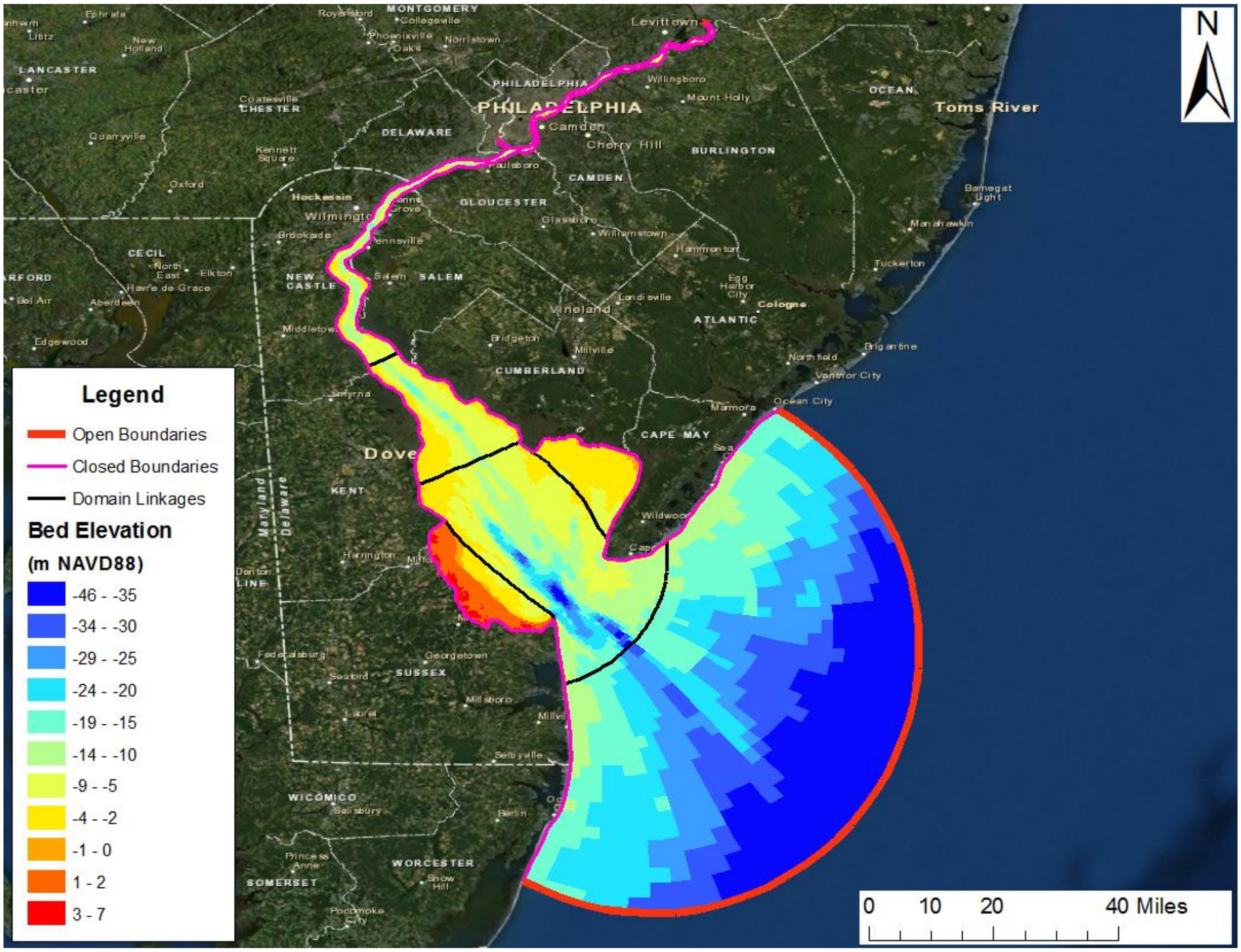

Figure 40. **Bathymetry for the entire model domain.**

A.2.3. Boundary Forcing Conditions

Depending on the type of model run, different driving factors were used to force the hydrodynamics of the model. During calibration and validation, the goal was to use a known set of conditions to adjust model parameters to best replicate measured water levels with model results. Therefore, it was necessary to drive the model with measured data.

For calibration/validation, tidal forcing was applied along the offshore boundary of the domain by using the NOAA measured water level time series for the time period of interest at Atlantic City, NJ and Ocean City, MD and interpolating between the two time series along the arc. Freshwater inflows were applied at the two upstream limits (the Delaware and Schuylkill Rivers) using the USGS daily discharge rates as time series. A time series of wind velocity and direction from NOAA station 44009 was applied uniformly over the domain to account for wind effects.

When the model is shown to behave well under a variety of applied conditions, production runs can begin, which in this case were an attempt to estimate long-term hydrodynamic conditions within the Refuge under normal conditions for multiple scenarios. For this study, there is a lack of measured data that is applicable for use as boundary conditions, because all measured data, has some degree of influence by sporadic or seasonal events and changes. In these runs, data from statistical analyses of boundary forcings were used to drive the model.

For the tidal boundary, reconstructed ‘synthetic’ water level time series for a complete tidal cycle were created at Atlantic City, NJ and Ocean City, MD based on NOAA’s harmonic constituents and applied in the same manner as the measured time series in the calibration runs. Since these time series covered an entire lunar cycle, the time series could be ‘piggybacked’ one after another to create as long of a run as deemed necessary by the model results. For Slaughter Creek and Prime Hook Creek within the Refuge, a time-independent constant flow rate was applied based on USGS Streamstats; the magnitude of these varied from no flow to base flow to bank full flow during testing and it was determined that base flow rates were the most realistic for a long-term scenario. Wind forcing, as well as inflow rates from the Delaware and Schuylkill Rivers, were not used, as these are less important during long-term average conditions versus storm conditions.

A.3. Model Calibration and Validation

Two primary model parameters were adjusted to obtain the best fit with measured data; first was the grid resolution, which affects the level of detail, runtime, and output file size, and second was the bottom friction formulation and value. Two time periods were examined. The grid and friction were varied while running the model for an 8-day period surrounding the peak of Hurricane Sandy until modeled water levels matched measured data to an acceptable degree. With these same parameters, the model forcing was changed to a 12-day period post-Sandy, from 11/21/12 to 12/03/12, to ensure that the calibrated model was useful for normal tidal as well as storm conditions.

No time period pre-Sandy was investigated because accurate topography of the breach area was not available to be incorporated in the model, and this was shown to be the most critical factor affecting flows into and out of the Refuge. Measured water levels, winds, and freshwater inflows for the modeled time periods were used to drive the model, and water levels were compared at the stations located in Delaware Bay and the Refuge from NOAA, DNREC, and USFWS. The water level calibration locations in Delaware Bay and within the Refuge are mapped in Figure 41 and Figure 42, respectively. Figure 43 shows the Refuge locations overlaid with model bathymetry to illustrate the level of detail in the model bathymetry grid.

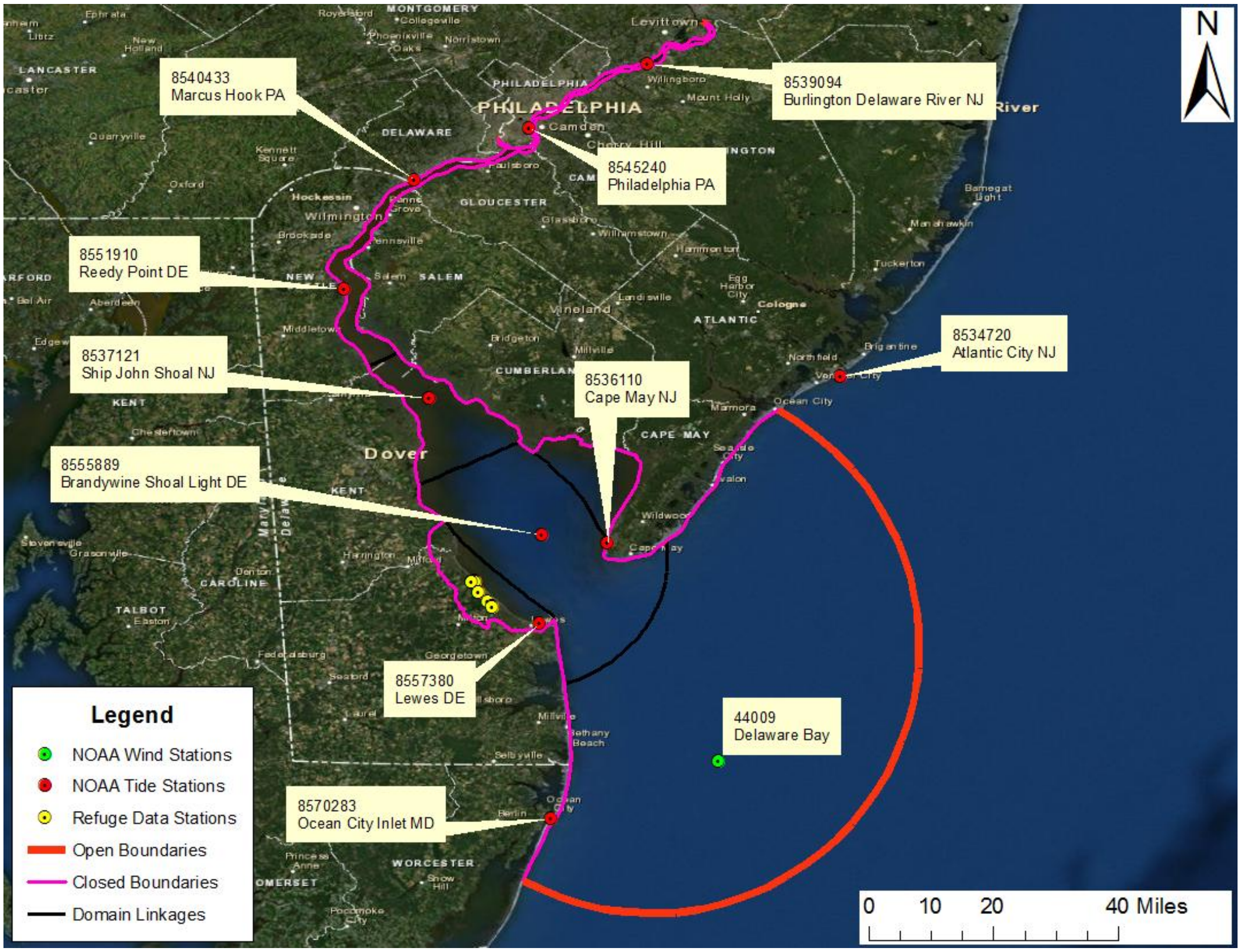

Figure 41. Water level calibration locations within Delaware Bay.

Figure 42. Water level and salinity calibration locations within the Refuge.

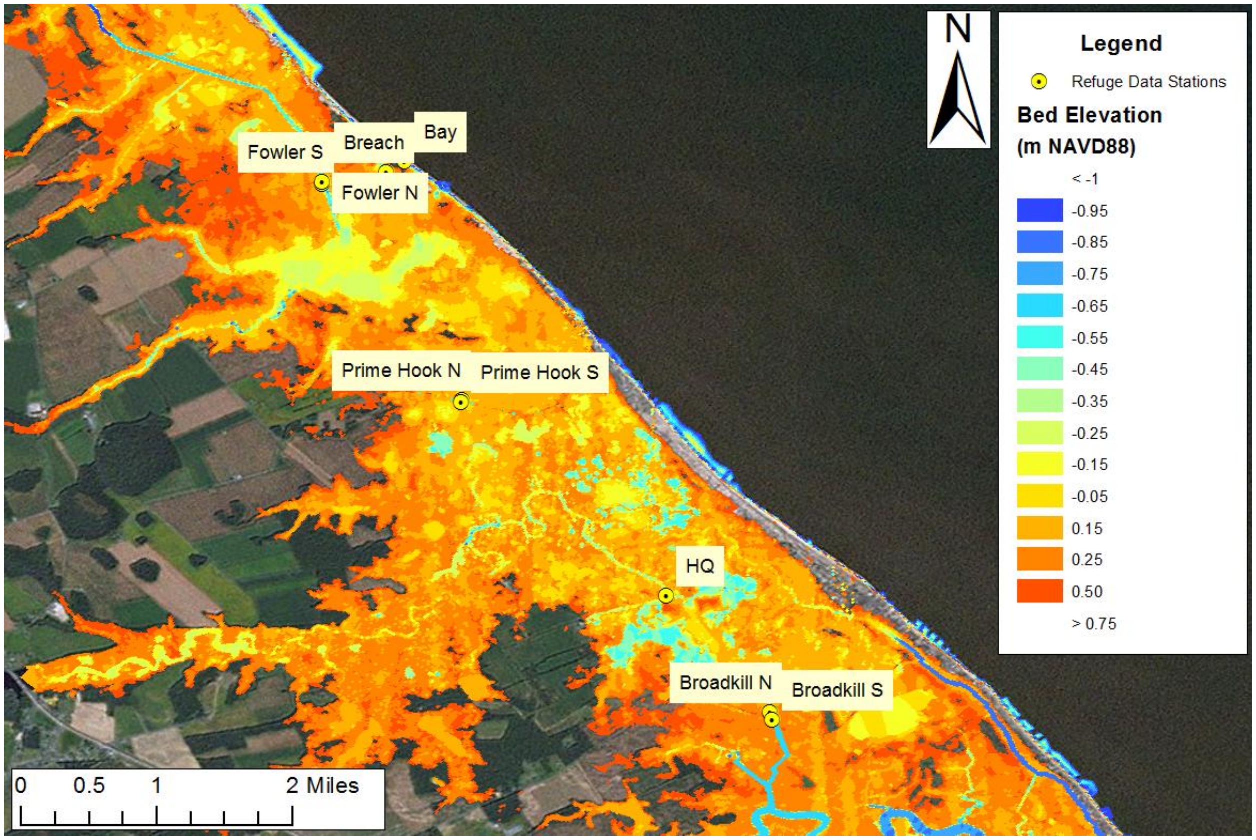

Figure 43. Water level and salinity calibration locations within the Refuge, with model bathymetry.

A.3.1. Hurricane Sandy

A regularly-spaced grid with a horizontal resolution of 10 m (33 ft) was chosen after testing multiple grid configurations for the Refuge domain. Elements were active or inactive based on the local water level and allowed to wet and dry as the tide and storm surge increased and decreased. Several bottom friction formulations were tested, including Chezy and Manning numbers, as well as spatially-uniform and depth-dependent. The best fit with measured water level data was a spatially-uniform Manning's *n* of 0.02. Figure 44 through Figure 47 illustrate the water level time series for the finalized Hurricane Sandy simulation in Delaware Bay and Units II, III, and IV, respectively. Data-model comparisons were best in the Bay and Unit II, where the available bathymetry was most accurate. Within the Refuge, the model replicates the peak storm surge elevation and matches overall trends shown in the data.

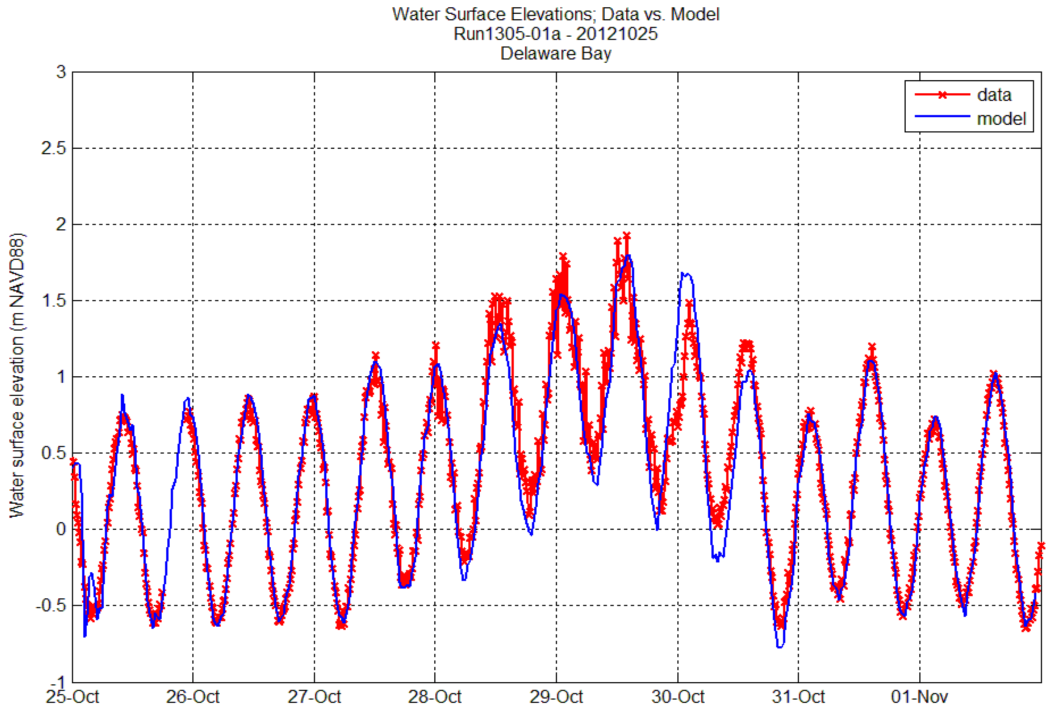

Figure 44. **Measured vs. modeled water levels, Hurricane Sandy: Delaware Bay adjacent to breach.**

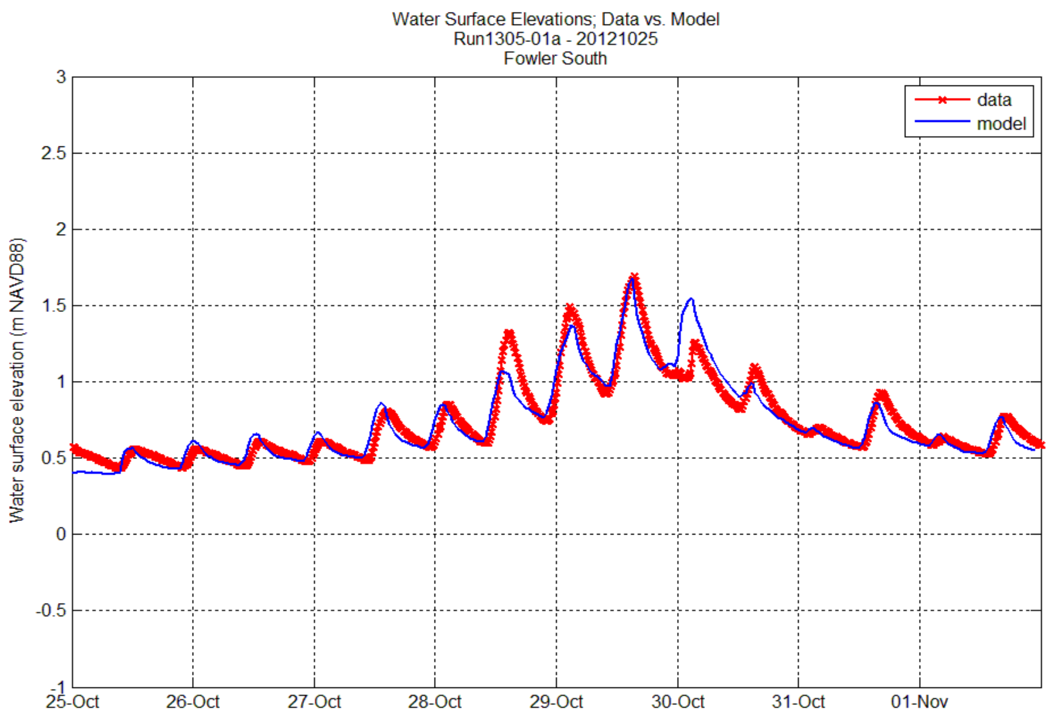

Figure 45. **Measured vs. modeled water levels, Hurricane Sandy: Unit II.**

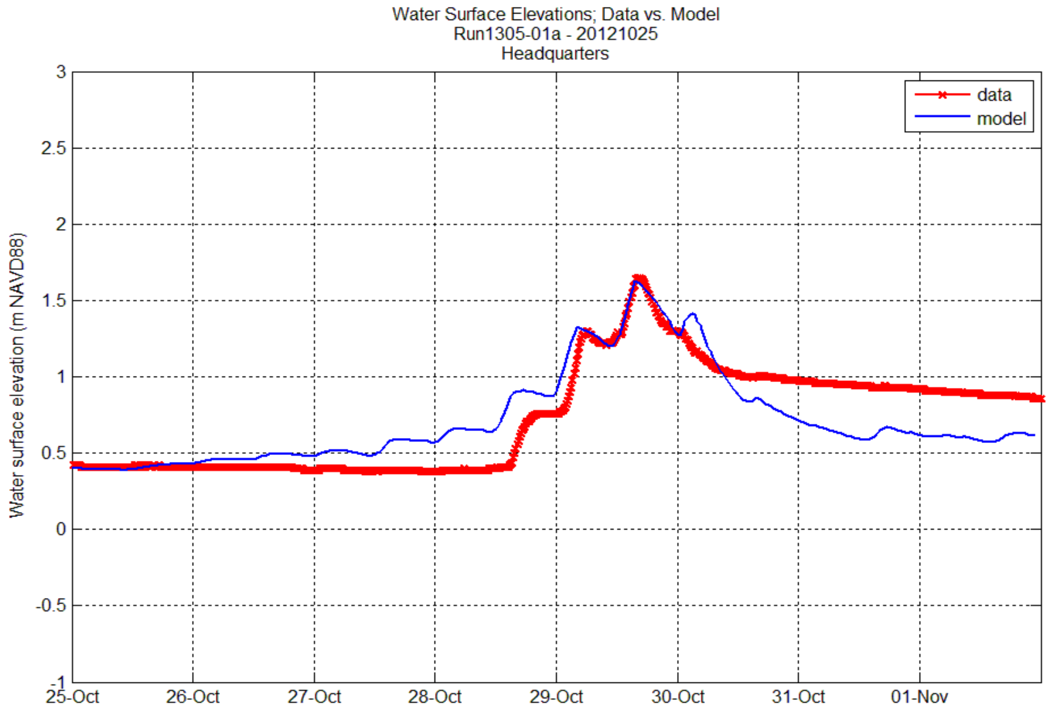

Figure 46. Measured vs. modeled water levels, Hurricane Sandy: Unit III.

