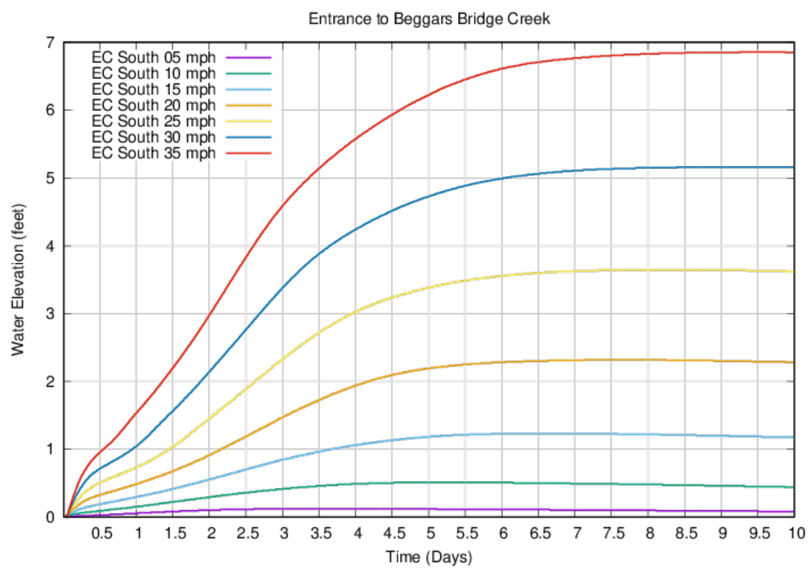
Dewberry



Numerical Modeling of Wind Tides in Back Bay and North Landing River

City of Virginia Beach, VA

CIP 7-030, PWCN-15-0014, Work Order 7B

Final Report

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Department of Public Works

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REVISION HISTORY

February 12, 2019 – Draft Report provided to City for review

March 26, 2019 – Final Draft Report addressing City comments

July 30, 2019 – Final Report addressing requested City updates

EXECUTIVE SUMMARY

This report summarizes a study concerning wind tides for the Virginia Beach Southern Watershed. Wind tide events are a result of wind that blows from the south, called southerly wind. During times of sustained southerly winds, water moves in a northerly direction from the Currituck Sound, located in North Carolina, up through the Back Bay and North Landing River. This process causes water levels to increase by several feet, and results in the flooding of low-lying areas. Four such events occurred in 2017 and 2018, increasing concern from residents and stakeholders. These flood events are generally poorly understood due to a lack of water level records in the area. The City commissioned this study to supplement limited observational data and improve the understanding of these events. An additional study “was initiated in February 2019 to study the return period of the southerly wind events. Readers should refer to technical documentation of Work Order 7C for further information (City of Virginia Beach, 2019).

This study was conducted to improve the understanding of wind tide events and how water levels may change in response to sea level changes in the future. The effect of multiple wind speed and duration variables on the water level across the Southern Watershed was examined. The report also summarizes a model application to provide an exploratory analysis of the influence of the Great Bridge Lock on water levels.

This study used an existing Advanced Circulation Model (ADCIRC) 2D coastal hydrodynamic model, produced by the Federal Emergency Management Agency (FEMA) for the Region III Storm Surge Study. The FEMA Region III ADCIRC grid was sub-sampled to a study area that included the Southern Watershed. The grid extended west to include the full hydraulic connection of the Albemarle and Chesapeake Canal from the North Landing River to the Southern Branch Elizabeth River, and south to Cape Lookout to capture the full fetch of the Pamlico, Albemarle, and Currituck Sounds. The model’s accuracy was validated against measured water elevations at Beggars Bridge for wind tide events in May 2017 and September 2018. The model was then used to simulate water level responses to sustained southerly winds from the southwest, south-southwest, south, south-southeast, and southeast directions. Wind speeds from 5- to 35-mph were simulated in 5 mph increments over a 10 day period. Results were compiled in 40 locations at the North Landing River and Back Bay. A series of response plots and tables were generated to summarize results.

Results found that sustained winds from due south resulted in the highest wind tides, followed by winds from due south-southeast, and then winds from south-southwest. It was also found that maximum water levels were reached between three to five days depending on wind speed and location.

Wind tide simulations for sea level rise (SLR) scenarios measuring 1.5- and 3-feet higher than present day conditions were also modeled. The simulations showed that the additional water depth provided by these conditions resulted in a shorter time to maximum wind tide. For example, the 1.5 foot SLR scenario would have peak wind tide approximately two days earlier than existing conditions, whereas the peak wind tide under the 3 foot SLR scenario could occur three days earlier.

City stakeholders claim that the Great Bridge Lock impounds water in the Southern Watershed during wind tide events, resulting in increased flood levels along the North Landing River and Back Bay. Simulations with a sustained southerly wind for 10 days were completed with the lock open and closed in the model. Results showed that while the closed lock does elevate the water by several feet immediately downstream of the lock, the effect is reduced to a few inches at the confluence of North Landing River and Salem Canal, and minimal at the West Neck Creek confluence.

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ACRONYMS

ADCIRC	Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters
C-CAP	Coastal Change and Analysis Program
DEM	Digital Elevation Model
FEMA	Federal Emergency Management Agency
ft	Feet
m	Meter
mph	Miles Per Hour
NAS	Naval Air Station
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
SLR	Sea Level Rise
USGS	U.S. Geological Survey
2D	Two-dimensional

1. INTRODUCTION

1.1. Wind Tide Conditions

The Southern Watershed of Virginia Beach, Virginia, has large areas of low-lying land that make it especially susceptible to recurrent coastal flooding (Figure 1). "Wind tide" events occur in response to sustained southerly winds, and result in instances of flooding in the Southern Watershed. While wind-driven high water can be a result of tropical or extra-tropical storm systems, it can also be a result of multiple days, medium-scale events, with consistent winds from the south.

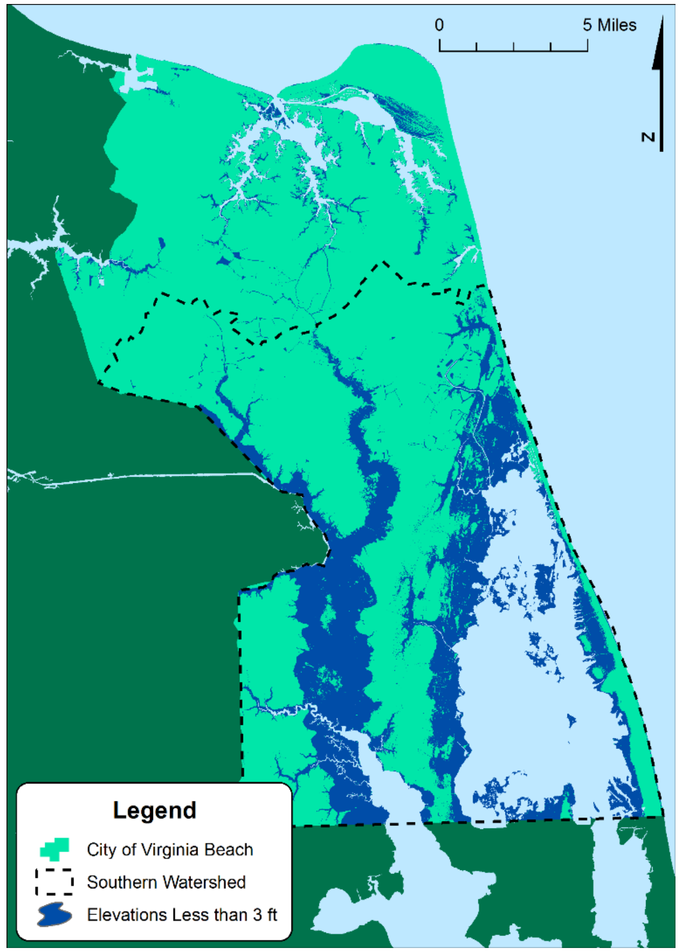


Figure 1: Areas less than 3 feet in the Southern Watershed experience are particularly vulnerable to wind-tide induced flooding.