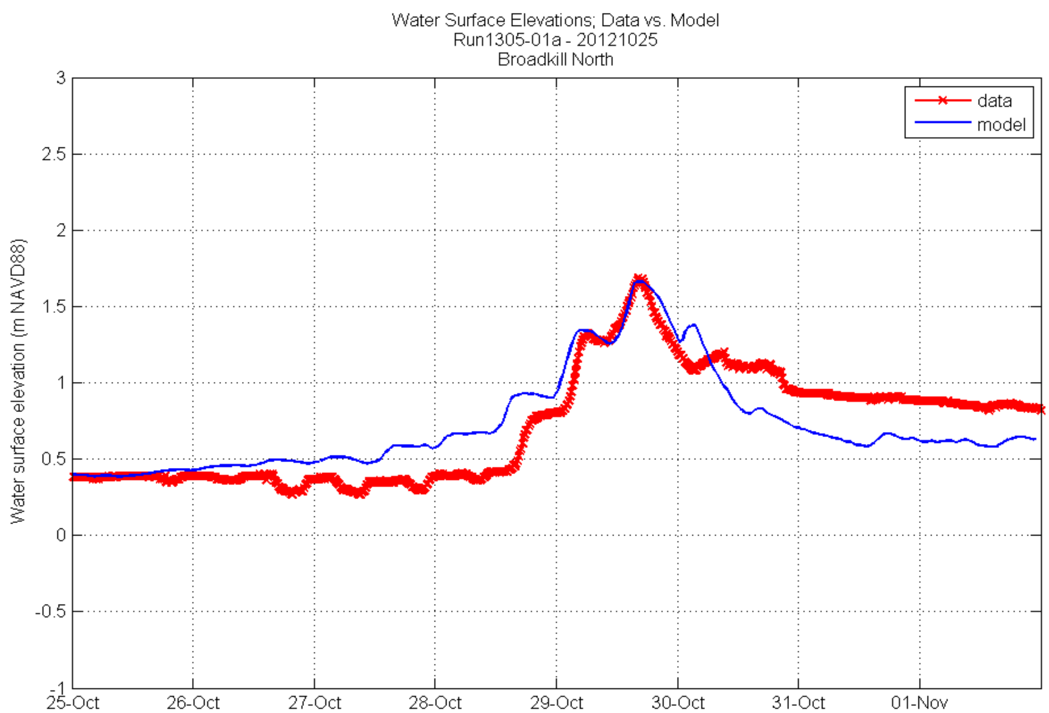

Figure 47. Measured vs. modeled water levels, Hurricane Sandy: Unit IV.

A.3.2. Post-Sandy 'Normal' Conditions

The model grid and parameters optimized during the Hurricane Sandy simulations were then applied to a 12-day period post-Sandy, from 11/21/12 to 12/03/12, to ensure that the calibrated model was useful for normal tidal as well as storm conditions. Figure 48 through Figure 51 illustrate the water level time series for the post- Sandy simulation in Delaware Bay and Units II, III, and IV, respectively. Small inconsistencies in water levels within the Refuge are likely due to freshwater inflows that were not accounted for due to a lack of measured data to apply to the model. The results show that the model is accurate with regard to water levels within the Refuge for 'normal' conditions, with the best results in Unit II.

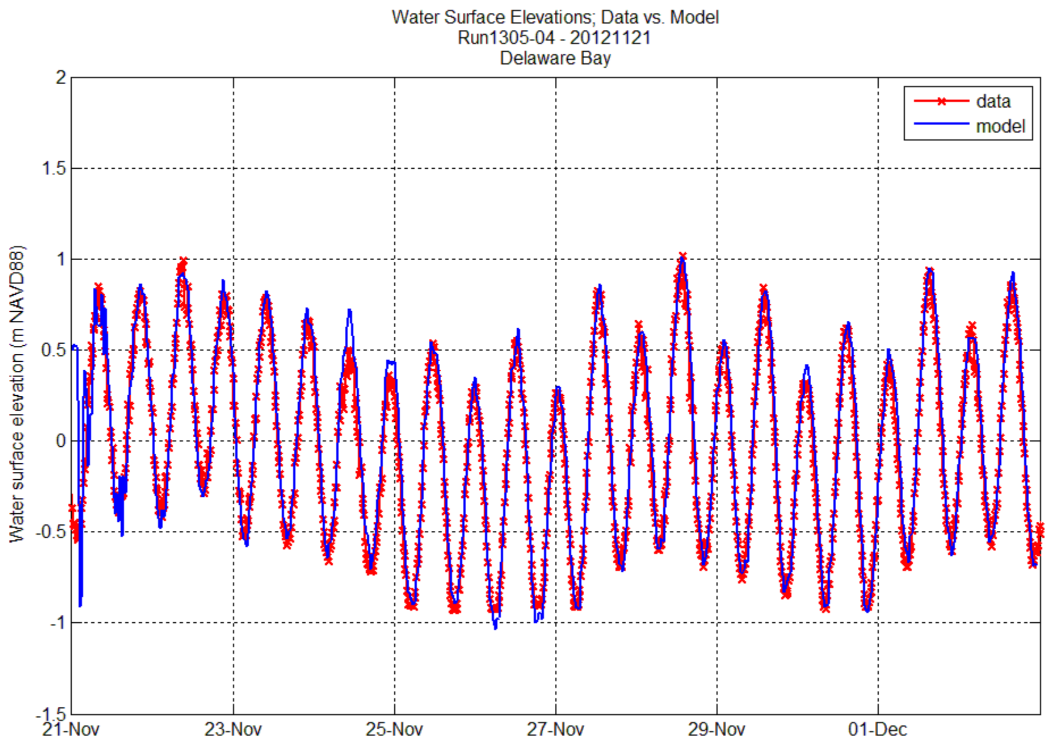

Figure 48. Measured vs. modeled water levels, post-Sandy: Delaware Bay adjacent to breach.

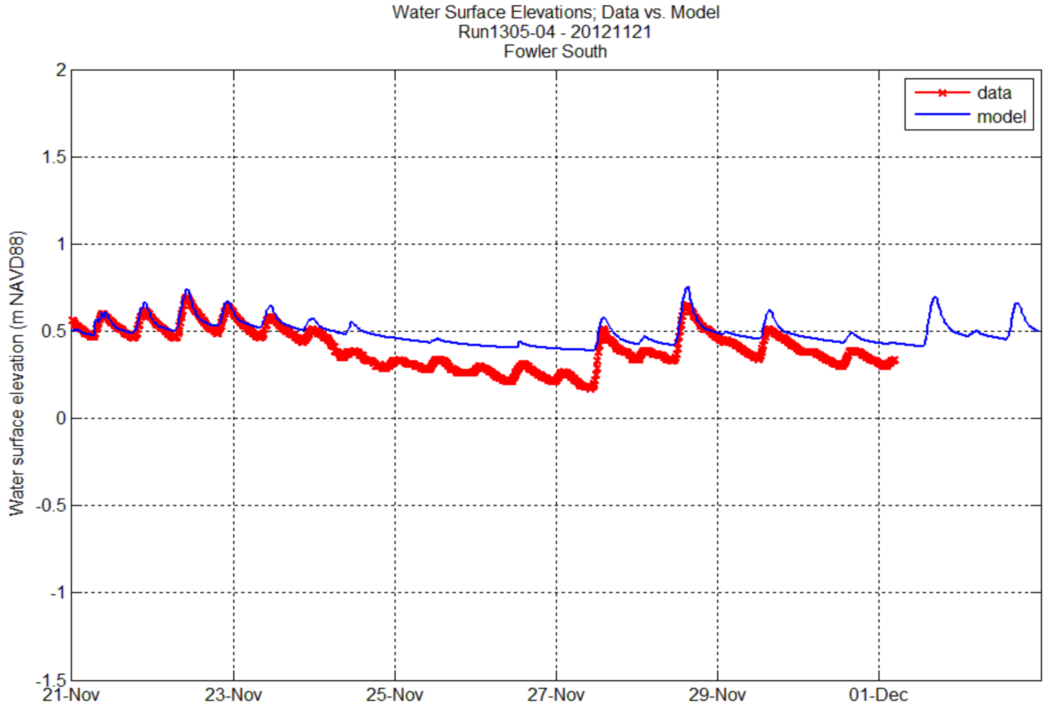

Figure 49. Measured vs. modeled water levels, post-Sandy: Unit II.

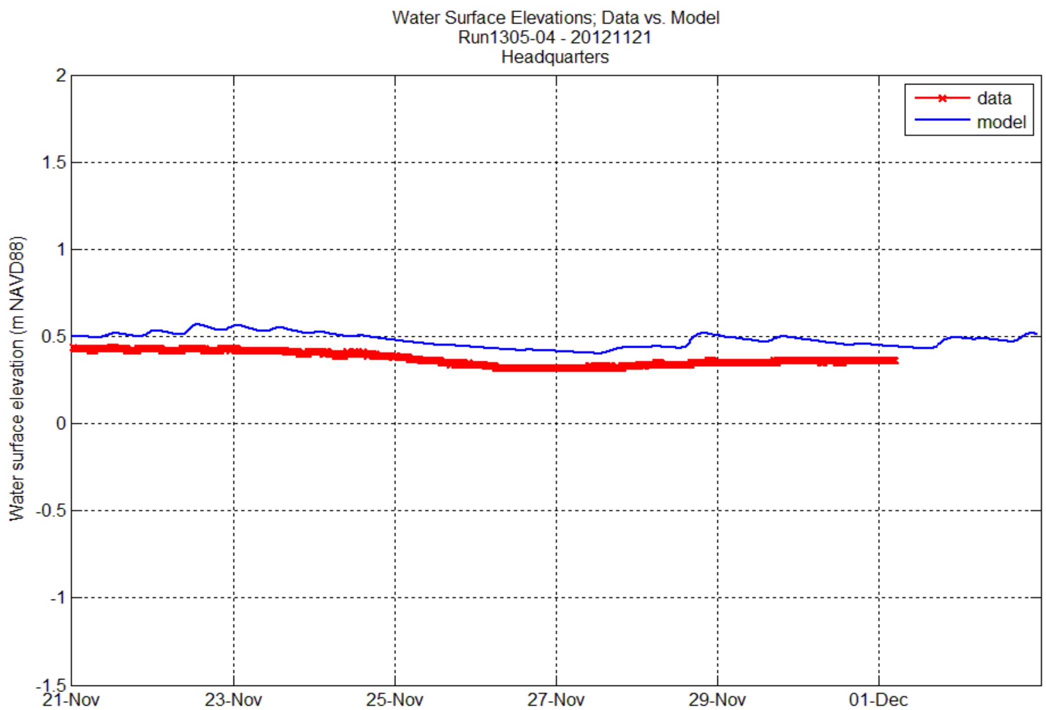

Figure 50. Measured vs. modeled water levels, post-Sandy: Unit III.

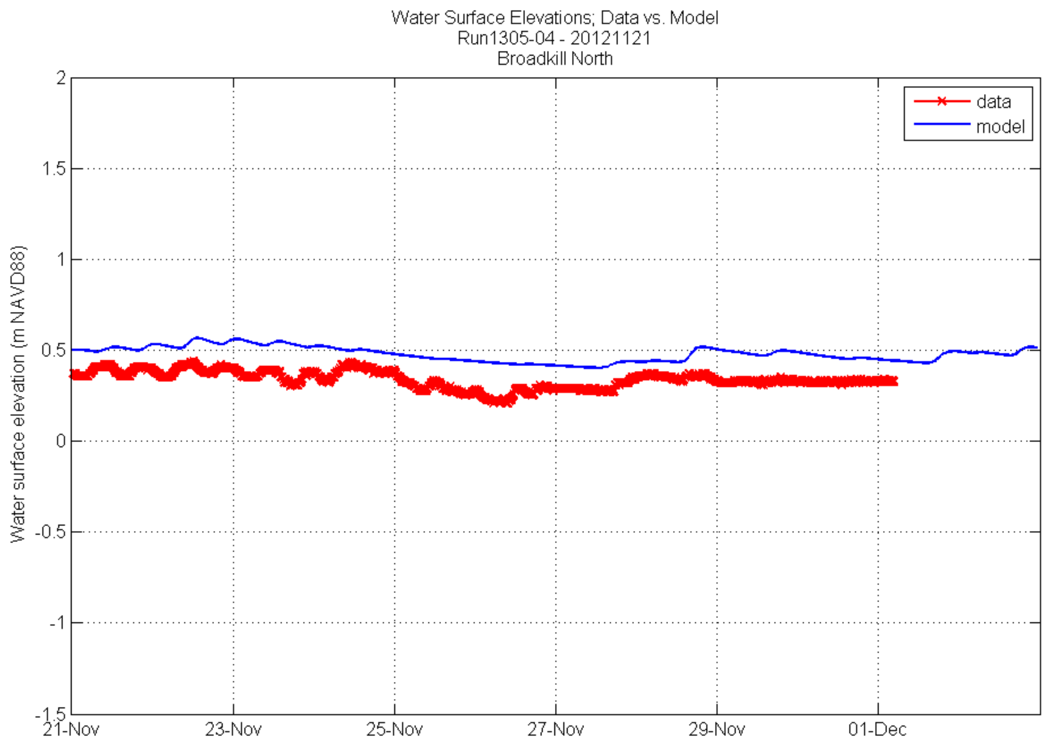

Figure 51. Measured vs. modeled water levels, post-Sandy: Unit IV.

A.4. Production Runs

Management alternatives were explored once the model was refined to accurately replicate tidal conditions within the Refuge for a variety of forcing factors. These alternatives, including modifications to the breach locations, roadways, and water control structures, were examined for their effect on water levels and salinity distribution within the refuge for long-term average as well as storm conditions. The long-term runs were 6 months in length, as this was found to be the amount of time necessary for the model to 'equilibrate' into a regular pattern as the tide moved through the spring-neap cycle. Simulations were executed in 1-month segments, with each month hot-started from the final state of the previous month, and the synthetic tidal boundary repeated. No wind forcing was applied, nor was freshwater flow from the Delaware and Schuylkill Rivers. Constant base flow rates from USGS Streamstats were applied to the upstream boundaries of Slaughter and Prime Hook Creeks. Higher and lower flow rates were tested, but base flow was determined to be the most representative of long-term influx for the purposes of modeling salinity trends within the Refuge. A range of initial salinities within the Refuge were tested, between 0 ppt and 31 ppt. In the long-term, the initial salinity appeared to be of secondary importance as the model settled into a regular pattern, but it was decided that a starting level of 0 ppt would be used.

A.4.1. Synthetic Tidal Boundary

As described previously, the long-term (non-storm) production runs were driven by a reconstructed synthetic tidal time series derived from NOAA's harmonic constituents at Atlantic City, NJ and Ocean City, MD. Figure 52 shows the modeled water levels at NOAA's Lewes, DE gauge compared to NOAA's harmonic tide for days 14-29 of a 29-day cycle; the close agreement between model and data show that the reconstructed boundary condition is accurate for modeling theoretical tides within Delaware Bay and the Refuge. Table 5 presents a comparison of tidal datums at Lewes between NOAA's data, the harmonic reconstruction, and the model results; the negligible differences between the three reinforce the validity of the synthetically-derived tidal boundary condition.

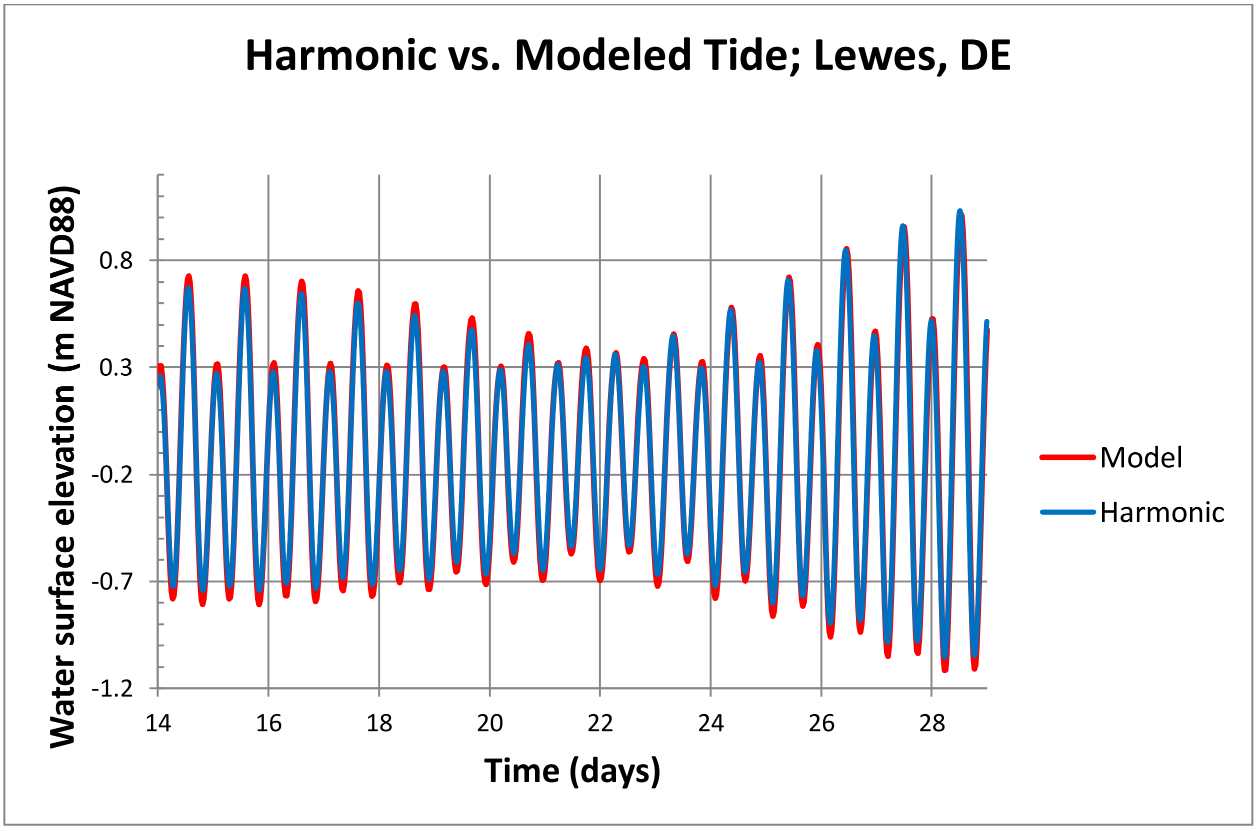

Figure 52. Comparison between NOAA harmonic constituents and modeled water level, Lewes, DE.

Table 5. Tidal datums from NOAA benchmarks, harmonics, and model results, Lewes, DE.

Tidal Datum	Water level (m NAVD88)		
	NOAA	Model	Harmonic
MHHW	0.62	0.65	0.62
MHW	0.49	0.51	0.48
MSL	-0.12	-0.12	-0.12
MLW	-0.75	-0.79	-0.73
MLLW	-0.80	-0.82	-0.78

A.4.2. Initial Alternatives and Observations

Atkins worked closely with USFWS staff to develop and refine the alternatives to be modeled. Results from previous model runs provided guidance for determining future runs; in this way, the alternative development was results-driven.

The first set of alternatives was characterized by variations in the breach configuration, the water control structures (WCS), and Fowler Beach Road. No modifications were made to elevations within the marsh. Table 6 outlines the different modeled scenarios. The model was run with existing conditions, one breach (Breach 4) open, and all breaches closed. For each of these situations, runs were performed with and without the WCS in place, and with and without the end of Fowler Beach Road (east of Slaughter Canal) intact.