Flooding in the Southern Watershed as a result of wind tides is not a recent phenomenon. Increased flooding for lands adjacent to Back Bay and the North Landing River has been noted as early as the 1930s (Waterfield, 1951). Relative sea level increases, have increased base water levels, and in turn have increased the frequency and depth of flooding from wind tide events. Such conditions, as assessed in this report, are expected to become worse in the future as sea level continues to rise.

The driving force behind wind tide events is a sustained southerly wind. Figure 2 presents a wind rose diagram showing wind direction and wind speed data collected at Naval Air Station (NAS) Oceana from 1945 to 2018 (cli-Mate: Midwestern Regional Climate Center, 2018). Each "spoke" shows the frequency (percentage of time) of wind coming from a particular direction. South and southwesterly winds occur almost 30 percent of the time during this period. An analysis of the characteristics of sustained southerly wind events, such as frequency of occurrence, has not been completed at this time. Information like this would help to understand if recent events reflect a change in sea level, wind patterns, or both.

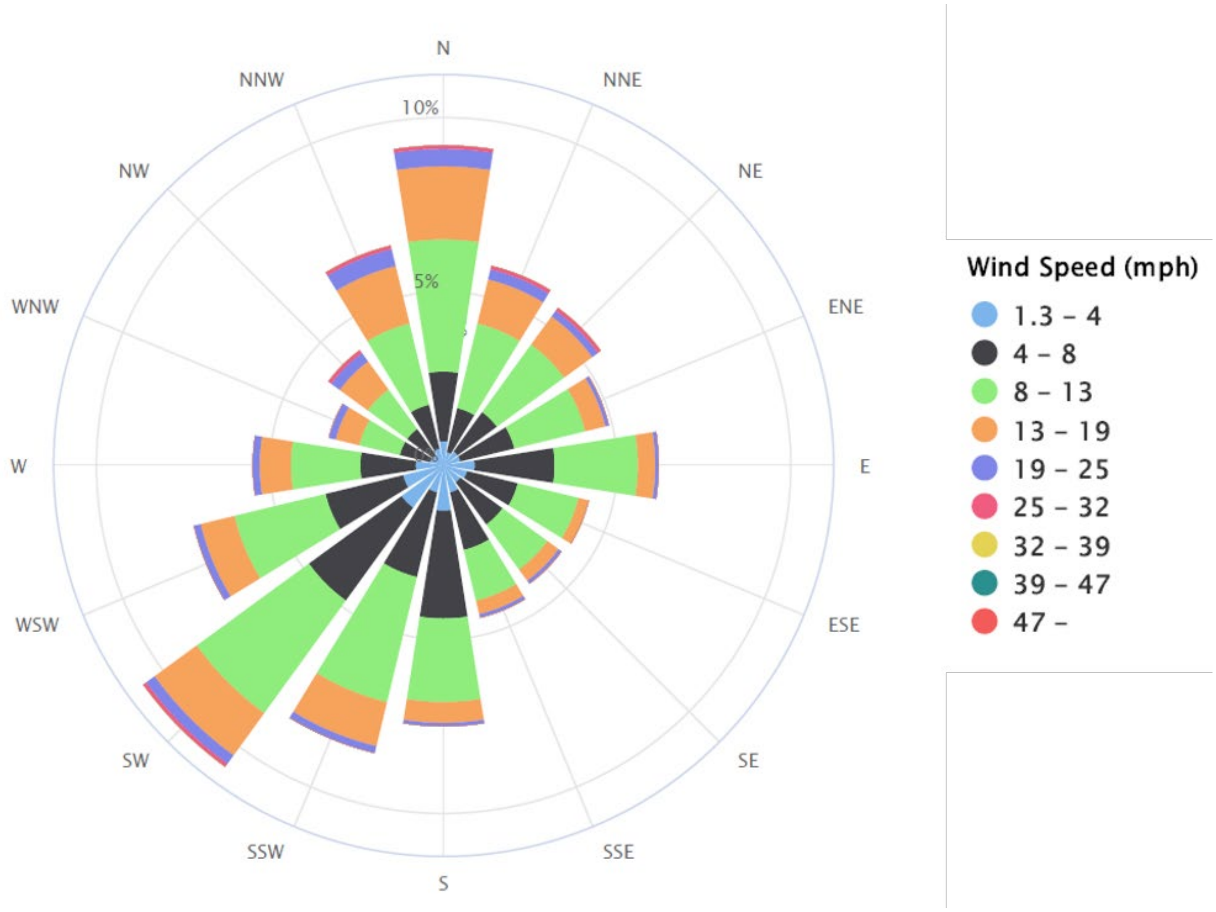


Figure 2: Wind rose diagram for NAS Oceana from 1945 to 2018 (cli-Mate: Midwestern Regional Climate Center, 2018).

Sustained winds over water result in waves, referred to technically as “wind setup”. Wind setup is an elevated water level condition occurring when water “piles up” along the shoreline in response to wind-driven flow. The “fetch” is the body of water that the wind blows over to create this condition. For the City of Virginia Beach, the fetch for southerly wind tides extends south into North Carolina’s Currituck, Albemarle, and Pamlico Sounds.

Figure 3: Southerly winds push water to southern Virginia Beach causing recurrent flooding.

2. MODELING APPROACH

Accurate modeling of the wind tide inundation for Back Bay and North Landing River requires the use of a highly resolved 2D hydrodynamic model. Development of these models are typically time-consuming and expensive. These factors led to the use of a pre-developed model consisting of the 2D hydrodynamic model Advanced Circulation Model (ADCIRC) mesh, previously used for the Federal Emergency Management (FEMA) Region III Storm Surge Study, for two primary reasons. First, the ADCIRC mesh has been thoroughly vetted by both public and private entities for accuracy and completeness. Secondly, the aforementioned ADCIRC mesh has been validated for multiple tropical and extra-tropical cyclonic events and found to produce accurate water levels. Readers are referred to the FEMA Region III Storm

Surge Study, Coastal Storm Surge Analysis: Computational System, Report 2: Intermediate Submission No. 1.2 (Blanton et. al, 2011) for further details.

2.1. Model Grid Development

The model domain used for the FEMA Region III Storm Surge Study extended well off the shores of Virginia and North Carolina. The inland boundary of the model runs along the 15- to 20-meter North American Vertical Datum of 1988 (NAVD88) contour, and the offshore boundary lies along the 60-degree west meridian (Figure 4). The computational mesh varies in resolution from approximately 50 meters to 30 kilometers from the shoreline to the 100 meter bathymetric contour (Blanton et. al, 2011). The total number of computational nodes for the ADCIRC mesh is 1,875,689, which requires high performance computing resources, such as a supercomputer, to execute. The model was reduced to include only the necessary geographic areas within North Carolina, which included the Southern Branch of the Elizabeth River, North Landing River, Back Bay, and the Pamlico, Albemarle, and Currituck Sounds (the reduced study domain is shown in Figure 12). This geographic reduction resulted in the final ADCIRC mesh for this study to include 165,596 computational nodes. This reduction allowed simulations to be performed efficiently on a desktop computer. An example of the model representation of terrain can be seen in Figure 5.