Table 6. Matrix of initial modeled alternatives.

Breach Scenario	Water Control Structures	Fowler Beach Road
Existing	Yes	Intact
Breach 4 open	Yes	Intact
Breach 4 open	Yes	Removed
Breach 4 open	No	Intact
Breaches closed	Yes	Intact
Breaches closed	Yes	Removed
Breaches closed	No	Intact

The results of the initial model alternatives indicated that the breaches are the primary factors affecting the hydrodynamics within the Refuge under normal circumstances; the WCS and Fowler Beach Road have smaller effects. Further, it became apparent from the model runs with a starting salinity of 0 ppt that, over time, the Refuge can become a brackish environment even with all breaches closed and tidal exchange with the Bay limited to Slaughter Canal, Petersfield Ditch, and Prime Hook Creek. Given that the breaches are open under current conditions and provide openings for flood waters from storm events in the adjacent coastal community of Prime Hook Beach, this was an important to identifying and selecting alternatives. Consequently, the primary management alternatives call for complete closure of the breaches to examine whether flooding potential can be reduced and water levels and tidal exchange can be sufficient for a healthy saltmarsh within the Refuge. Figure 53 shows the water levels over time in Unit III for each of the initial alternatives group together according to breach alternative, demonstrating that the breaches drive most of the variability in water level. Figure 54 shows the salinity over time in Unit II for a 'breach closed' scenario. By the fifth month, a pattern corresponding to the spring-neap tide cycle is established, and the salinity fluctuates between 4 ppt and 20 ppt, indicating potential brackish (low salinity) habitat.

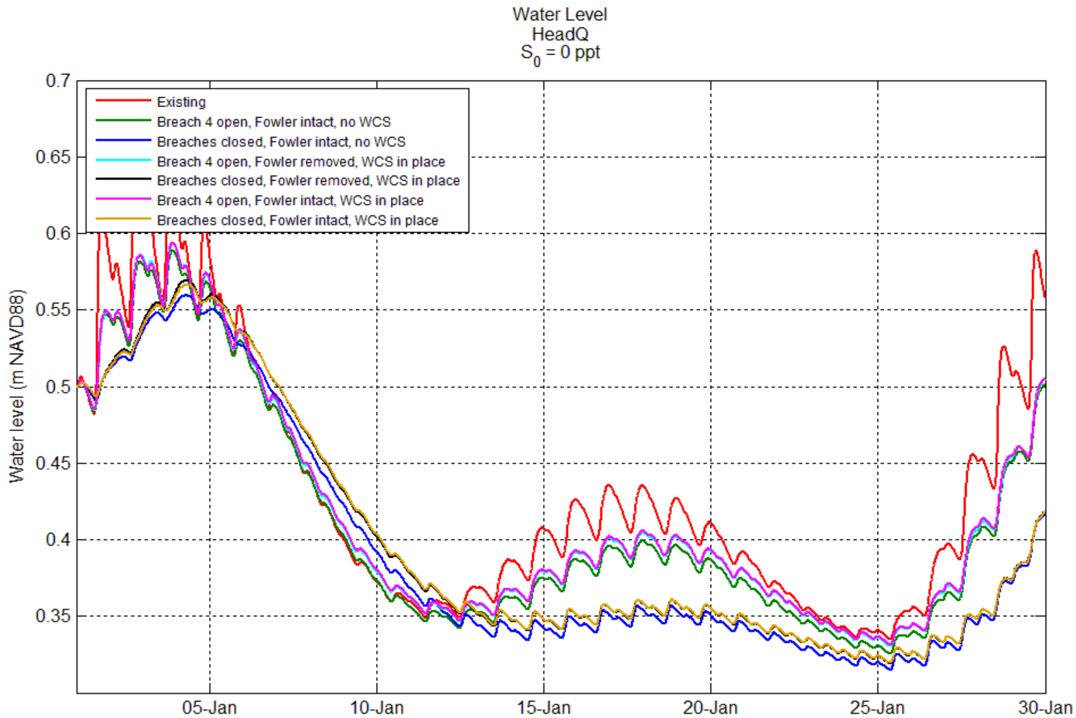

Figure 53. Water levels in Unit III for initial alternatives; note 'grouping' by breach configuration.

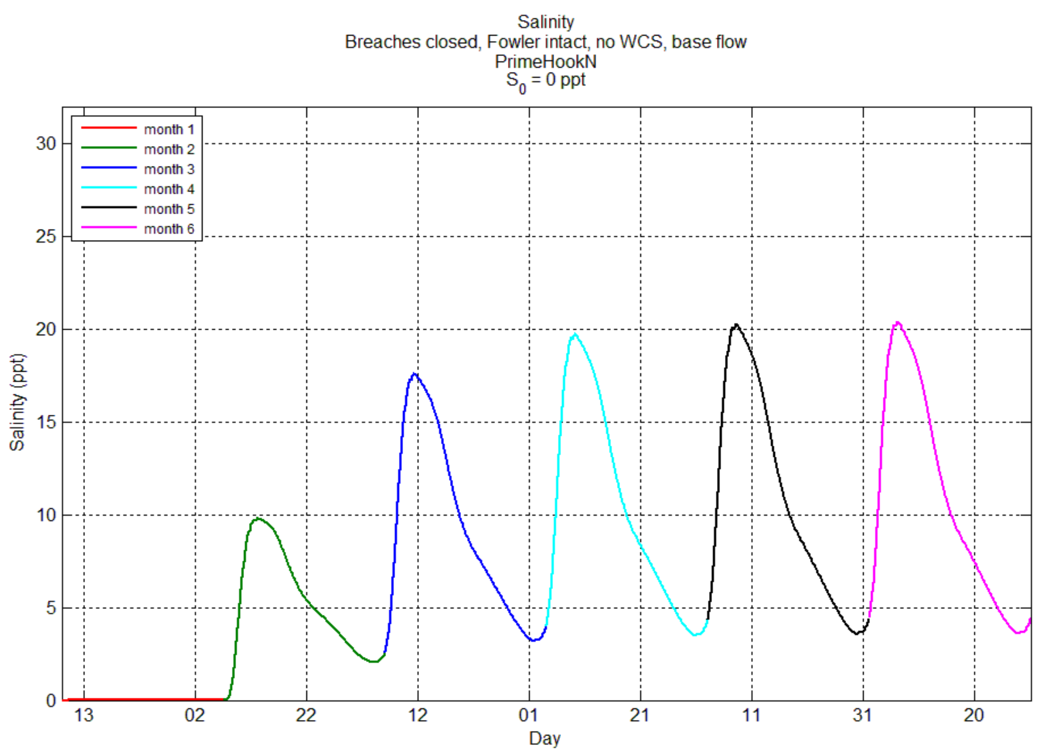

Figure 54. Long-term salinity in Unit II for a 'breaches closed' scenario.

A.4.3. Primary Alternatives

Results and implications of the initial model runs were discussed during meetings with Refuge staff and consensus was reached with respect to primary alternatives. Subsequent model runs focused on scenarios in which all of the breaches were closed so that saltmarsh restoration and flood protection could be examined. Three primary alternatives were developed to examine how changes within the Refuge could impact exchange between the Refuge and Delaware Bay with the breaches closed.

The three scenarios modeled included different channel configurations within the Refuge to increase circulation via the Mispillion Inlet and Roosevelt Inlet. Alternative 1 was simply the breaches closed with no internal channel modifications. Alternative 2 added a channel that connects Slaughter Canal (and Mispillion Inlet) in the north end of Unit I to both Prime Hook Creek and Petersfield Ditch in southern Unit III, which in turn connects to the Broadkill River and Roosevelt Inlet. The channel was approximately 40 ft in width at the bottom and sloped upward to grade 1 model cell width (30 to 40 ft) in either direction. The elevation of the channel bottom was -2.3 ft NAVD88. These dimensions, other than the side slope, are similar to the dimensions of the existing Slaughter Canal and others in the Refuge. Finally, Alternative 3 built upon Alternative 2 by adding a second conveyance channel through Prime Hook Road, between Unit II and Unit III, and added several ‘finger’ channels in Unit III to aid in the distribution of saline water. For all main and secondary channels, an attempt was made to follow existing channels, lower elevation areas, and historical channel paths in order to follow a natural design and minimize the amount of removed material. Precision in the channel characteristics and paths was limited by the model resolution and will be refined in the final design stages; the purpose of the modeling effort was to determine conceptually if the potential for circulation enhancement existed. Figure 55 through Figure 57, respectively, illustrate the channel paths and existing creeks/waterways within the Refuge for Alternatives 1 through 3. ‘Prime Hook E’ and ‘Prime Hook W’ denote the approximate locations where the proposed channel crosses the existing Prime Hook Road. The channel maintains its depth and width when crossing the road.

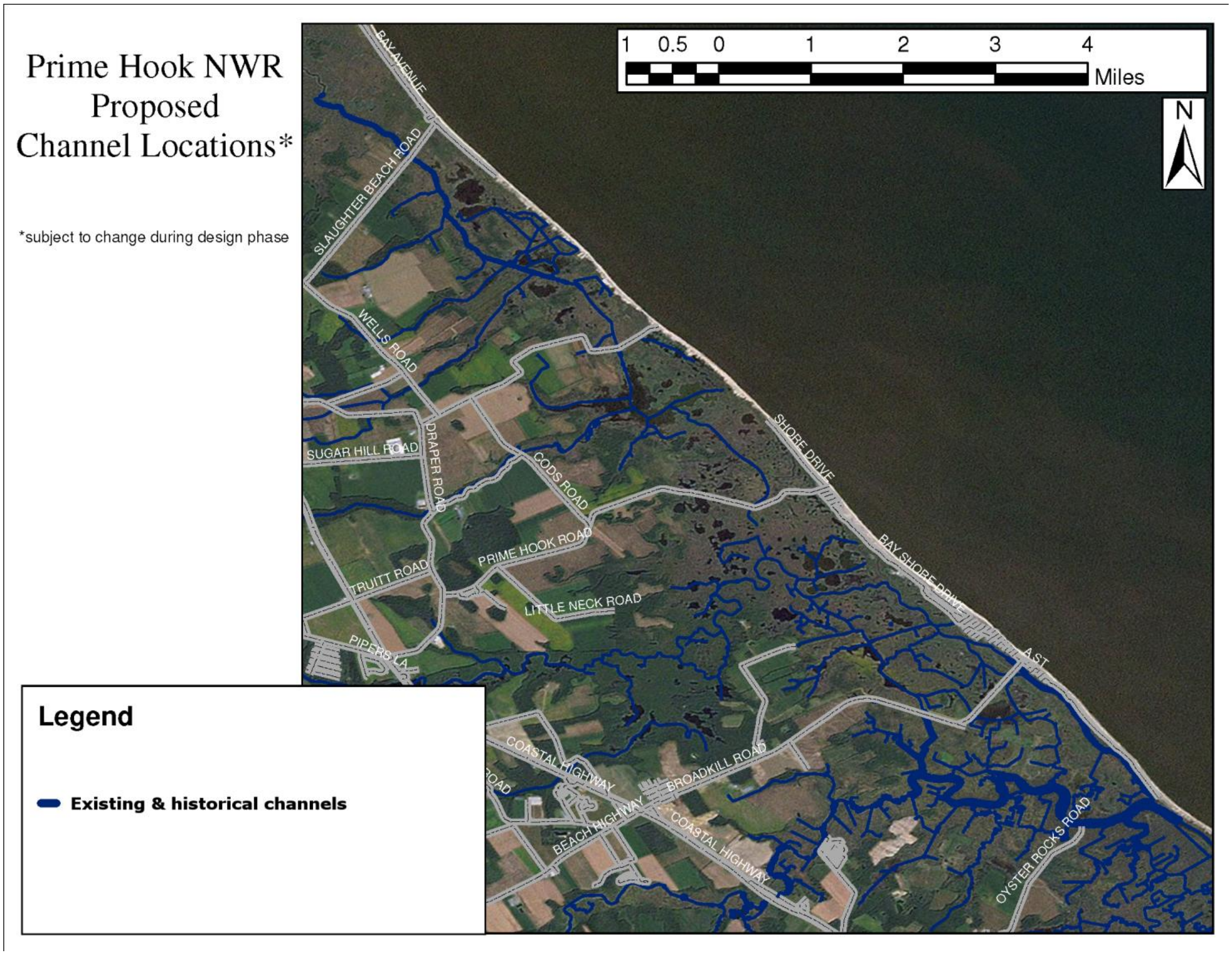

Figure 55. Channel configuration in the Refuge, Alternative 1 (no modifications).

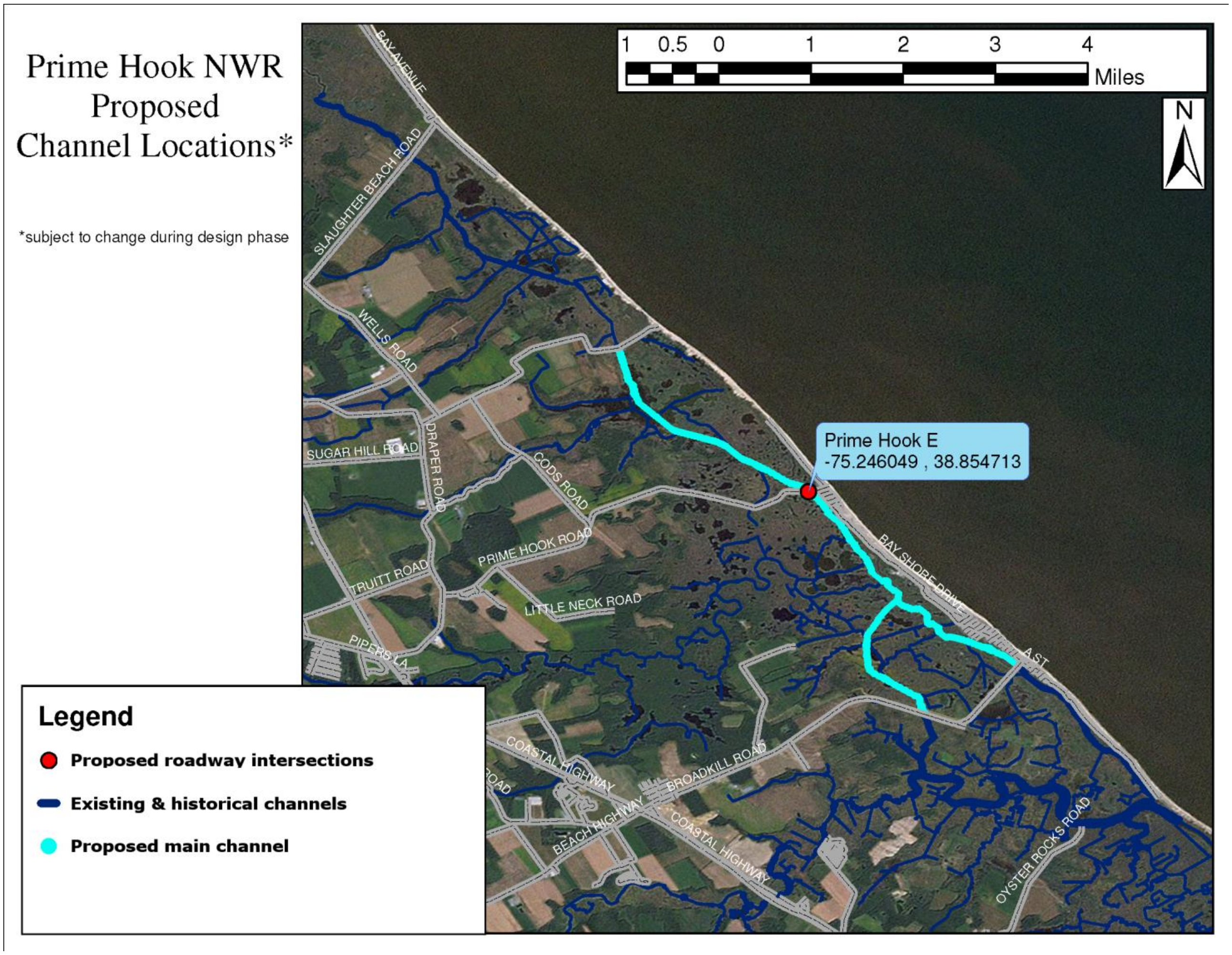

Figure 56. Channel configuration in the Refuge, Alternative 2 (main channel).

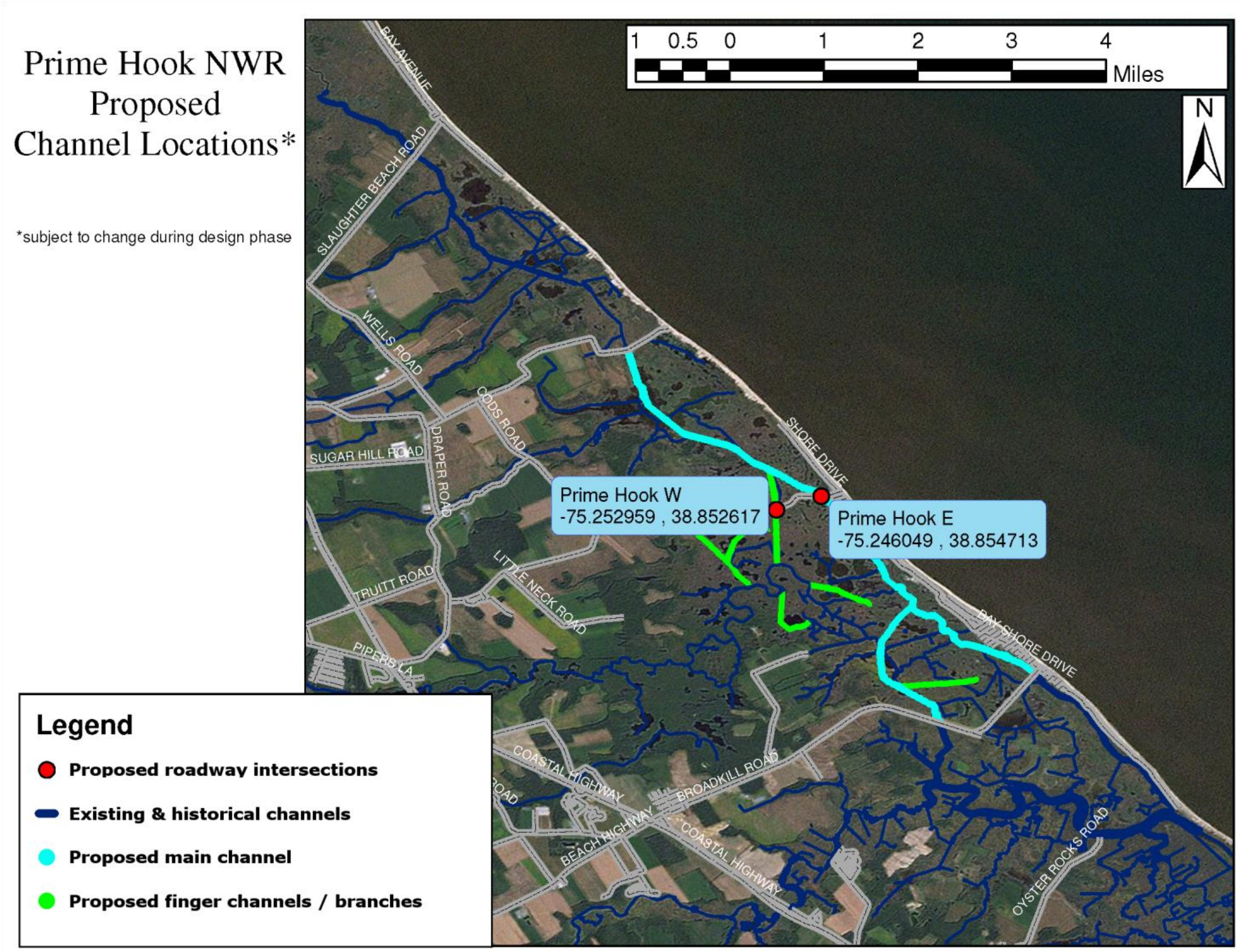

Figure 57. Channel configuration in the Refuge, Alternative 3 (main channel w/ branches).

A.4.3.1. Normal Tidal Conditions

Each management alternative was run for 6 consecutive, identical tidal 'months' of 29 days, allowing for conditions within the Refuge to equilibrate into a consistent pattern corresponding to the spring-neap tidal cycle. All three alternatives had the following in common:

- Harmonic-derived tidal boundary condition
- No wind forcing
- All breaches closed
- All water control structures removed
- East end of Fowler Beach Road removed
- Constant base inflow from Slaughter Creek and Prime Hook Creek (21 cfs and 79 cfs, respectively)
- Initial salinity of 0 ppt within Refuge

Conditions during month 6, representative of normal fluctuations outside of seasonal and storm effects, were used to compare water levels and salinities throughout the Refuge and help inform decisions regarding potential restoration options and further investigations.

A.4.3.2. Hurricane Sandy

In addition to the model runs described previously, which simulated long-term 'normal' conditions, the three alternatives were also run using the forcing conditions for Hurricane Sandy, as detailed in the calibration and validation section of the report. The results of this 8-day storm run can be used in the planning and design of any roadway, bridge, or community improvements for flood protection, and when compared to modeled existing conditions illustrate how the breach and channel modifications have an effect on flood elevations within the Refuge during a significant storm event.

A.4.4. Model Results

The following section illustrates and discusses the results of the primary alternatives modeling for both normal conditions and the Hurricane Sandy simulations.

A.4.4.1. Normal Tidal Conditions

When interpreting the results of the model runs simulating normal tidal conditions, attention was focused on month 6 of these runs, after the model had equilibrated to the applied inflow and tidal boundary conditions. Table 7 presents high, average, and low water level benchmarks in the four Refuge Units for each of the three primary alternatives. Table 8 is a table of high, average, and low salinity levels in each of the four Units. Figure 58 through Figure 60 show the representative 6-month water level time series for Units II, III, and IV, respectively. Figure 61 through Figure 63 show the representative 6-month salinity time series for Units II, III, and IV, respectively.

Keep in mind that values in the tables, time series, and discussion are an attempt to get representative values for each Unit; the reality is more spatially variable, which is defined in much more detail in the mapped output figures which will be presented subsequent to the time series plots.

The water level table and time series plots show that during the spring-neap tidal cycle, water levels in the Refuge have a range of about 0.4 m (1.3 ft), with overall levels decreasing slightly from north to south. This is consistent with the fact that flow through the Refuge generally enters from Slaughter Canal and flows southward, likely due to the increase in tidal range in Delaware Bay from south to north. In addition, the daily tidal influence is more prominent in the southern part of the Refuge versus the northern. When the channels are added to the system, the low water level drops by about 0.1 m (0.33 ft); this is probably because the increased throughput allowed by the channel additions let more water freely flow through rather than 'stack up' inside the Refuge.

The modeled salinities demonstrate that the addition of conveyance channels is a successful method of allowing more salt water to enter from Delaware Bay and increase salinity levels within the Refuge. While the low salinities remain relatively constant among alternatives, the average and peak salinities exhibit a marked increase when channels are added. For example, representative peak salinities in Unit III increase from 12-13 ppt to 19-20 ppt. In addition, Figure 62 shows that while peak salinities are unchanged when adding the finger channels in Unit III, the minimum salinity is increased, proving that the finger channels serve to distribute and hold more saline water within the Refuge. The results were subsequently mapped to provide further spatial detail of the model results.

Table 7. Water level benchmarks in each of the four Units for the three primary alternatives.

Benchmark	Configuration	Unit I	Unit II	Unit III	Unit IV	Lewes (NOAA)
High Water Level (ft NAVD88)	Alternative 1 (no mods)	1.83	1.70	1.62	1.55	+1.64 (MHW)
	Alternative 2 (main channel)	1.75	1.60	1.55	1.70	
	Alternative 3 (main w/ branches)	1.78	1.58	1.55	1.57	
Mean Water Level (ft NAVD88)	Alternative 1 (no mods)	1.19	1.19	1.12	1.13	-0.39 (MSL)
	Alternative 2 (main channel)	1.02	0.98	0.93	1.12	
	Alternative 3 (main w/ branches)	1.00	0.99	0.93	1.12	
Low Water Level (ft NAVD88)	Alternative 1 (no mods)	0.94	1.01	0.91	1.07	-2.46 (MLW)
	Alternative 2 (main channel)	0.74	0.66	0.44	1.07	
	Alternative 3 (main w/ branches)	0.74	0.69	0.42	1.07	

Table 8. Salinity benchmarks in each of the four Units for the three primary alternatives.

Benchmark	Configuration	Unit I	Unit II	Unit III	Unit IV
High Salinity (ppt)	Alternative 1 (no mods)	30-31	23-24	12-13	25-26
	Alternative 2 (main channel)	30-31	27-28	19-20	28-29
	Alternative 3 (main w/ branches)	30-31	27-28	19-20	28-29
Mean Salinity (ppt)	Alternative 1 (no mods)	22-23	14-15	6-7	12-13
	Alternative 2 (main channel)	29-30	17-18	10-11	14-15
	Alternative 3 (main w/ branches)	29-30	17-18	10-11	14-15
Low Salinity (ppt)	Alternative 1 (no mods)	15-16	7-8	2-3	7-8
	Alternative 2 (main channel)	24-25	8-9	3-4	10-11
	Alternative 3 (main w/ branches)	24-25	8-9	3-4	10-11

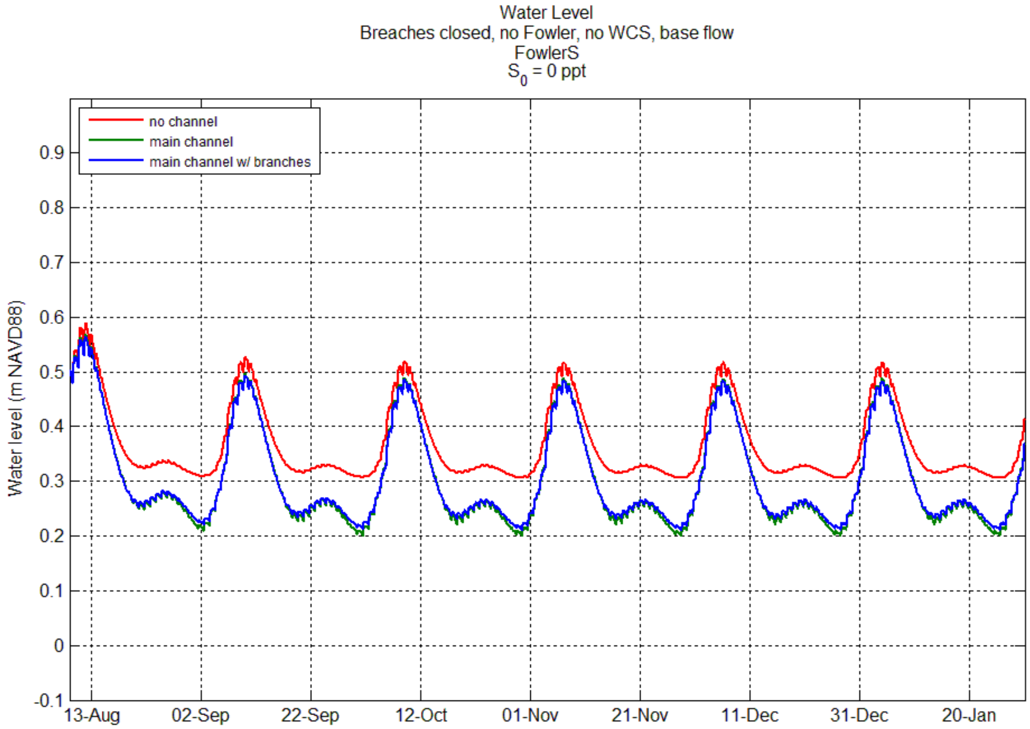

Figure 58. Water level time series for the three primary alternatives: Unit II.

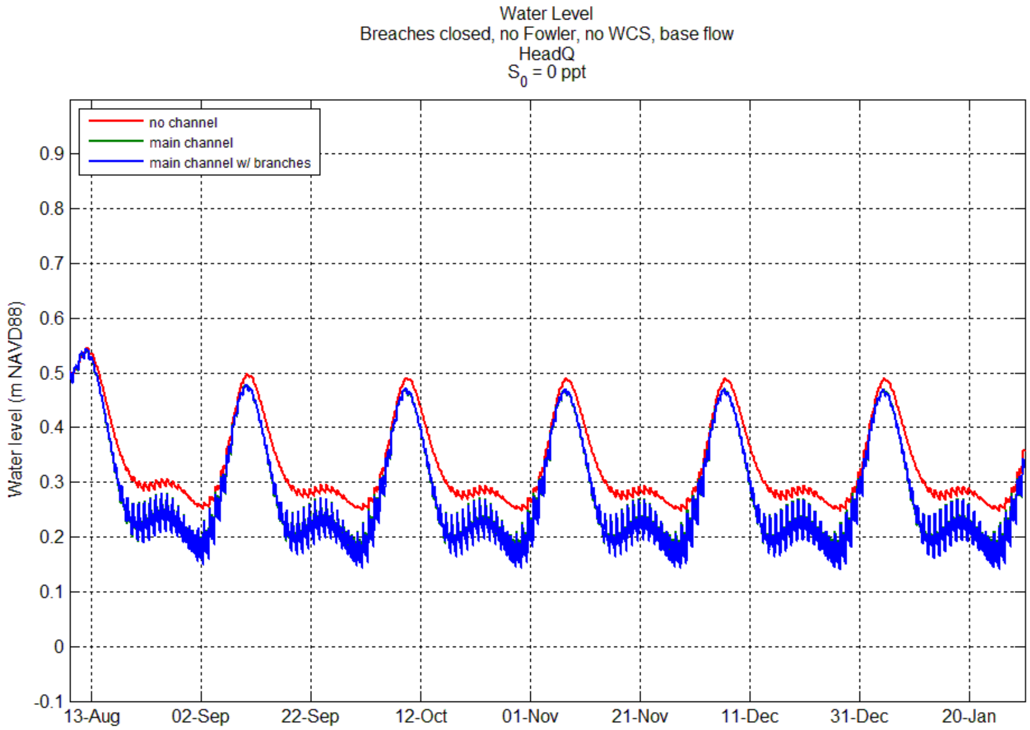

Figure 59. Water level time series for the three primary alternatives: Unit III.

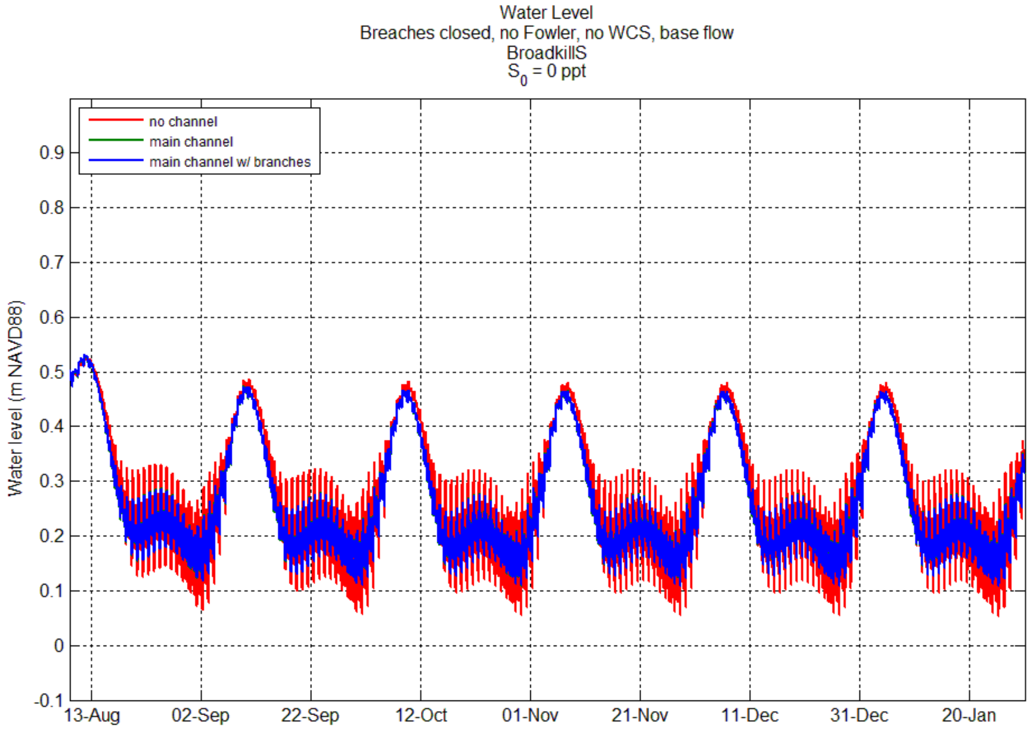

Figure 60. Water level time series for the three primary alternatives: Unit IV.

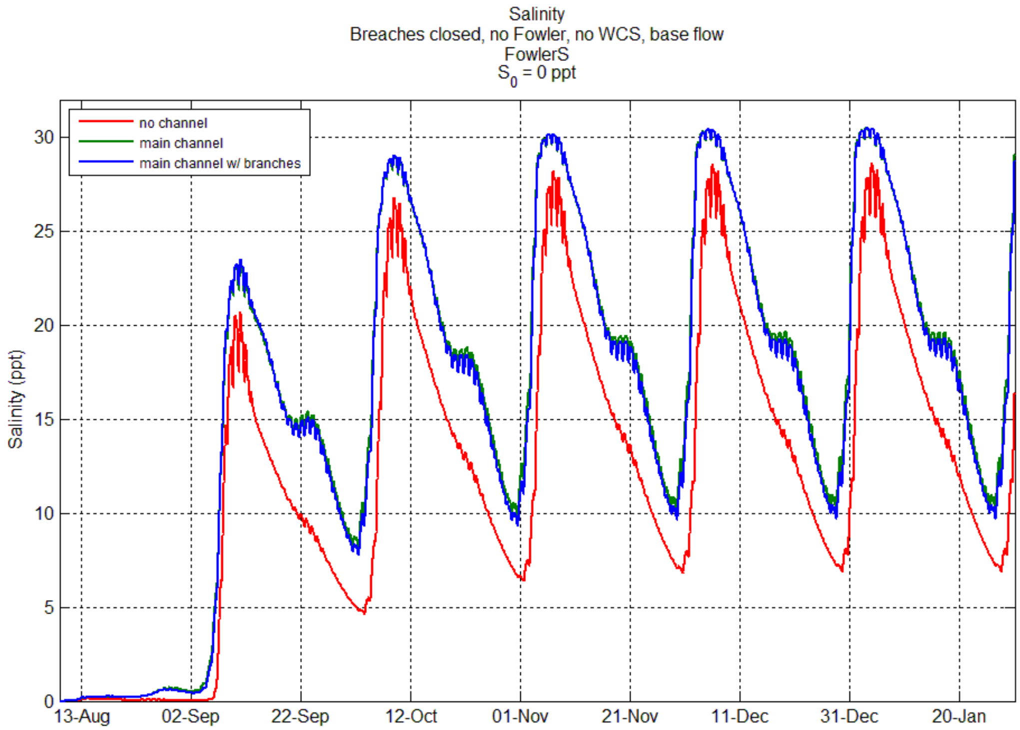

Figure 61. Salinity time series for the three primary alternatives: Unit II.

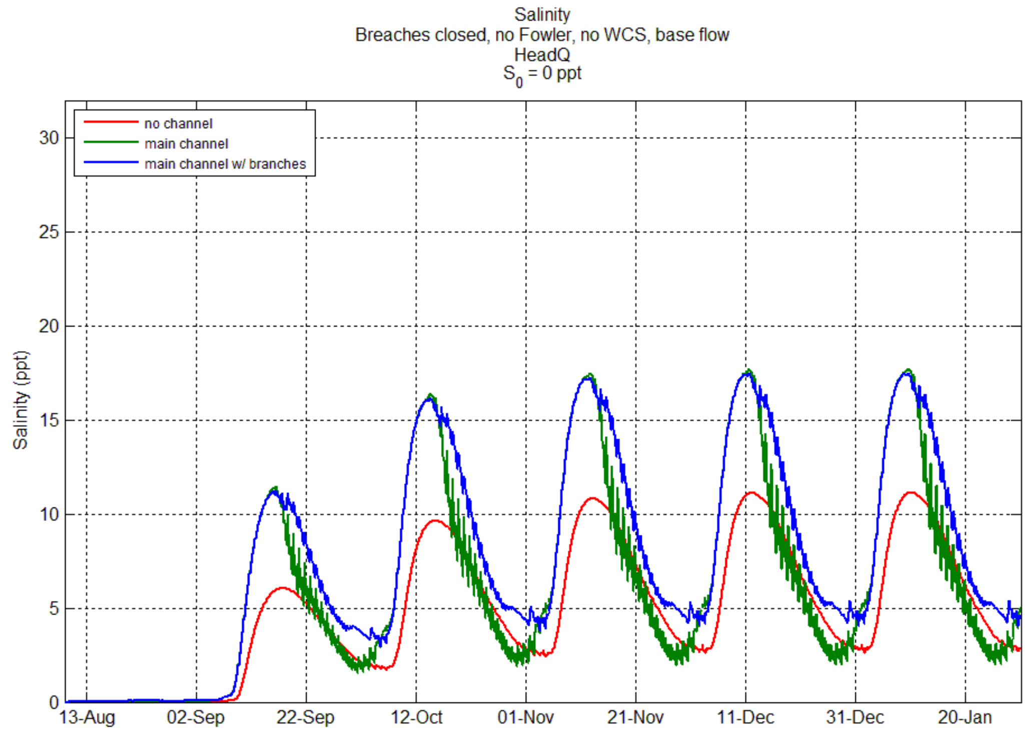

Figure 62. Salinity time series for the three primary alternatives: Unit III.

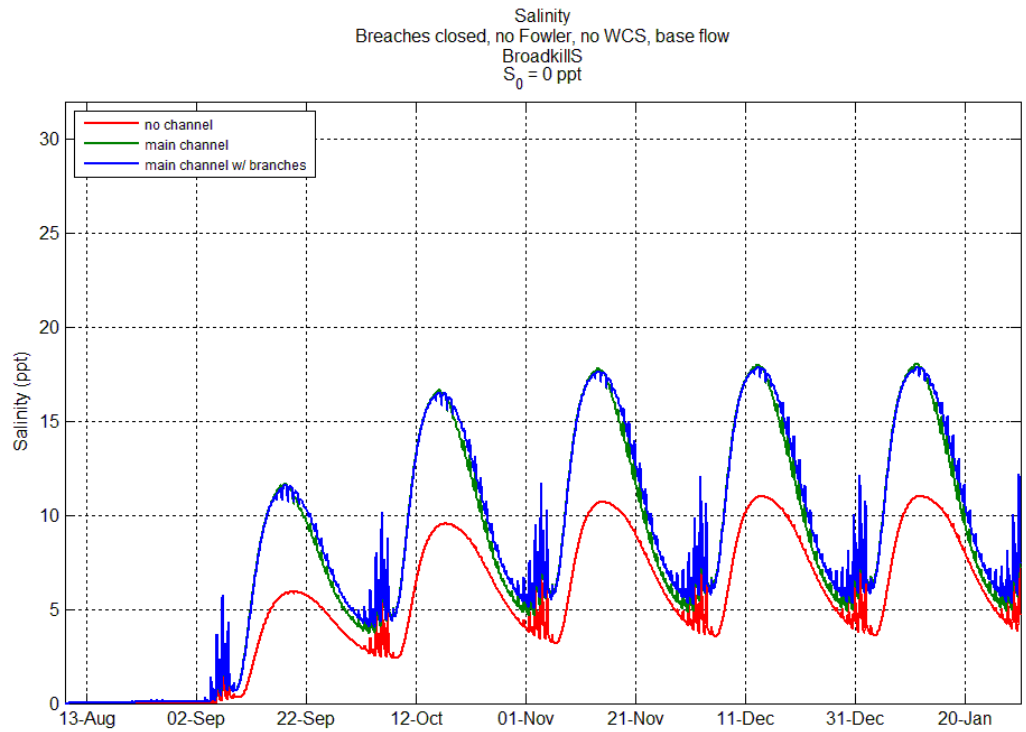

Figure 63. Salinity time series for the three primary alternatives: Unit IV.

Figure 64 through Figure 72 illustrate the mapped output for the minimum, average, and maximum water levels for each of the three alternatives. Figure 73 through Figure 81 illustrate the minimum, average, and maximum salinities for the three alternatives. All mapped output is in reference to month 6 of the simulations, after the model has equilibrated.

The mapped water levels highlight the noticeable drop in minimum and average water levels in Units I-III when the main channel is added; it is likely that the increased throughput allowed by the channel prevents as much water from ‘stacking’ within the Refuge. Maximum water levels vary only slightly between alternatives.

The mapped salinities clearly demonstrate how average and maximum salinities have the potential to be increased within the Refuge by adding channel(s) allowing for more exchange with Delaware Bay from Slaughter Canal and the Broadkill River. In Unit II, the highest average salinity without modifications is 21-22 ppt, which increases to 27-28 ppt when channels are added to the system. The lowest peak salinity in Unit II increases from 21-22 ppt with no modifications to 25-26 ppt with the channel additions.

In Unit III, the highest average salinity increases from 11-12 ppt without modifications to 19-20 ppt with the channel and finger canals. The lowest peak salinity in Unit III without modifications is 19-20 ppt, but confined to the area immediately south and west of Prime Hook Road. This increases to 23-24 ppt when channels are added, and although this larger salinity is confined to a small area, nearly the entire unit (outside of the upstream area of Prime Hook Creek) now sees a peak salinity of 19-20 ppt.