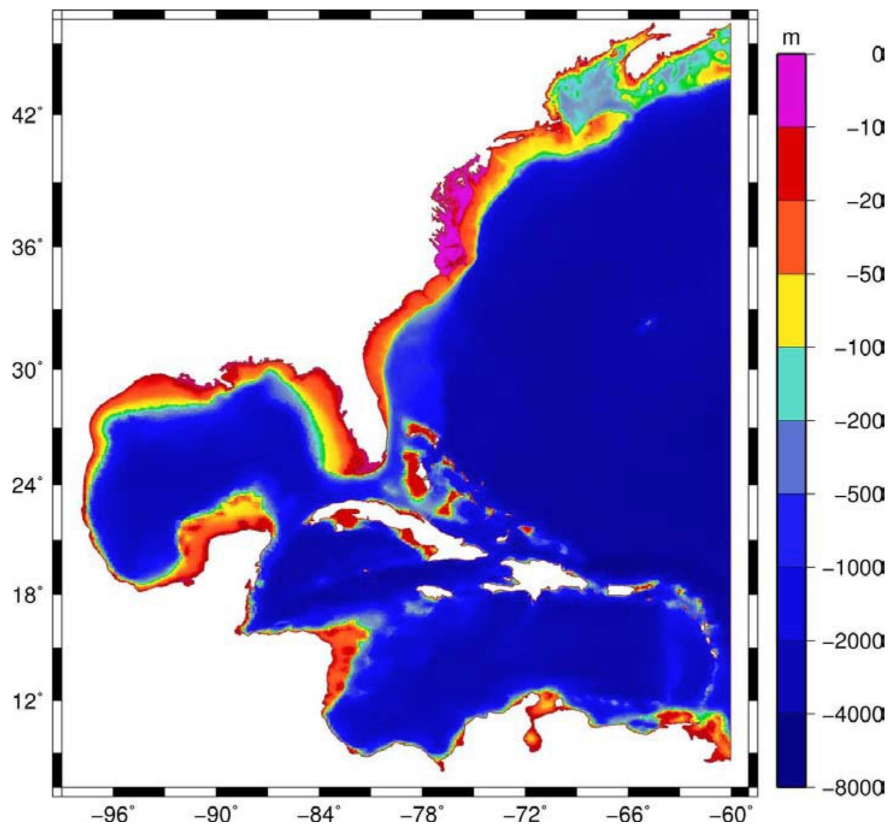


Figure 4: FEMA Region III ADCIRC mesh domain and elevation contours, meters NAVD88 (Blanton et. al, 2011).

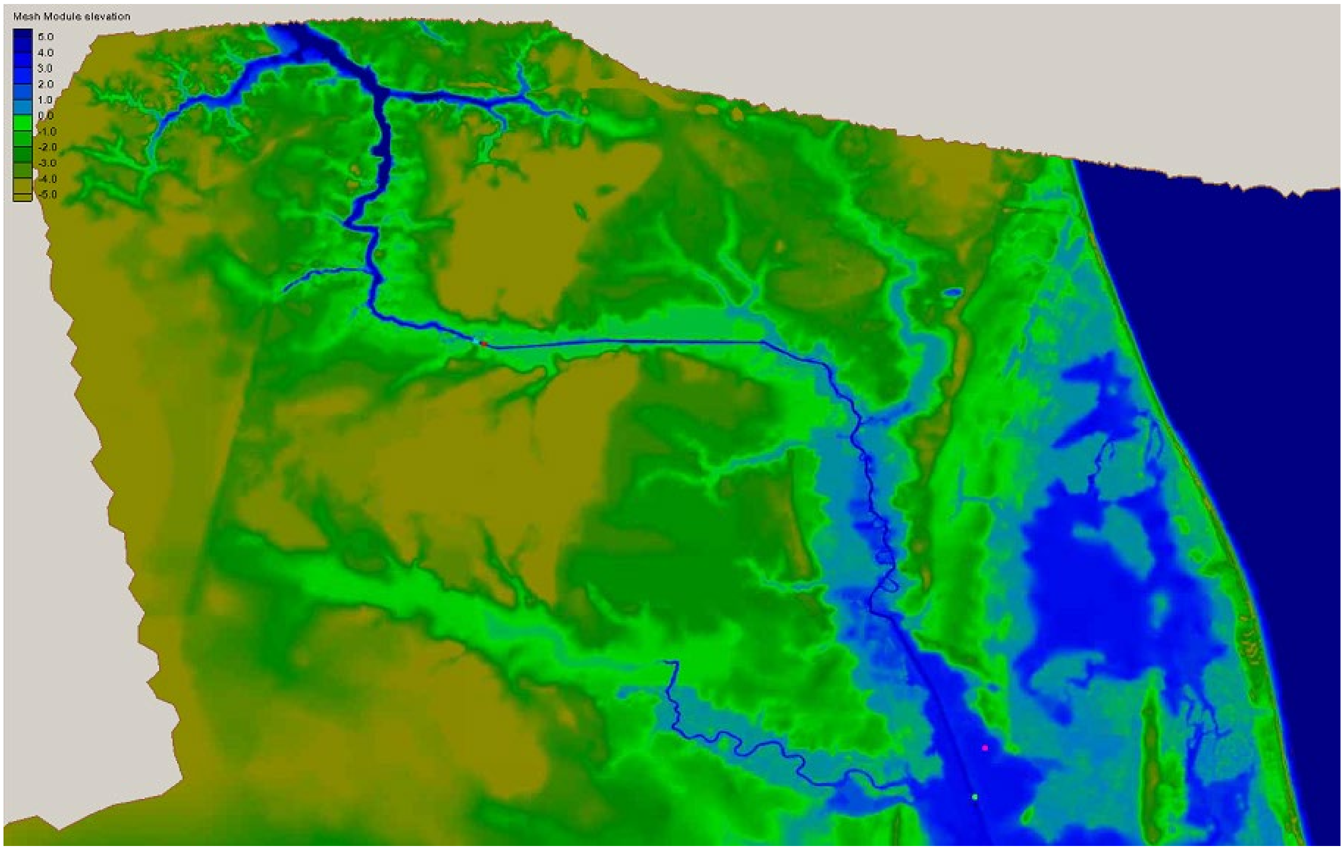


Figure 5: Illustration of topographic and bathymetric representation in ADCIRC model grid.

2.2. Boundary Conditions and Settings

The ADCIRC model uses several input files to describe the characteristics of the underlying topography, bathymetry, and land classification, which are described below:

2.2.1. Grid and Boundary Information File (fort.14)

The ADCIRC grid file (fort.14) represents the underlying topography and bathymetry within the model domain. The file also includes parameters describing the boundary type and boundary condition for the perimeter of the model grid. For this effort, all boundary conditions were set to “Mainland” boundary type and “Natural (with tangential slip)” boundary condition. These parameters would allow water at the boundary to flow out of the model domain, instead of artificially piling up.

2.2.2. Nodal Attributes File (fort.13)

The Nodal Attributes File (fort.13) represents varying spatial parameters within the model domain. These attributes include frictional land values like Manning’s n, and the Surface

Canopy Coefficient used to reduce wind speed in forested areas. For this effort, the fort.13 file utilized three components: Manning's n at Sea Floor, the Surface Canopy Coefficient, and the Primitive Weighting in Continuity Equation.

Land use information for the Manning's n at Sea Floor and the Surface Canopy Coefficient were derived from the National Oceanic and Atmospheric Administration's (NOAA) Coastal Change Analysis Program (C-CAP) dataset.

2.3. Model Validation

A crucial step in determining the accuracy of the model is to perform a model validation run. Model validation uses measured water elevations within the model domain and compares the data to the modeling results. There are two known gauges that can be used for the Back Bay area: The United States Geological Survey (USGS) Beggars Bridge Creek (Gauge ID 0204300267) gauge, and the North Landing River at Marina near Creeds, Virginia (VA, USGS Gauge ID 02043269) gauge. Both gauges were installed recently through an agreement between the USGS and the City of Virginia Beach. As a result, the gauges have somewhat limited water level records, dating back to April 2016.