Overall, the mapped water level and salinity results demonstrate the following key points when analyzing the ‘breaches closed’ scenarios:

- Adding a main channel connecting Slaughter Canal (and thus Mispillion Inlet) to the Broadkill River and Roosevelt Inlet (via Prime Hook Creek and Petersfield Ditch) allow for greater exchange between Prime Hook NWR and Delaware Bay.
- The increased exchange and throughput provided by this channel system lowers the water level within the Refuge by reducing the amount of water ‘stacked’ within the Units.
- The augmented exchange increases the average and maximum salinity levels within all four Units.
- The secondary finger channels that feed from the main channel are successful in distributing saline water to a larger area of the Refuge than the main channels alone.

The water levels and salinities from these modeled alternatives are crucial in planning and developing any restoration activities within Prime Hook NWR.

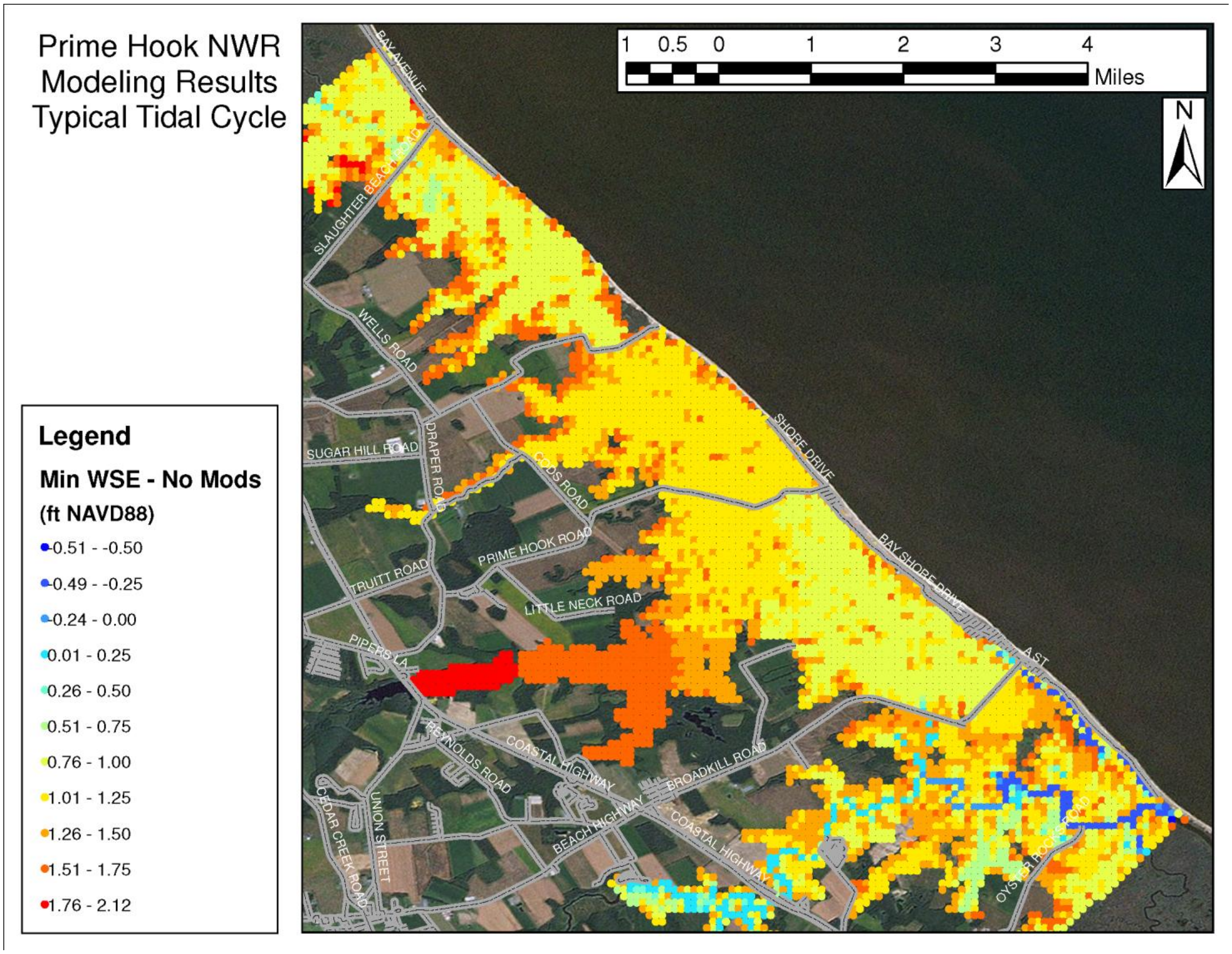

Figure 64. Minimum water levels in Prime Hook NWR, Alternative 1 (no modifications).

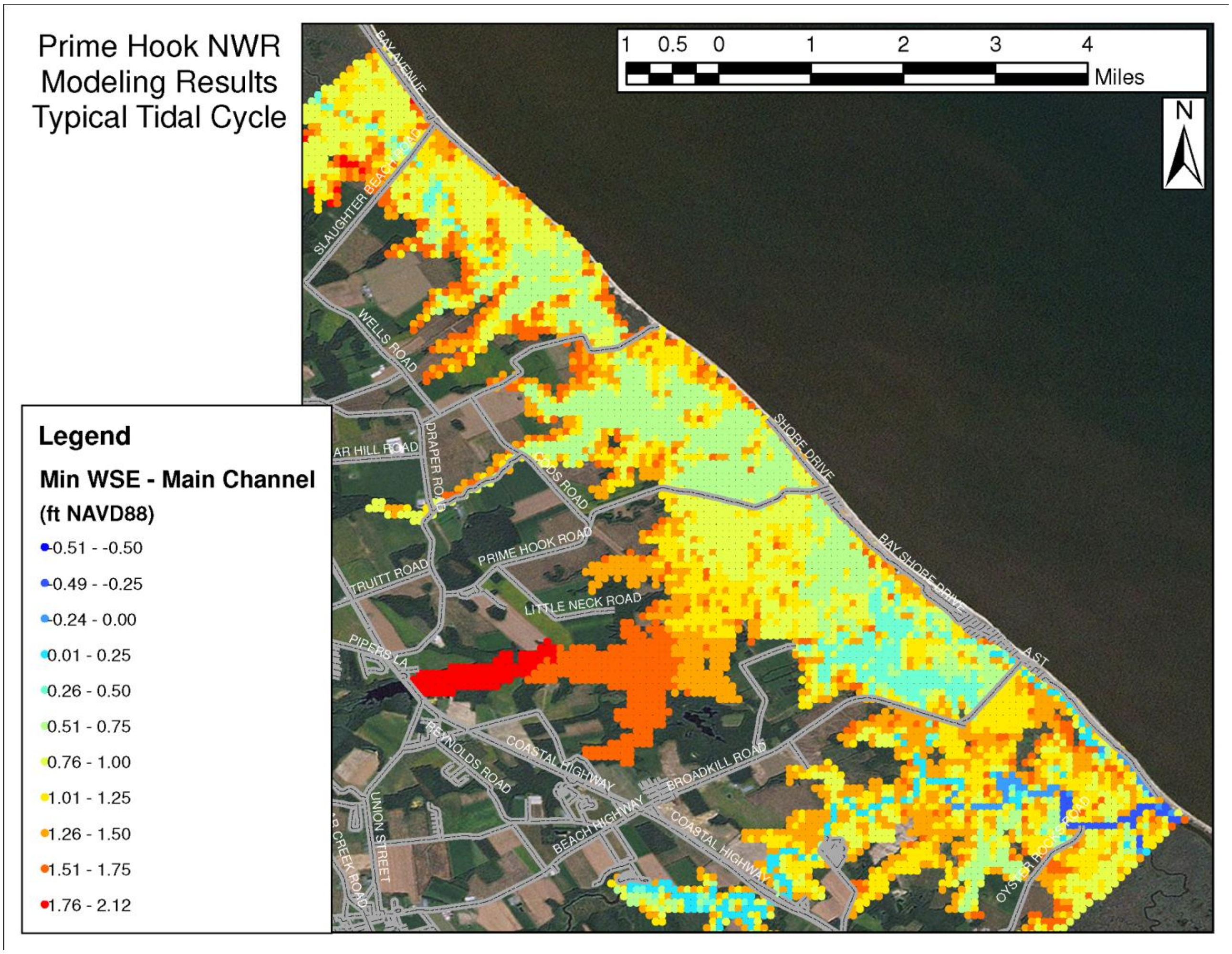

Figure 65. **Minimum water levels in Prime Hook NWR, Alternative 2 (main channel).**

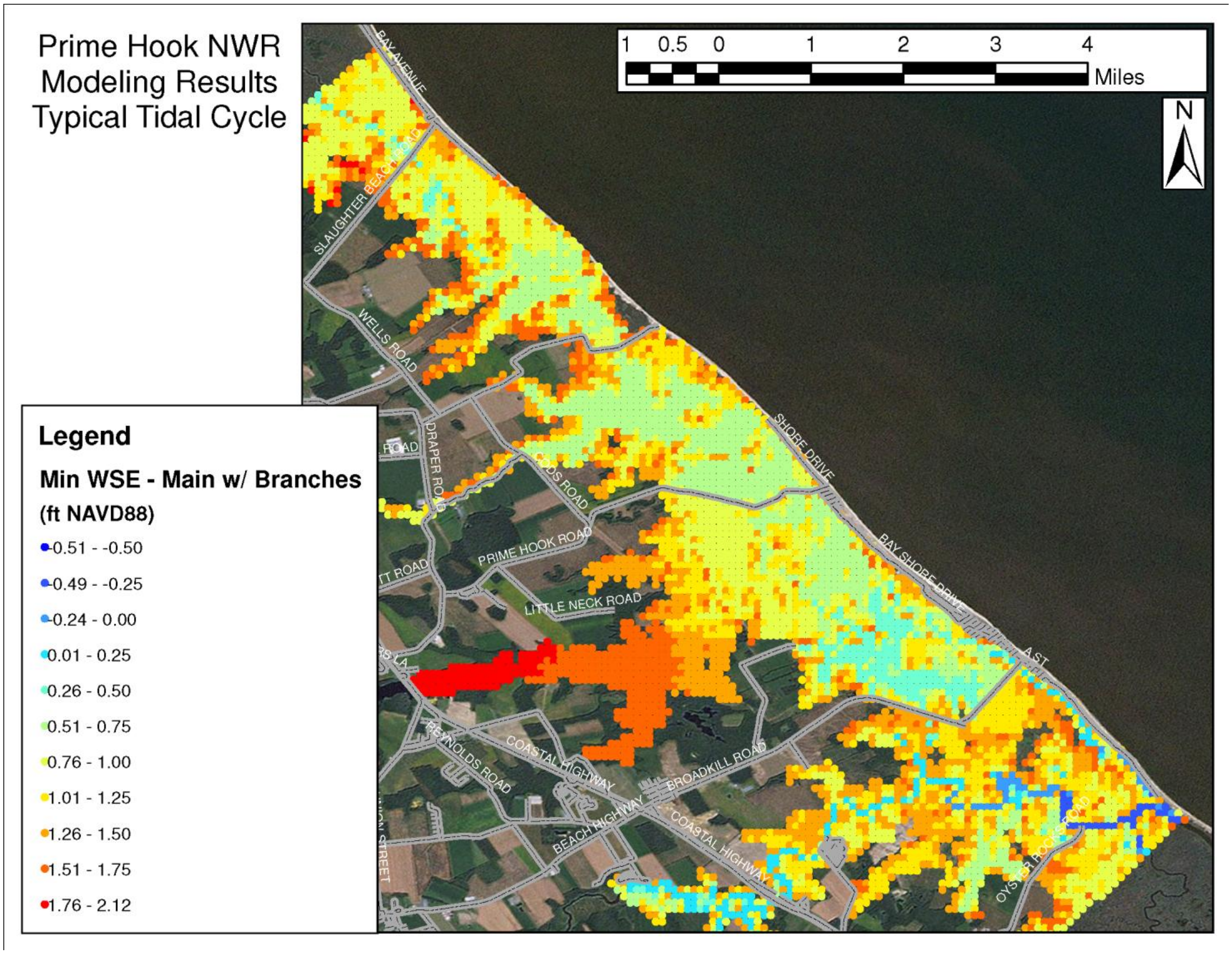

Figure 66. **Minimum water levels in Prime Hook NWR, Alternative 3 (main channel w/ branches).**

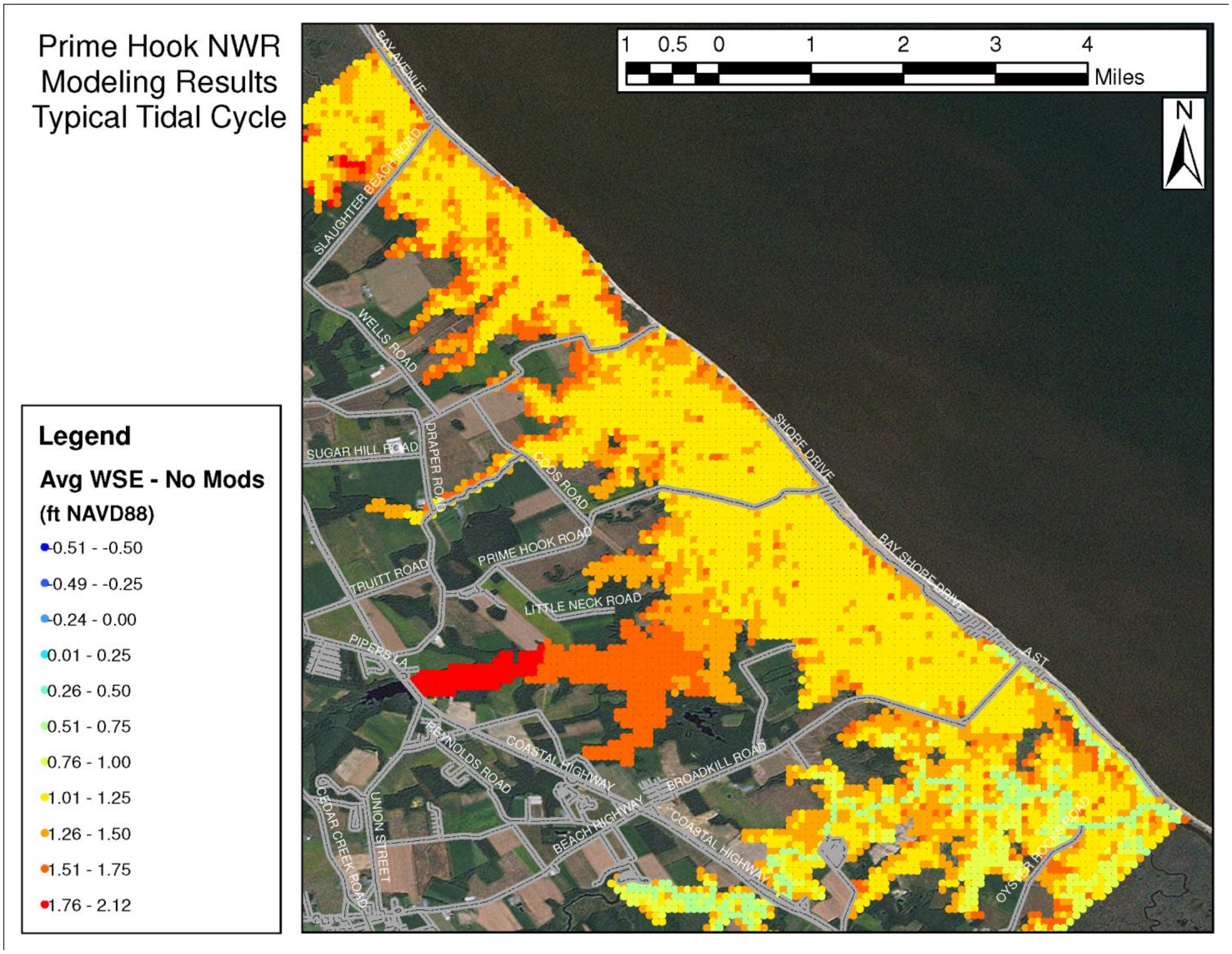

Figure 67. **Average water levels in Prime Hook NWR, Alternative 1 (no modifications).**

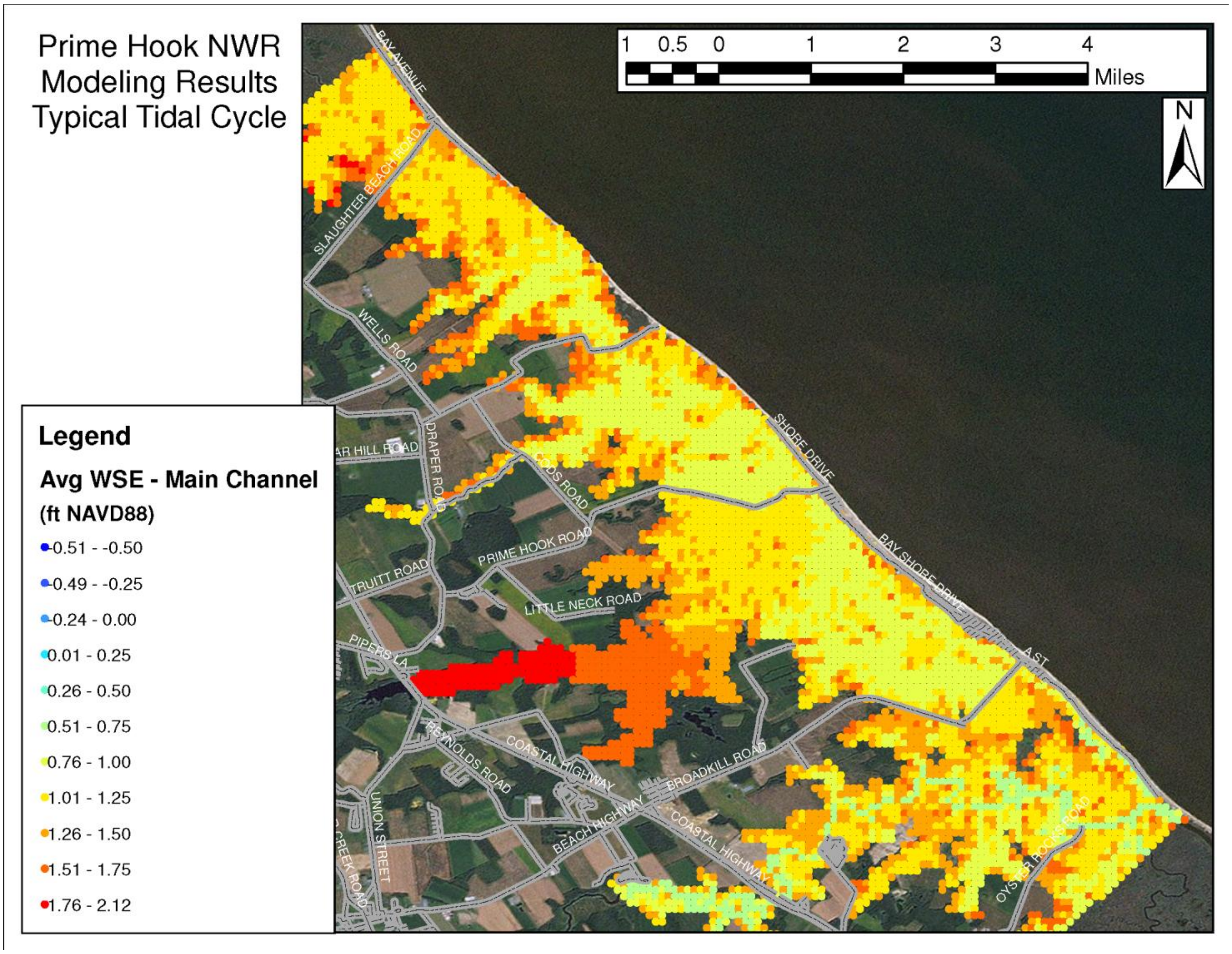

Figure 68. **Average water levels in Prime Hook NWR, Alternative 2 (main channel).**

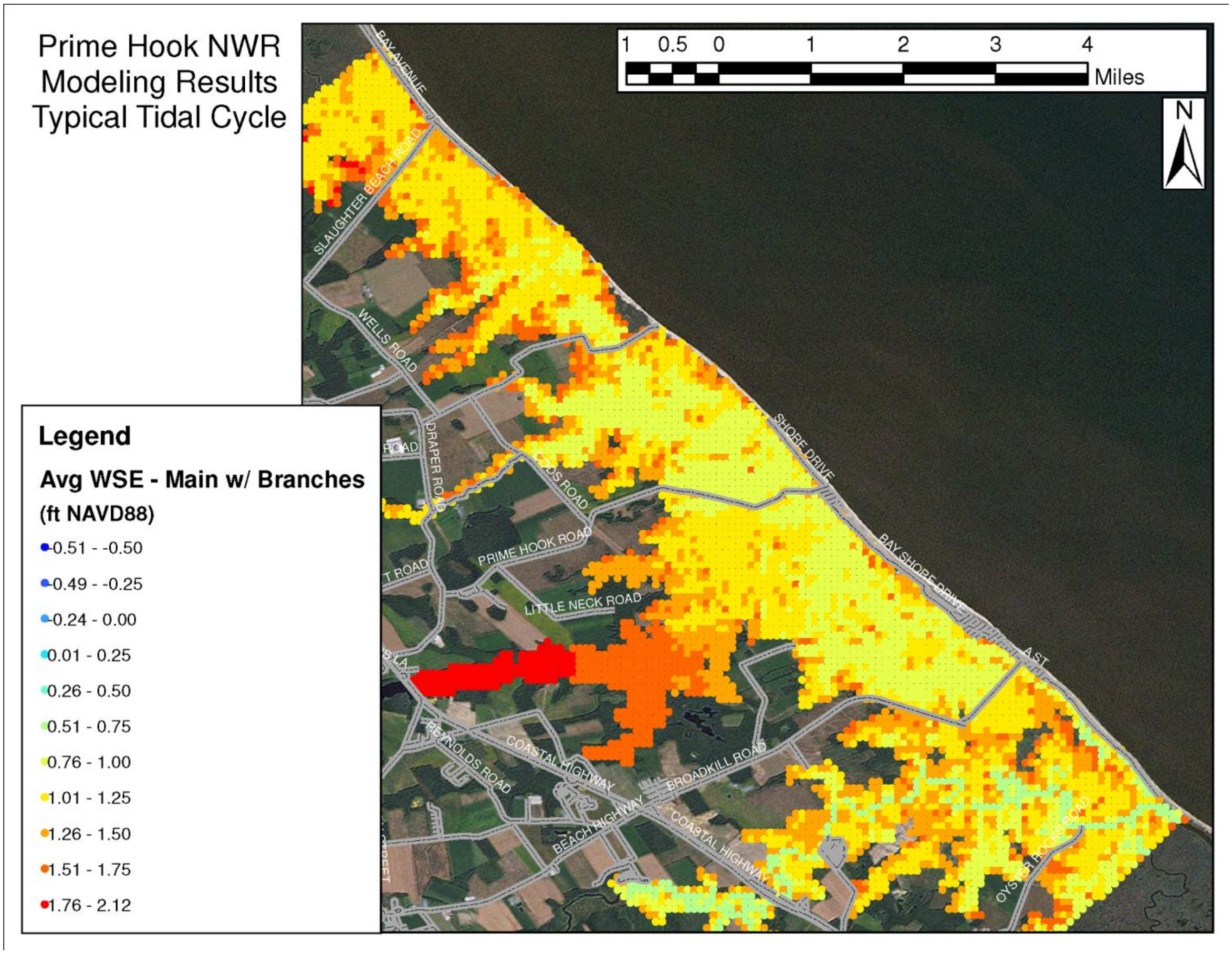

Figure 69. Average water levels in Prime Hook NWR, Alternative 3 (main channel w/ branches).

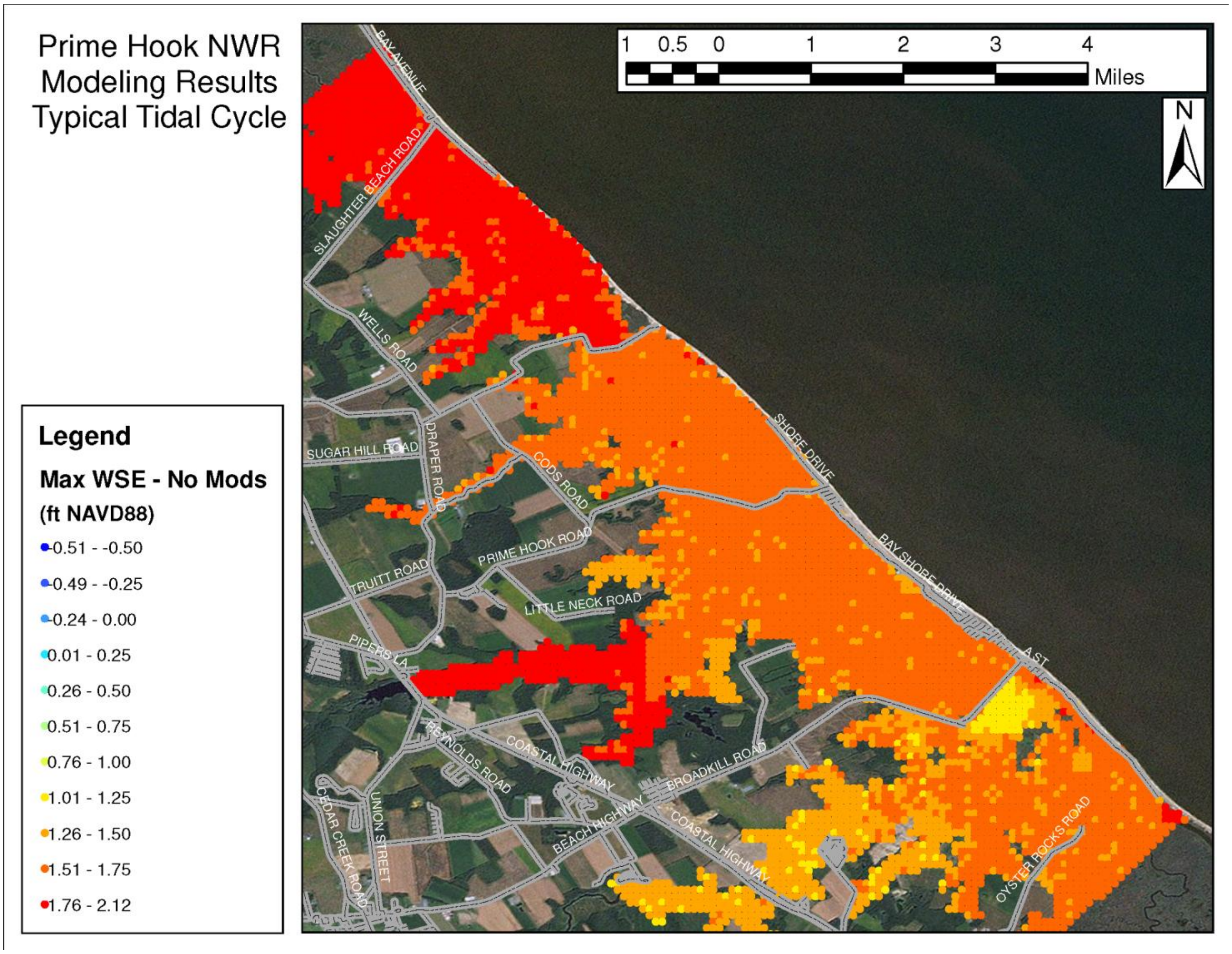

Figure 70. Maximum water levels in Prime Hook NWR, Alternative 1 (no modifications).

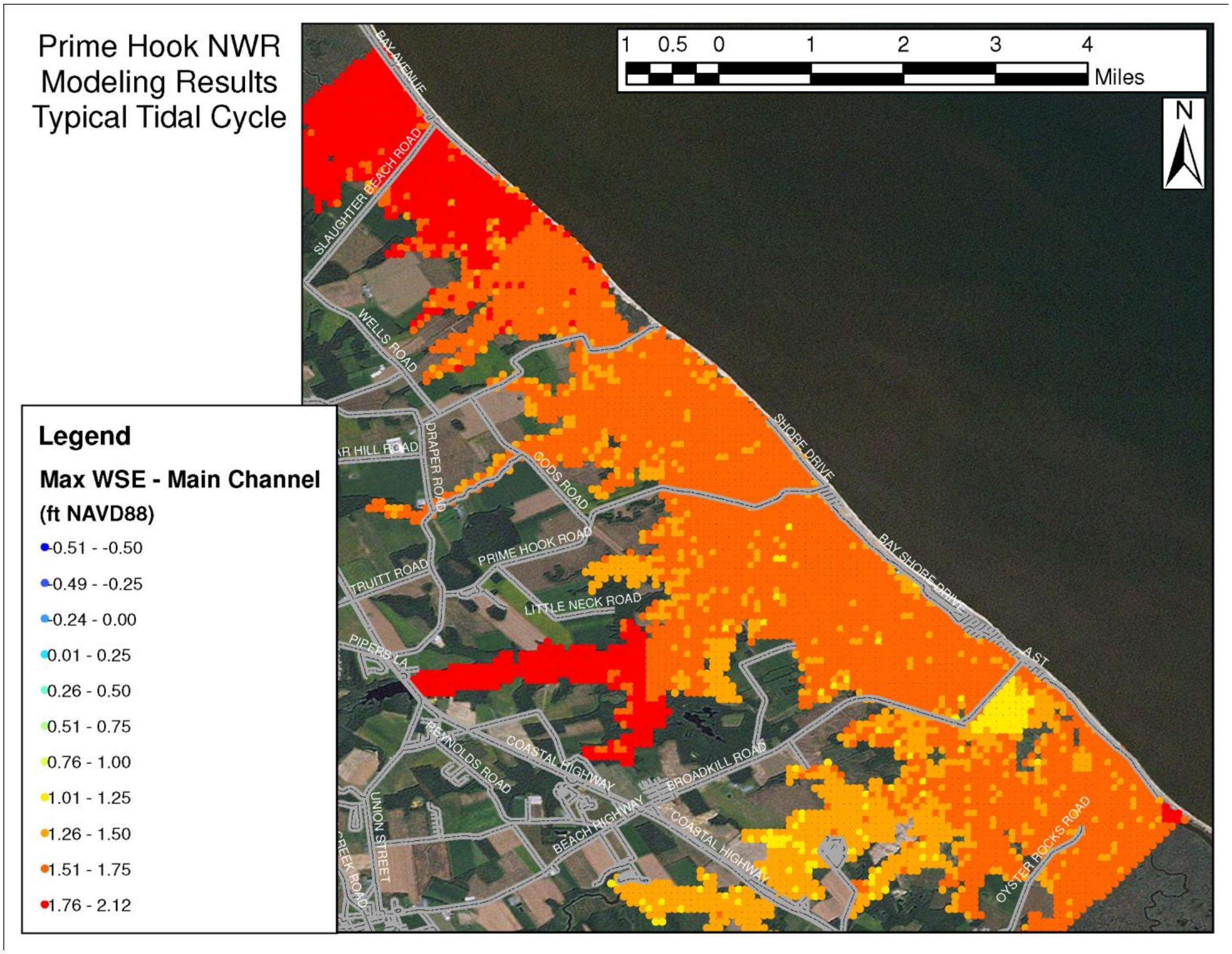

Figure 71. Maximum water levels in Prime Hook NWR, Alternative 2 (main channel).

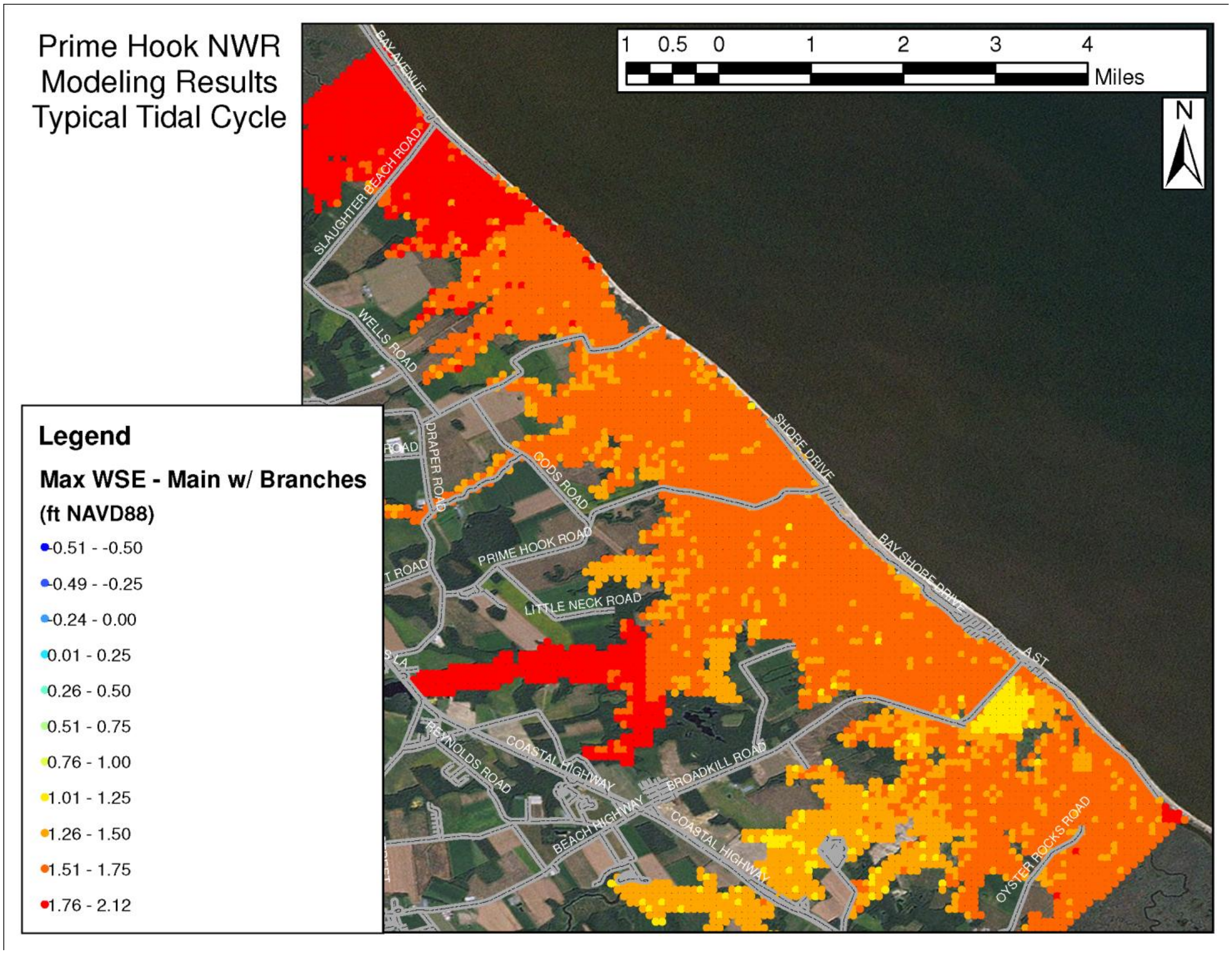

Figure 72. Maximum water levels in Prime Hook NWR, Alternative 3 (main channel w/ branches).

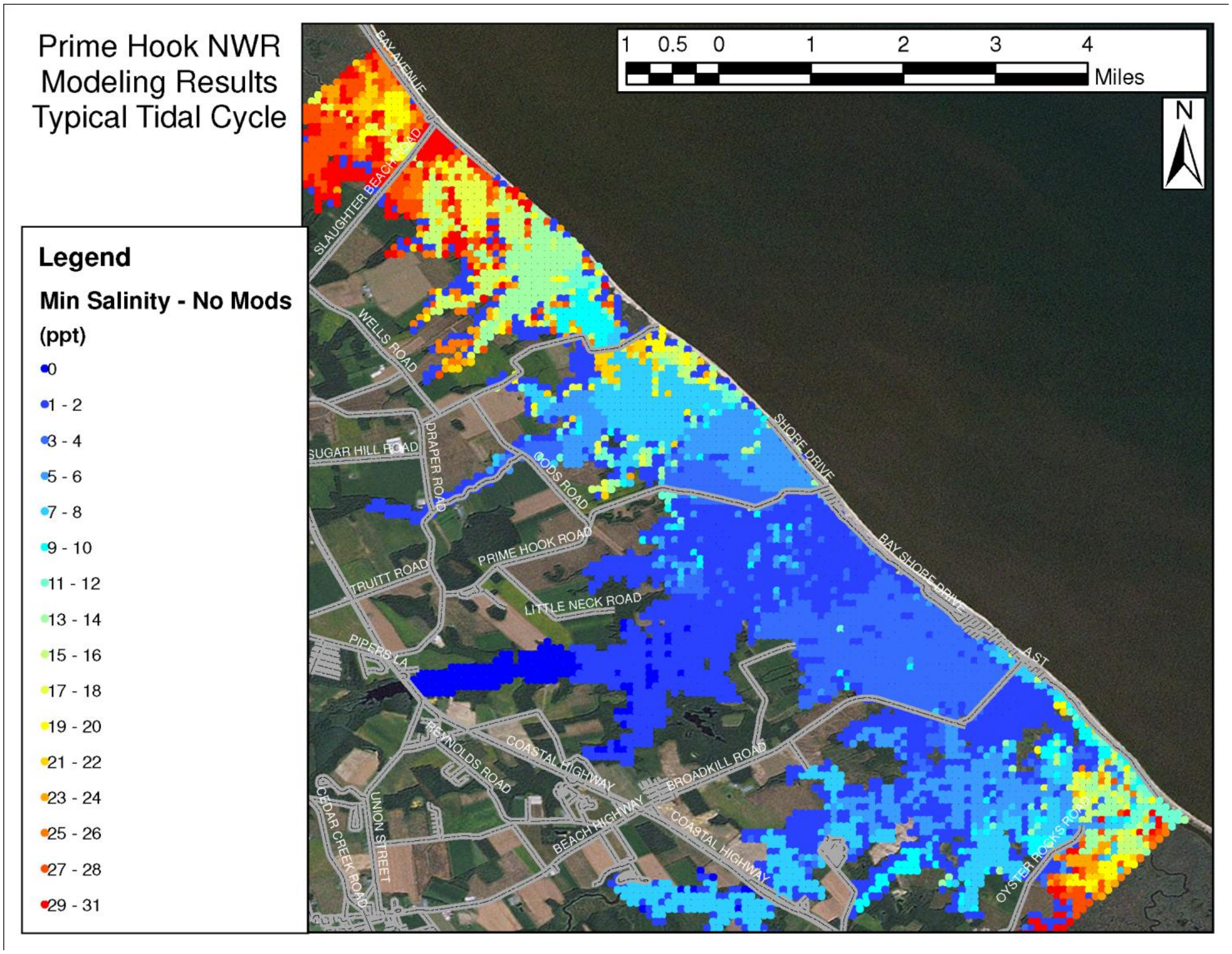

Figure 73. **Minimum salinities in Prime Hook NWR, Alternative 1 (no modifications).**

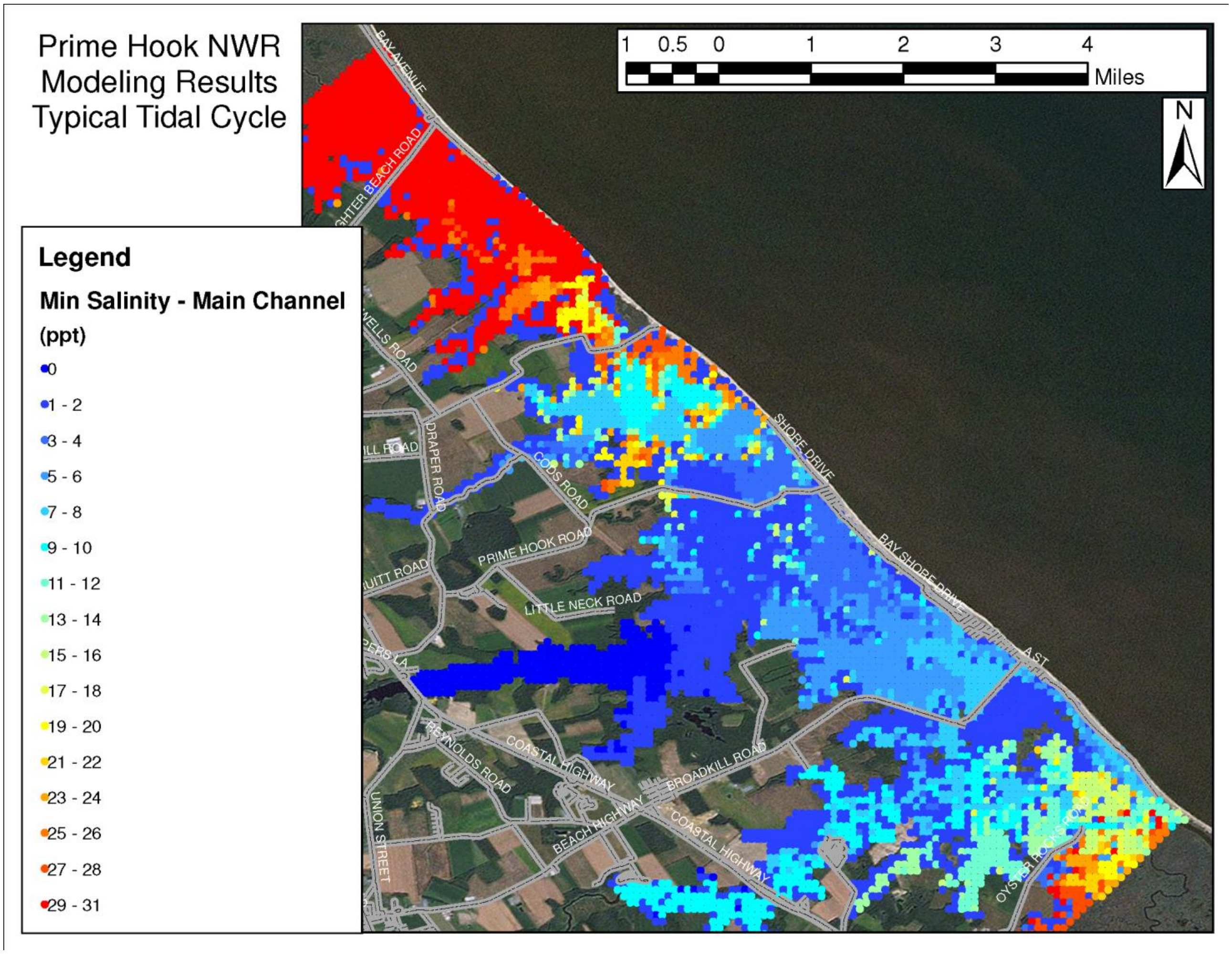

Figure 74. **Minimum salinities in Prime Hook NWR, Alternative 2 (main channel).**