2.4. May 2017 Pungo Flooding Event

In early May 2017, wind tides and rainfall resulted in property damage and multiple road closures in the Southern Watershed. The flood event started late in the evening on April 26, 2017, with winds blowing consistently from the southwest, and lasted until early morning on May 2. Wind speeds, as observed at Duck, NC, stayed consistently between 10 and 15 mph during the start of the event, and increased to between 20 to 25 mph during the day on May 1. Late evening on May 2, the wind diminished and shifted to a predominantly northerly wind, with speeds between 5 and 10 mph. More than 2.4 inches of rain were recorded, with a peak water level just over 2.5 feet at Beggars Bridge Creek (Figure 6).

Wind speed and direction data were needed to validate the model against this event. The Beggars Bridge Creek gauge wind sensor was not installed at the time, so other wind sources were used to investigate the event. Land based wind observations were immediately discarded to avoid frictional affects from the land that could potentially alter wind speed and direction and result in poor validation. Two NOAA tide gauges were located in proximity to the watershed, Duck, NC and Cape Henry, VA. The Duck, NC gauge was selected as the basis for representative wind forcing for the model domain based on its location within the fetch for wind tides into the Southern Rivers Watershed and also having minimal land friction that would interfere with the wind speeds. Although the Cape Henry gauge is closer in proximity to the study area, its location north of Virginia Beach would not provide the best representation of southerly winds within the Back Bay due to the frictional land effects of Virginia Beach. It should also be noted that the wind sensors (anemometers) at the North Landing River and Beggars Bridge USGS stations are not mounted at standard 10 m (32.8 feet heights).

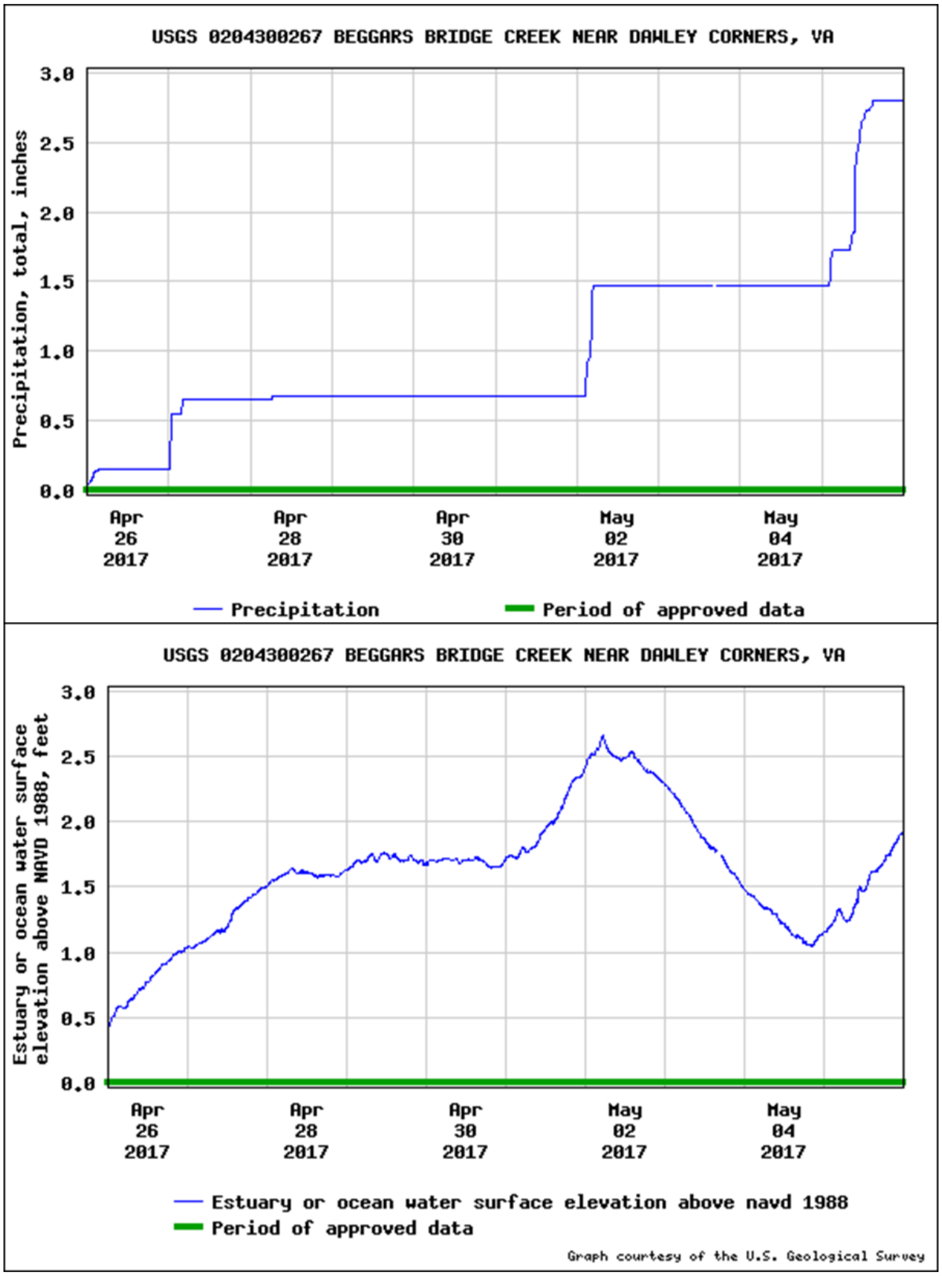


Figure 6: The top figure shows precipitation totals (inches) and the bottom figure shows water surface elevations at Beggars Bridge between April 26 and May 5, 2017.

Figure 7 shows a comparison of the measured versus modeled water levels at the Beggars Creek USGS gauge from April 26, 2017 to May 5, 2017. At the beginning of the model run, the ADCIRC model produced slightly lower water levels than observed but after approximately three days accurately replicated the levels. During the height of the event, the timing and value of the simulated and observed peak water level were consistent, with the modeled water level at 2.7 feet NAVD88 and the actual measured water level at 2.68 feet NAVD88. The variance in water level at the beginning of the run could be partially attributed to a rainfall event that occurred early on April 27th, resulting in 0.6 inches of rain measured at the Beggars Creek gauge. This caused the ADCIRC simulation to under predict water levels because the model does not take into consideration hydrologic influences. At the time, this was the best event for validation given available water level observation records (the model was later validated against Hurricane Florence, described in the following section). The event started to end about 190 hours later (on the evening of May 2nd) as the winds shifted the north, seen in Figure 7. Winds from the Cape Henry gauge indicate that a more intense northerly wind could have occurred in this region than what the Duck, NC gauge indicated, and therefore the model may not be fully replicating the decrease in water levels occurring at the Beggars Creek gauge.

In addition to unknown wind velocities over the region during the event, another factor to consider when observing the difference between modeled versus measured is the input of wind information into the ADCIRC model. For this case, wind speed and direction were not spatially varied, meaning that the full synoptic scale event may not be fully realized during the model run.