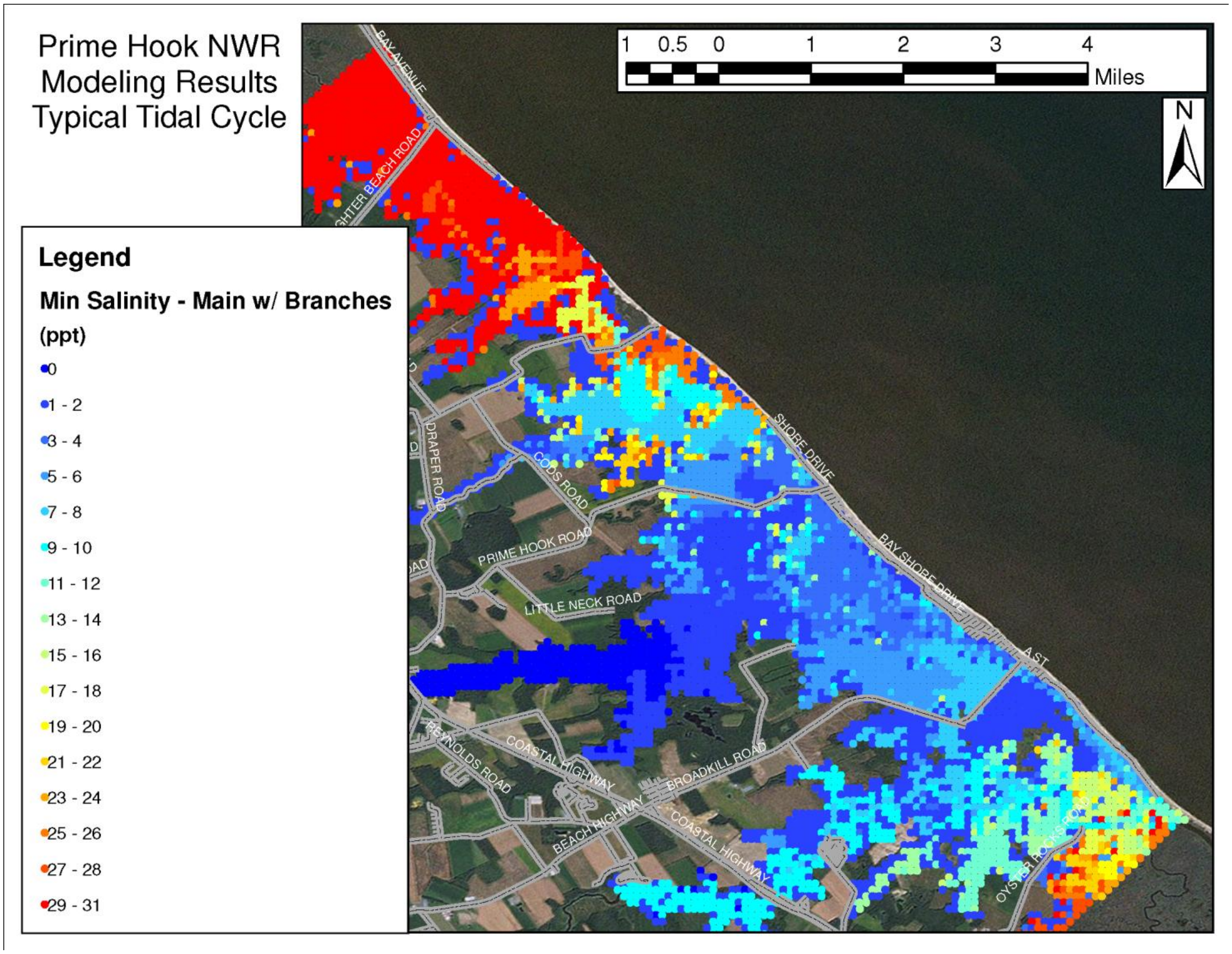

Figure 75. **Minimum salinities in Prime Hook NWR, Alternative 3 (main channel w/ branches).**

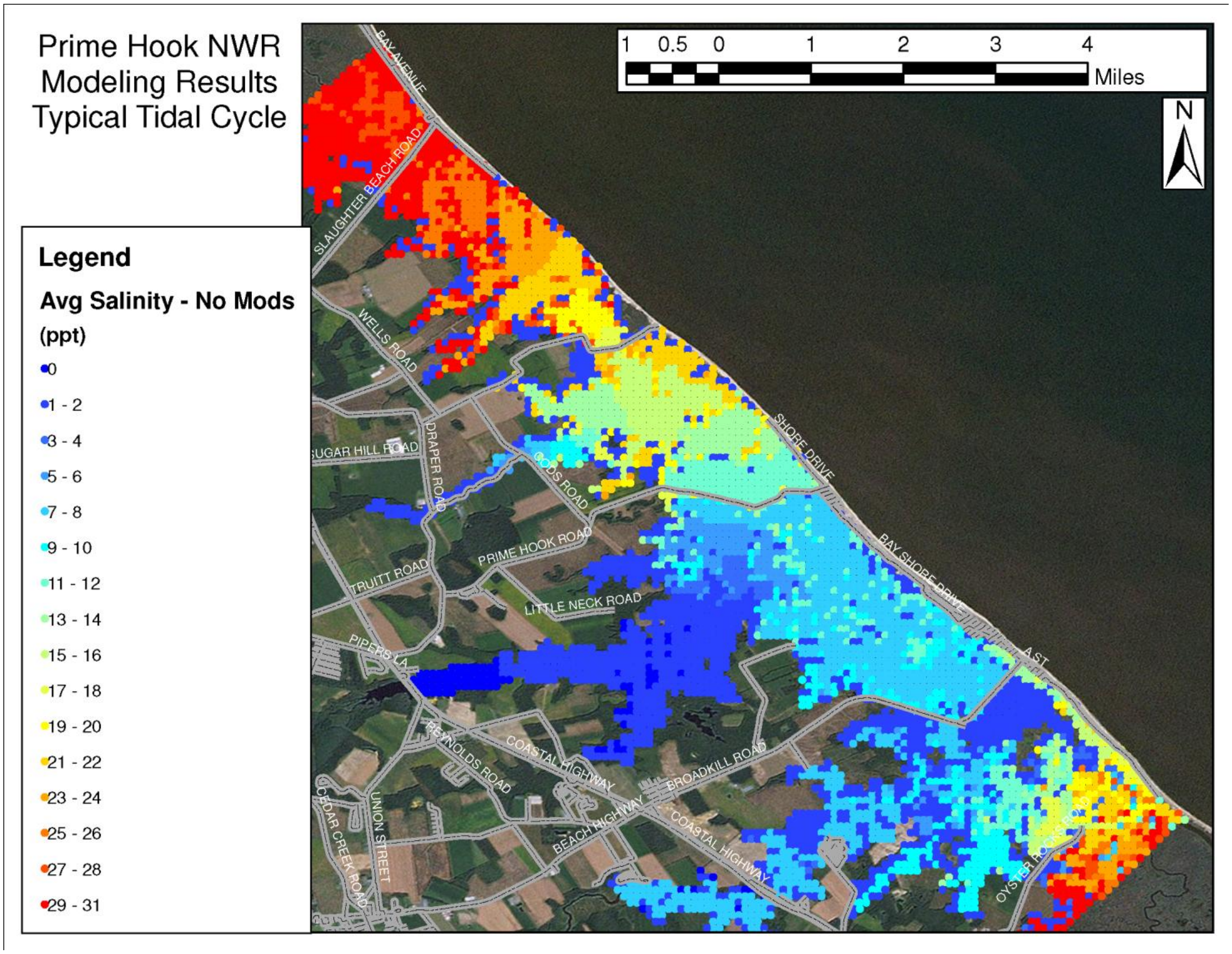

Figure 76. **Average salinities in Prime Hook NWR, Alternative 1 (no modifications).**

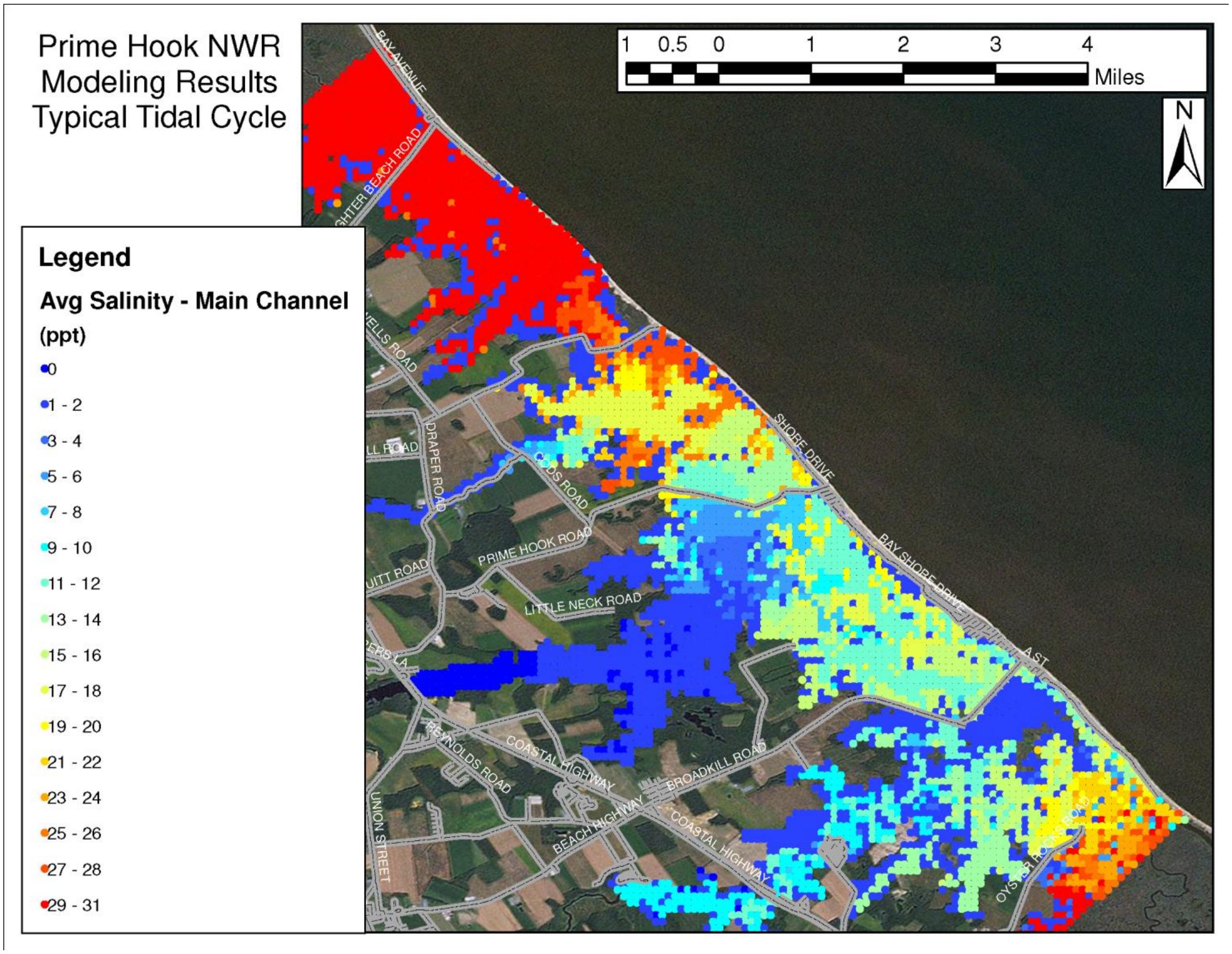

Figure 77. **Average salinities in Prime Hook NWR, Alternative 2 (main channel).**

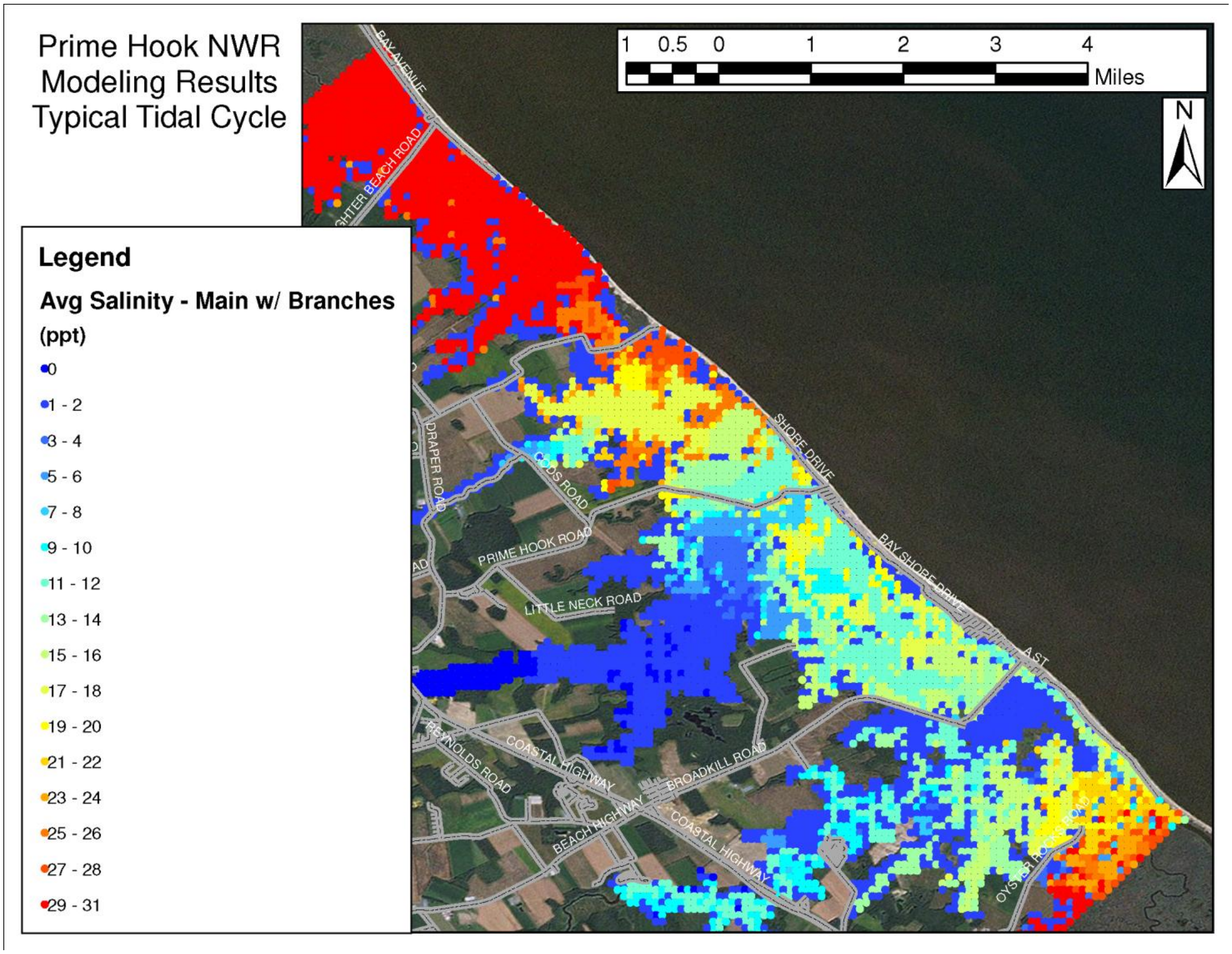

Figure 78. Average salinities in Prime Hook NWR, Alternative 3 (main channel w/ branches).

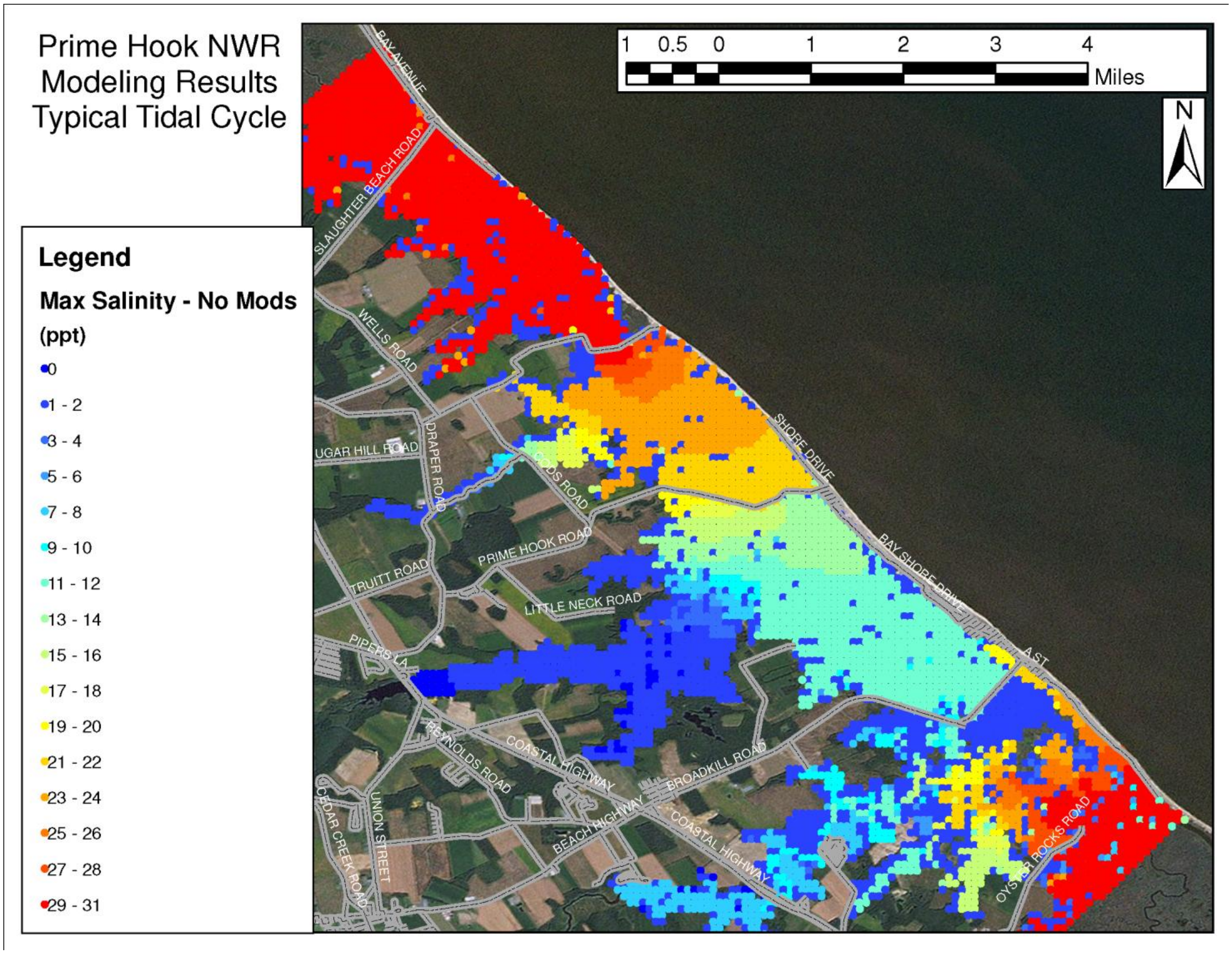

Figure 79. Maximum salinities in Prime Hook NWR, Alternative 1 (no modifications).