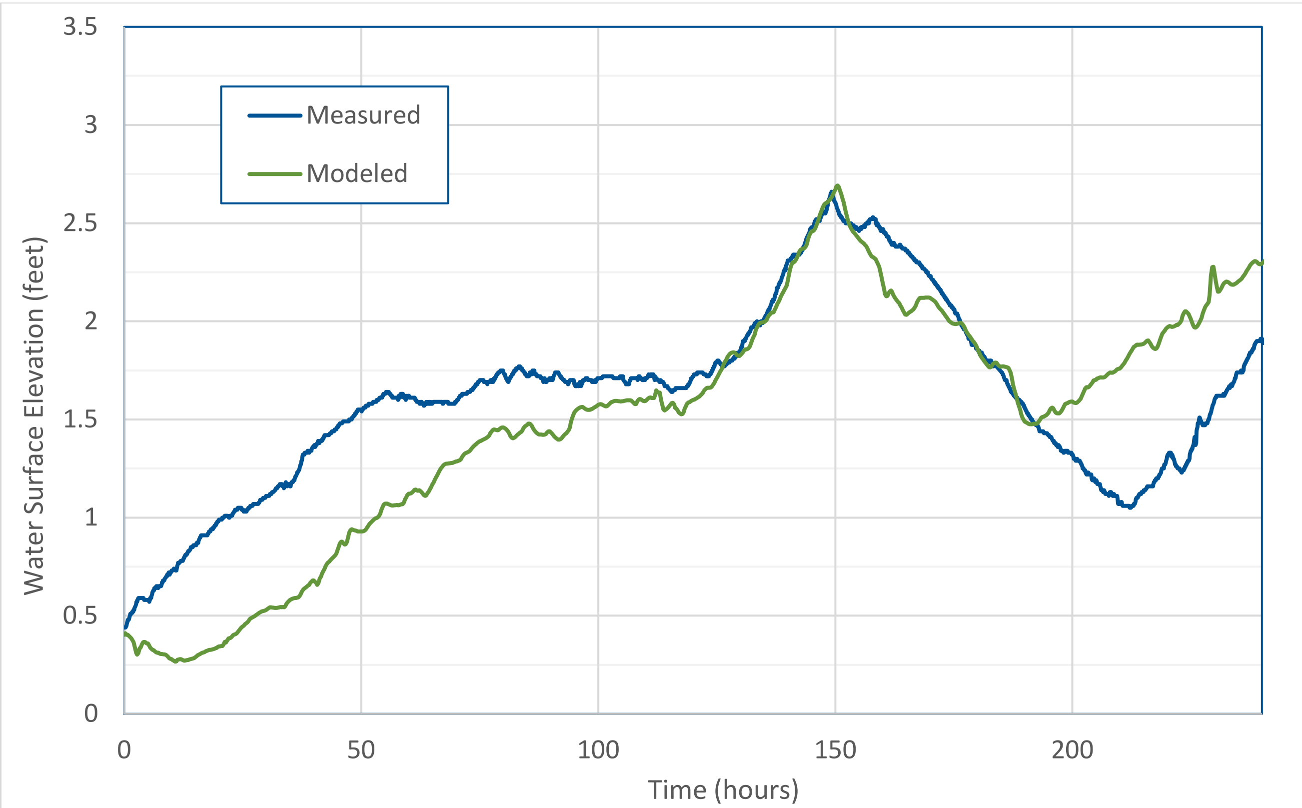


Figure 7: Measured versus modeled water levels at Beggars Bridge Creek gauge for the April/May 2017 flooding event. The starting date and time of the graph is 04/26/2017 at 00:00.

2.5. Hurricane Florence

Hurricane Florence made landfall in Wrightsville Beach, North Carolina on the evening of September 14th, 2018 as a progressively weakening Category 1 storm. After making landfall, the forward speed of the storm decreased, and it slowly moved in a west southwesterly direction along the North Carolina/South Carolina coast, before turning west into western South Carolina/North Carolina, and eventually going in a northeasterly direction through western Virginia on September 17th.

While Florence moved along the Appalachian mountain range, a high pressure system was located off the coast of New England (Figure 8), causing southeasterly and southerly winds in the Back Bay area due to the pressure gradient. Starting around 4 am on September 17th, winds at Duck, NC came from the southeast at 16 mph and gradually veered and increased during the next 10 hours. At 2 pm, sustained winds reported at the Duck gauge were 24 mph from the south southeast. Starting around 3 pm on the September 17th, the winds continued to veer and slowly decrease throughout the day on the September 18th (Figure 9). In comparison, winds recorded at the Beggars Creek gauge never exceeded 10 mph and were generally around 5 mph (Figure 10).

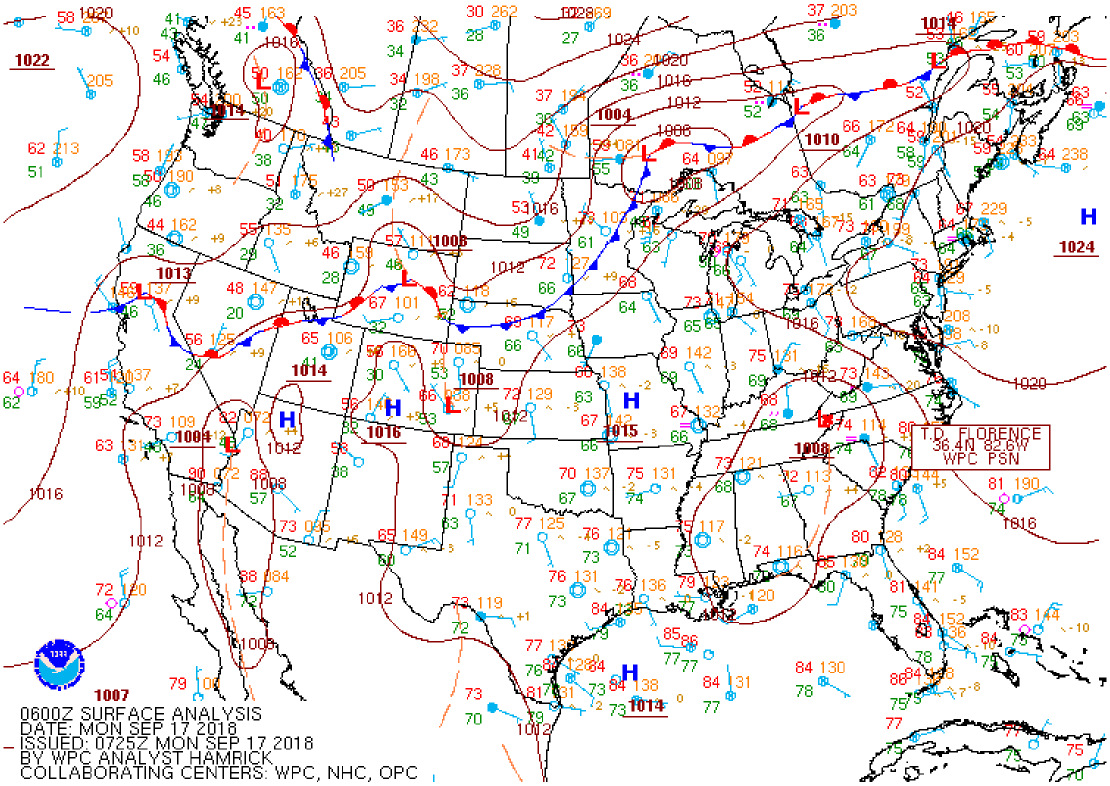


Figure 8: Surface analysis for the morning of September 17th showing Tropical Depression Florence and the interaction of the high pressure system off the New England coast.

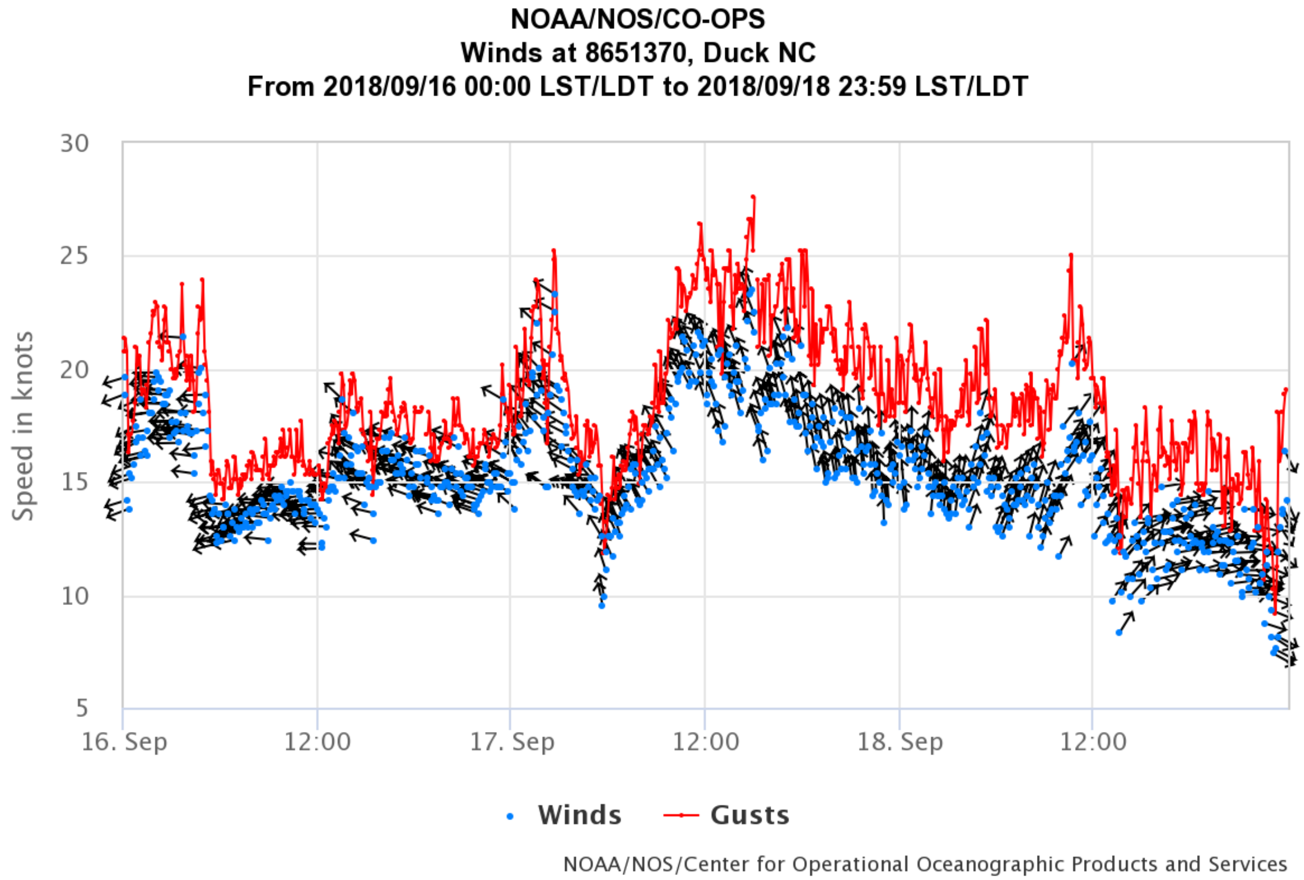
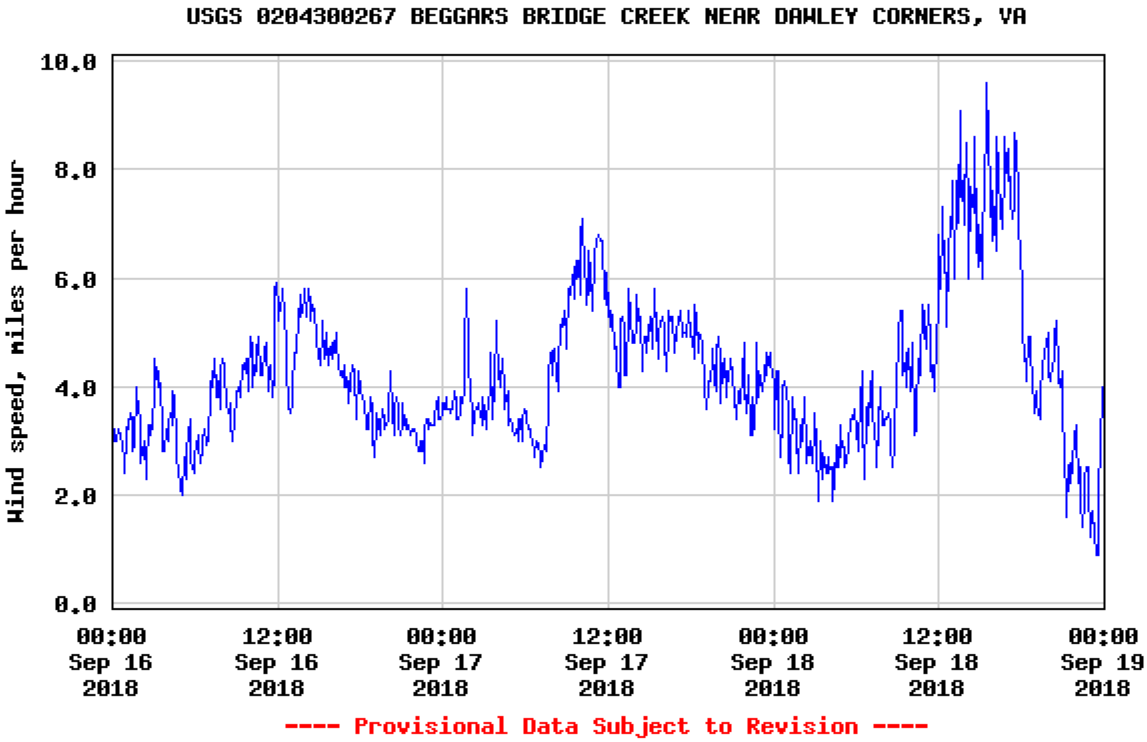


Figure 9: Observed winds at Duck, NC gauge for September 16 through September 18.



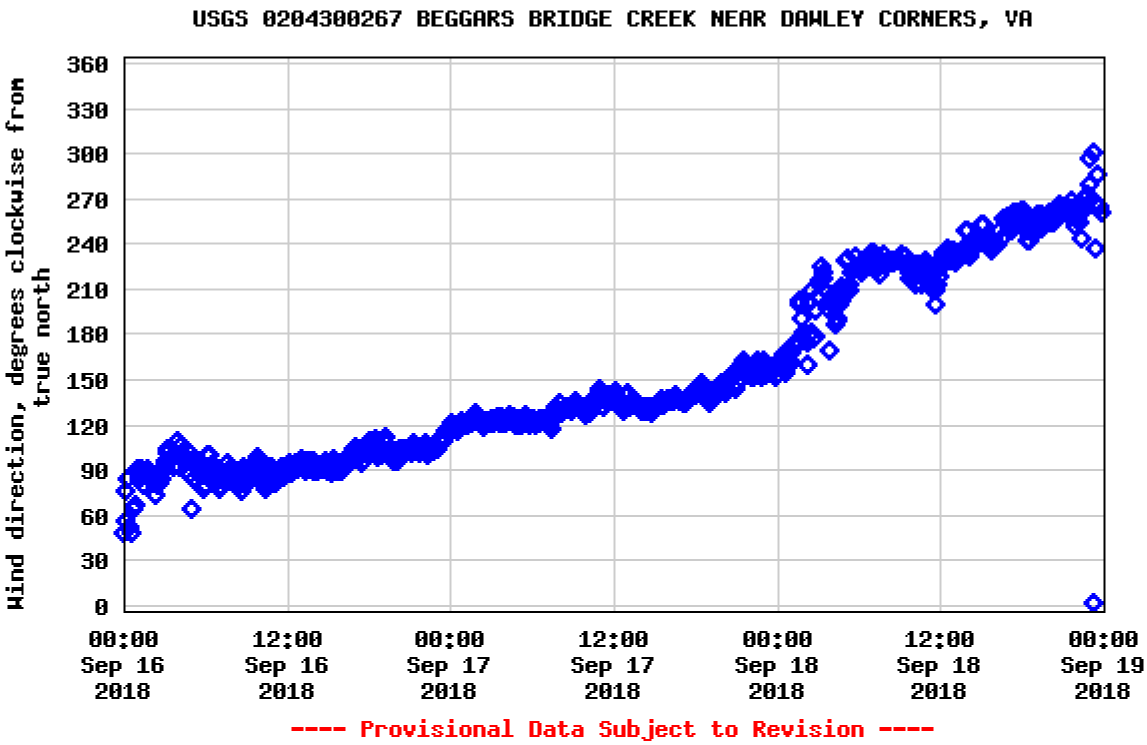


Figure 10: Wind observations (top image) and wind direction (bottom image) at Beggars Creek gauge from September 16 through September 18.