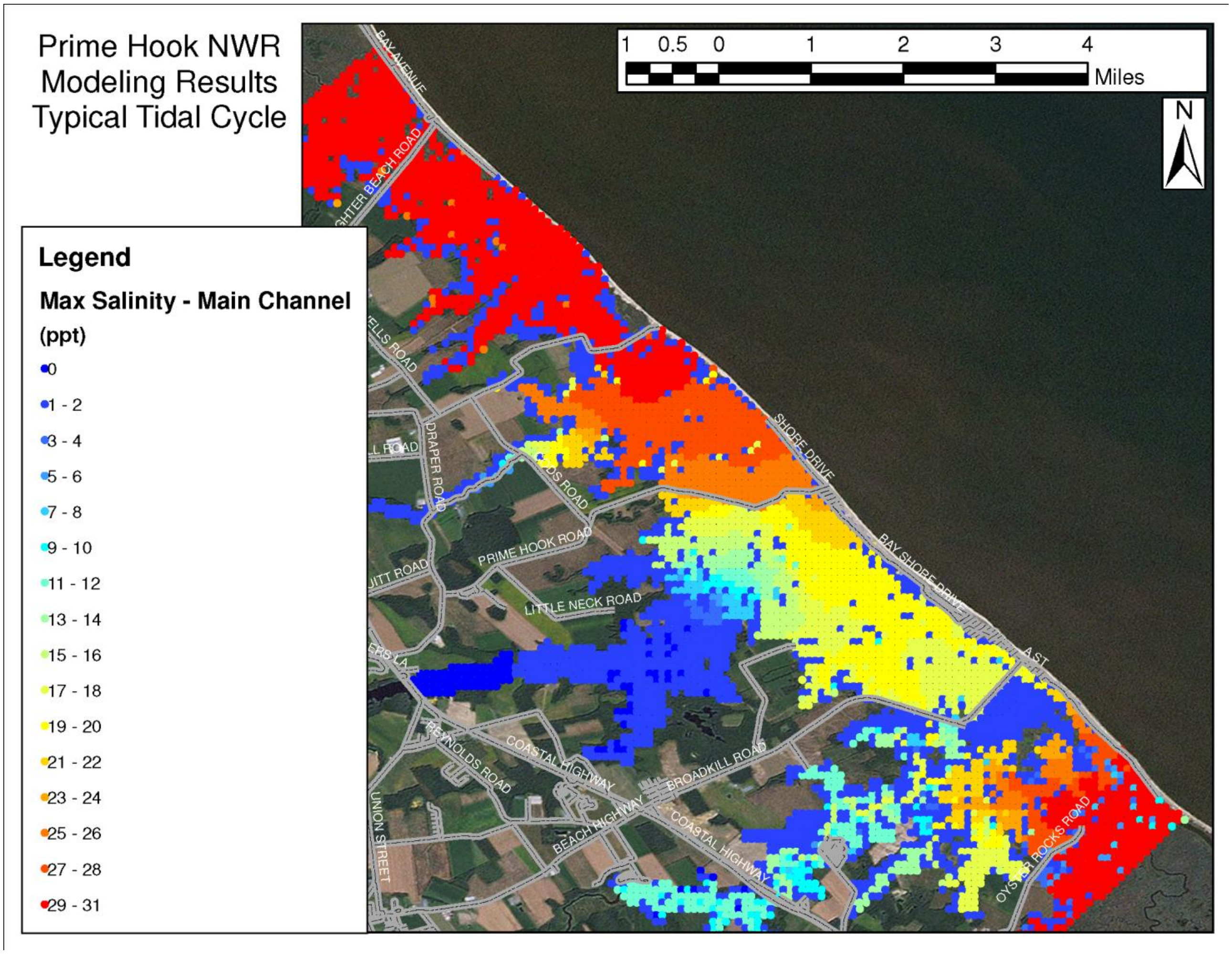

Figure 80. **Maximum salinities in Prime Hook NWR, Alternative 2 (main channel).**

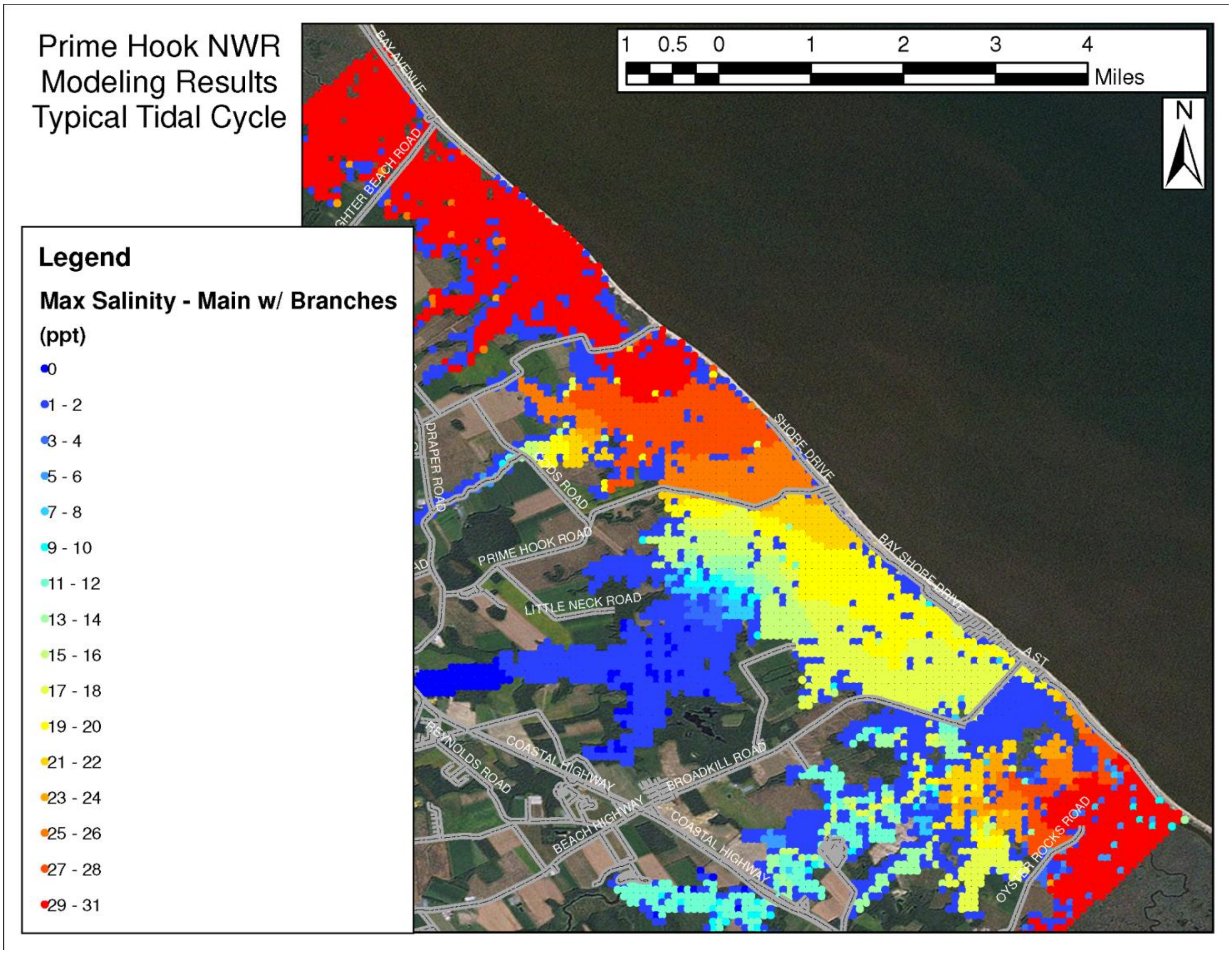

Figure 81. **Maximum salinities in Prime Hook NWR, Alternative 3 (main channel w/ branches).**

A.4.4.2. Hurricane Sandy

Figure 82 through Figure 84 illustrate the water level time series for Hurricane Sandy in Unit II, showing water levels under existing conditions, with a single breach opening, and the three primary alternatives with the breaches closed. In each Unit, the peak storm surge in all three alternatives is reduced by about 1.6 ft (0.5 m) compared to existing conditions, from 5.9 ft (1.8 m) NAVD88 to 4.3 ft (1.3 m) NAVD88. After the peak, water levels drop at the same pace in each scenario, suggesting that water is not being trapped in the Refuge without having breaches to act as conduits.

The Sandy storm runs are also important for the design of any modifications to the roadways and infrastructure within the Refuge; in particular, Prime Hook Road would likely be redesigned to accommodate the proposed conveyance channels between Unit II and Unit III. Table 9 presents a summary of the proposed channel dimensions, storm elevations, and peak channel velocities during Hurricane Sandy for each of the three primary alternatives. Figure 85 illustrates the approximate locations of the proposed channels through Prime Hook Road for Alternative 3; the location of ‘Prime Hook E’ is identical in both Alternatives 2 and 3.

Table 9. Modeled channel dimensions, water levels, and velocities in the vicinity of Prime Hook Road; Hurricane Sandy simulation.

Parameter*	Units	Main Channel	Main w/ branches	
		Prime Hook E	Prime Hook E	Prime Hook W
Channel width @ bottom	(ft)	40	40	40
Channel bottom elevation	(ft NAVD88)	-2.3	-2.3	-2.3
Side slopes**	(V:H)	1V:8H	1V:8H	1V:8H
High tide elevation	(ft NAVD88)	1.57	1.54	1.54
Storm water elevation	(ft NAVD88)	4.1	4.1	4.0
Peak channel velocity (storm)	(ft/s, depth-avg)	8.4	7.6	7.1
Roadway water elevations	(ft NAVD88)	3.9 to 4.1, W to E along road (storm elev)		

*may be refined in final design

**will be altered in final design due to limits in model resolution

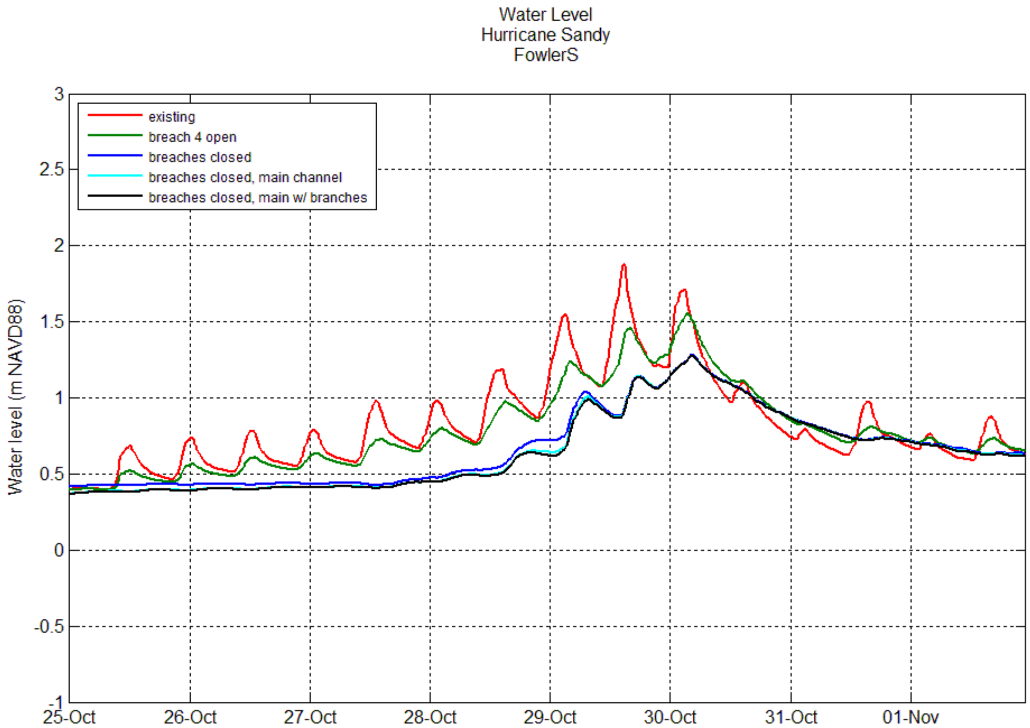

Figure 82. Hurricane Sandy water level time series for the three primary alternatives: Unit II.

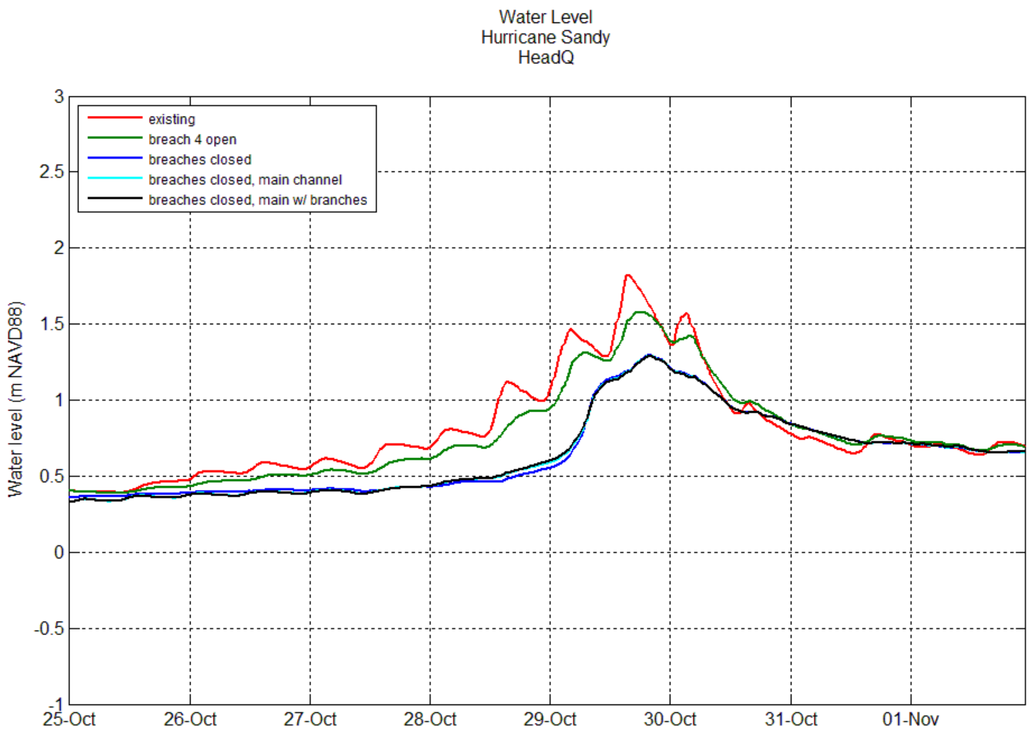

Figure 83. Hurricane Sandy water level time series for the three primary alternatives: Unit III.

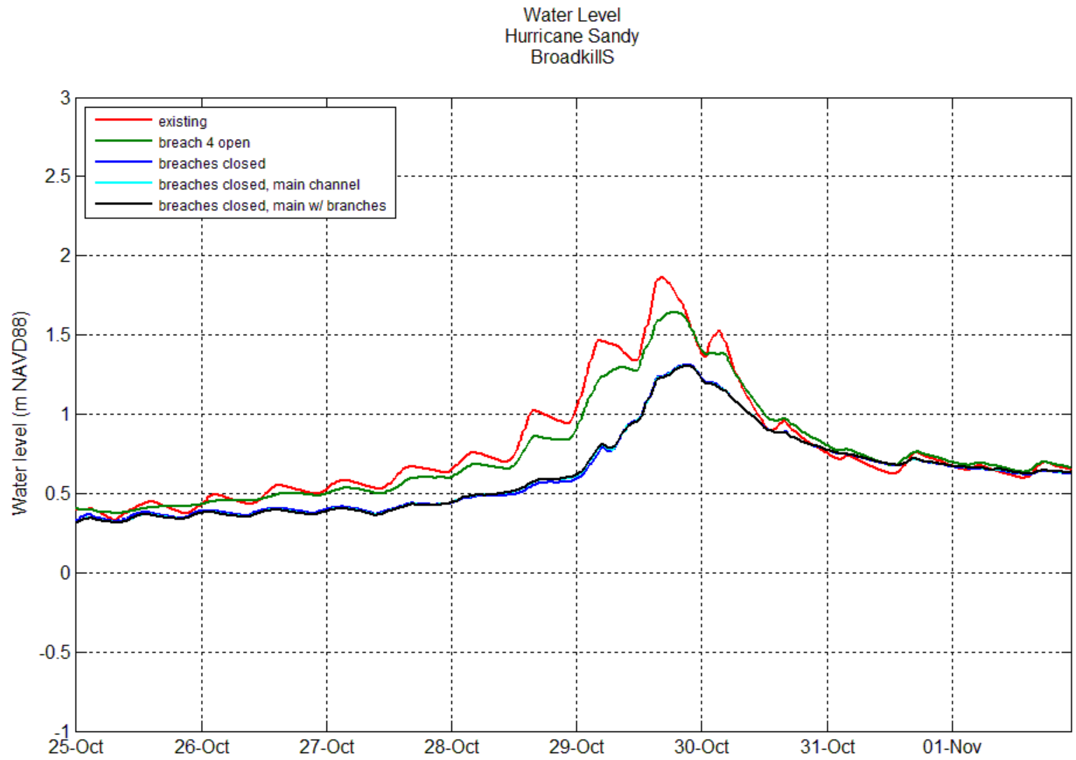

Figure 84. Hurricane Sandy water level time series for the three primary alternatives: Unit IV.

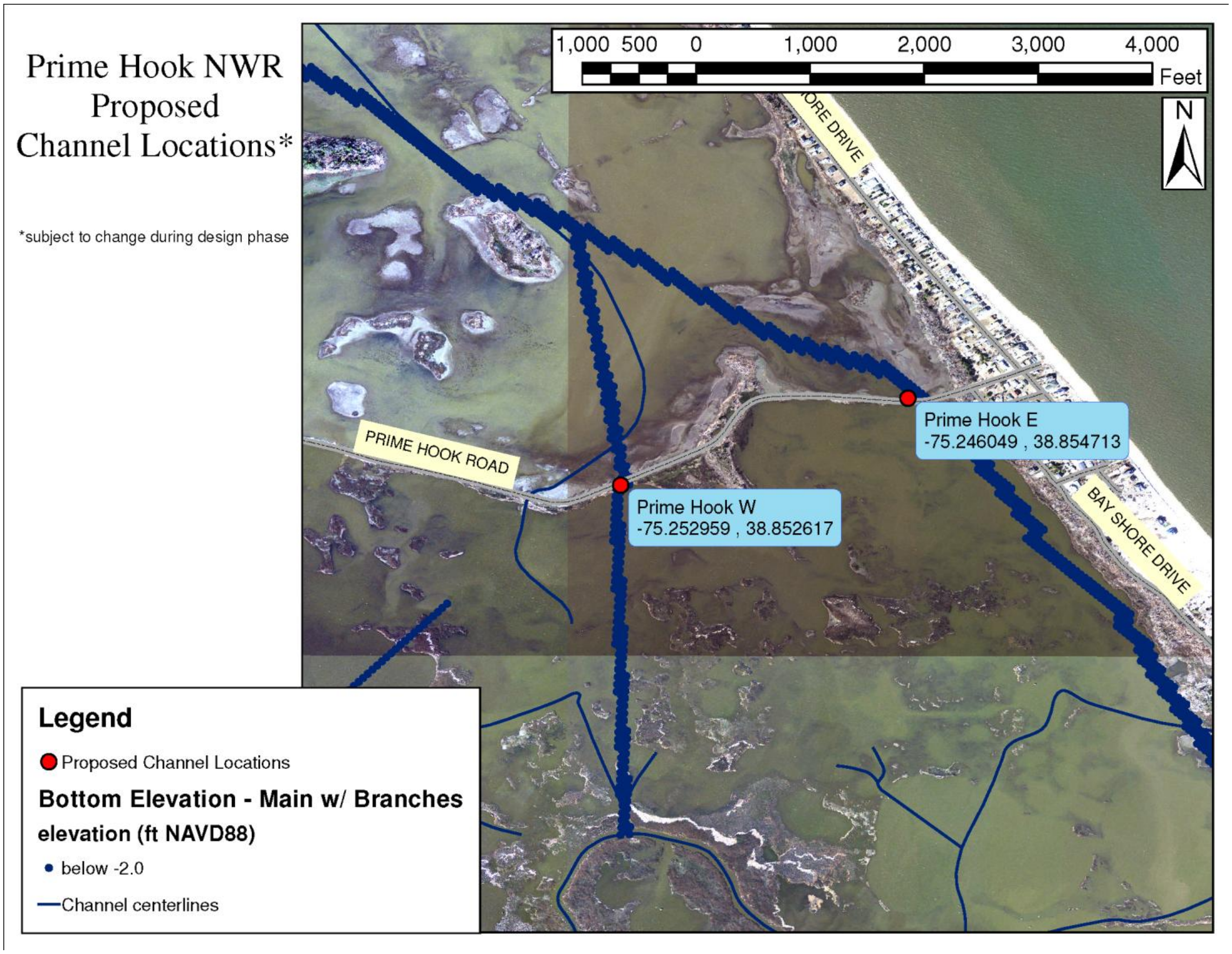

Figure 85. Approximate locations of the proposed channels through Prime Hook Road.