As a result of the generally southern winds (southeast to southwest) for a period of close to 36 hours, the Back Bay area experienced abnormally high water levels, with the Beggars Creek gauge recording a maximum value of 2.9 feet.

Similar to the May 2017 event, the wind observation data from the Duck, NC gauge were used to validate the ADCIRC model for the study area. The model started on September 10th to allow a "warm-up" period prior to Florence affecting the region, and continued through September 22nd. Figure 11 shows a comparison of the observed versus modeled results at the Beggars Bridge Creek gauge. The modeled results validate well with the measured water surface elevations, with differences of less than 0.25 feet throughout the entire model run.

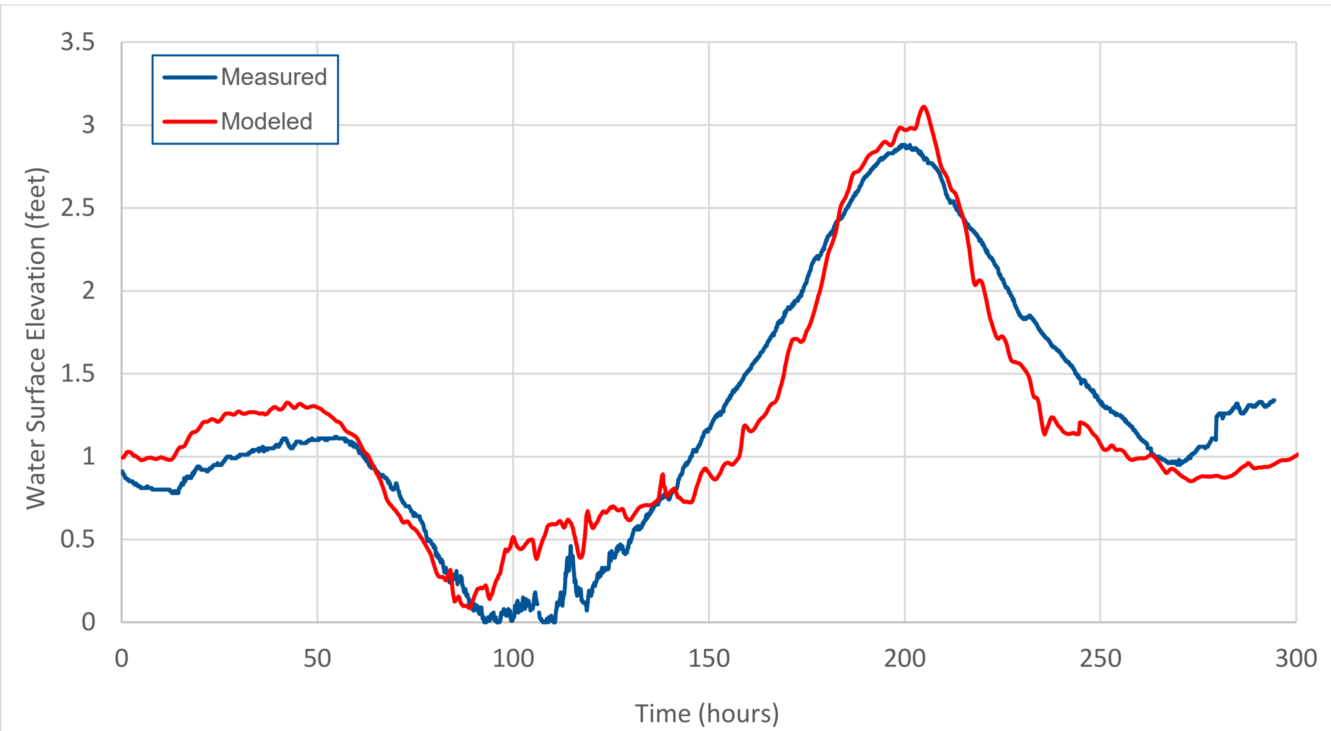


Figure 11: Comparison of measured versus modeled results for Hurricane Florence at Beggars Bridge Creek gauge. The starting date and time of the graph is 09/10/2018 at 00:00.

2.6. Wind Parameters

The Southern Watershed can experience long duration winds from multiple directions due to synoptic scale weather patterns. These events can last over five days, and coupled with a southerly direction, can propagate a significant amount of wind induced surge overland.

For this study, five separate wind directions were identified to be modeled in order to ensure complete modeling of all events that could potentially create significant inundation in the study area. The wind directions chosen are: south southwest, southwest, south, southeast, and south southeast. For each wind direction, seven separate wind speeds were considered: 5, 10, 15, 20, 25, 30, and 35 miles per hour (mph), resulting in a total of 35 simulations, with each simulation lasting 10 days. It should be noted that these speeds are referenced to a standard 10 m (32.8 feet) height above ground.

The wind velocity was held constant for the entire simulation and applied to the entire model domain (i.e. no changes in the direction or speed of the wind were considered throughout the 10 day simulation). An example of the wind forcing with respect to the model domain can be seen in Figure 12.

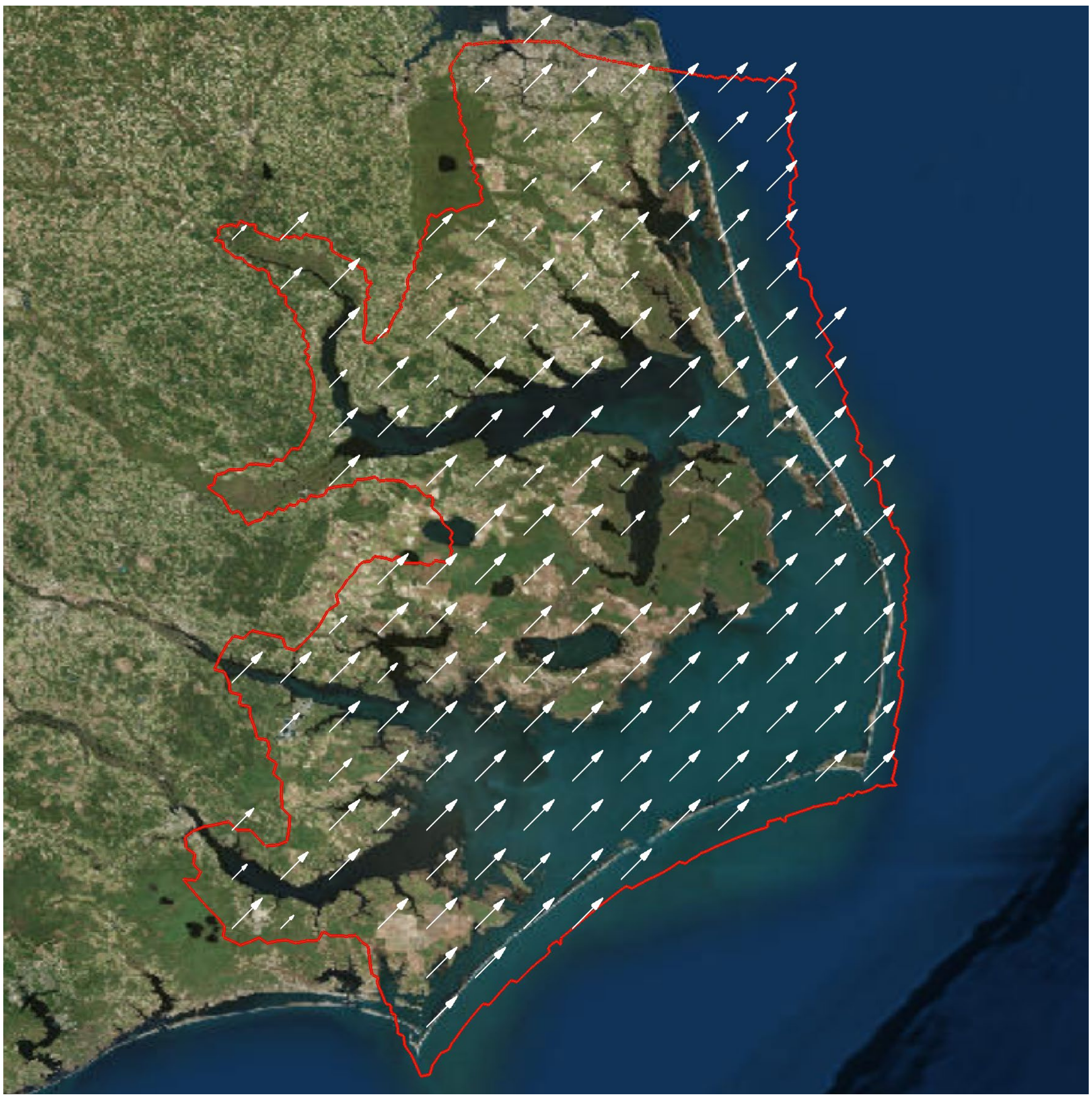


Figure 12: Example of a southwesterly wind at 35 mph on the Back Bay model domain.

2.7. Output Locations

Although the model provides 2D outputs of water level and velocities, forty output locations were chosen throughout the study area and surrounding waters to perform a more detailed analysis of the effects of the wind tide modeling. These locations were placed at points of interest across the study area. Figure 13 shows thirty seven of the locations (three were located south of Corolla, North Carolina and are not shown). A summary of locations, coordinates, and descriptions is provided in Table 1.

At each of these locations, detailed plots of time versus water height were created. These allow users to determine a resulting water height for a forecasted wind direction and duration. An example is provide in Figure 14.

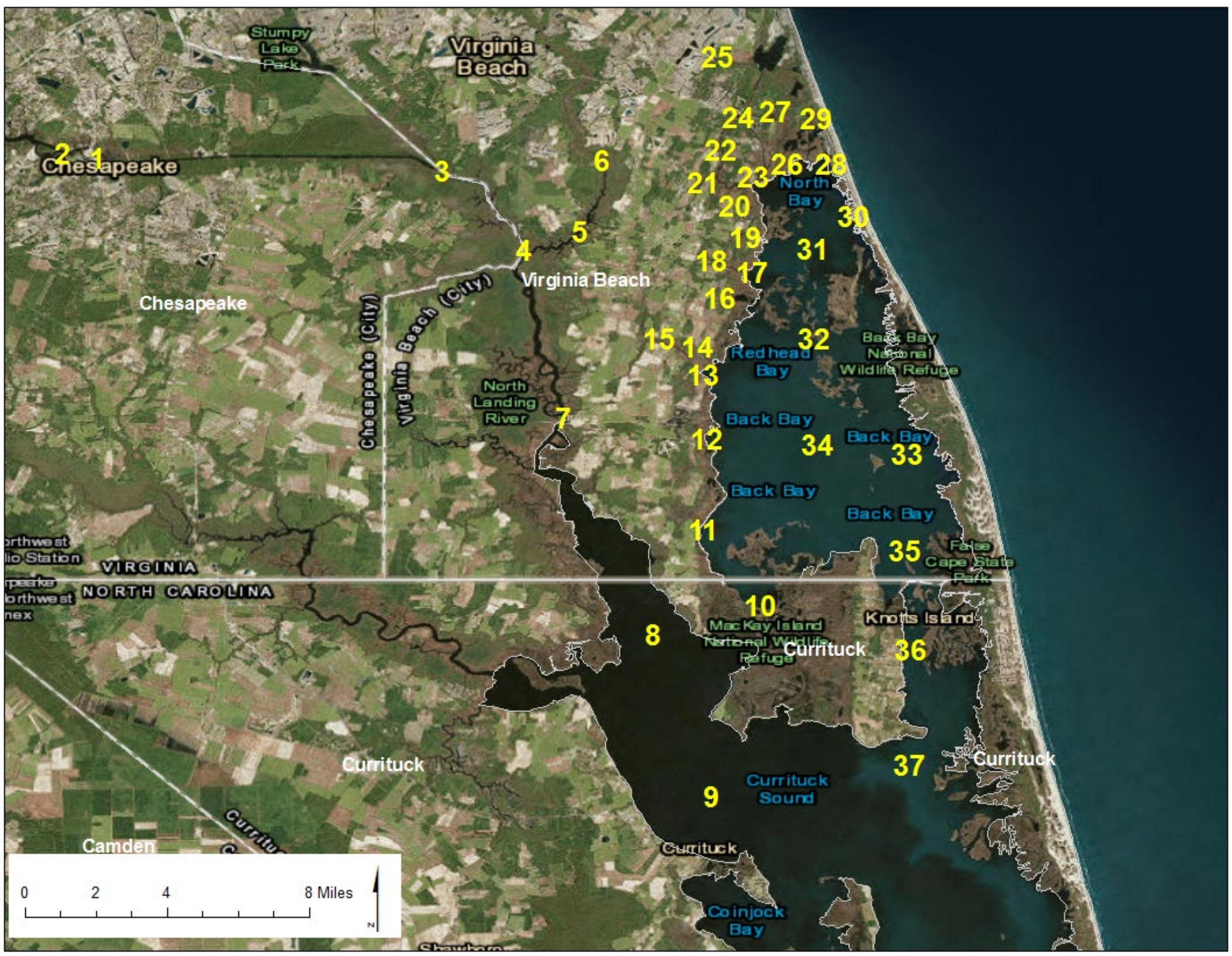


Figure 13: Observation locations for wind tide water level response modeling results.

Table 1: List of observation locations and descriptions.

Location	Longitude	Latitude	Description
1	-76.245539	36.722644	Downstream of Great Bridge Lock
2	-76.247799	36.723471	Upstream of Great Bridge Lock
3	-76.098590	36.716967	North Landing River at confluence with Salem Canal
4	-76.065105	36.684714	North Landing River at confluence with West Neck Creek
5	-76.042588	36.691978	West Neck Road
6	-76.033554	36.720870	West Neck Creek at Indian River Road
7	-76.048780	36.616289	North Landing River at Pungo Ferry Road
8	-76.012410	36.527816	North Landing River near Mackay Island
9	-75.988906	36.461898	North Landing River at Currituck Sound
10	-75.967763	36.536977	Knotts Island Causeway
11	-75.991810	36.570261	Southwest Back Bay at Public Landing Road
12	-75.990588	36.607680	Middle Western Back Bay
13	-75.992761	36.638561	Entrance to Nawney Creek
14	-75.994397	36.644979	South Muddy Creek Road
15	-76.010030	36.648412	Upper Nawney Creek
16	-75.985375	36.665057	Muddy Creek Road at Gum Bridge Road
17	-75.971878	36.675496	Entrance to Beggars Bridge Creek
18	-75.983481	36.680098	Muddy Creek Road at Pleasant Ridge Road
19	-75.975302	36.692843	Stuart Road
20	-75.979021	36.702541	Muddy Creek Road at Horn Point Road
21	-75.987882	36.710486	North Muddy Creek Road
22	-75.985096	36.731232	Sandbridge at North Bridge Road
23	-75.970734	36.710991	Entrance to Muddy Creek
24	-75.977607	36.738763	Asheville Bridge Creek at confluence with Hell Point Creek
25	-75.986164	36.763136	Northern Ashville Bridge Creek
26	-75.952920	36.719214	Northern Central North Bay
27	-75.962539	36.741114	Central Sandbridge Road
28	-75.941356	36.719430	Central Sandbridge
29	-75.945970	36.738219	Northern Sandbridge
30	-75.930759	36.698480	Southern Sandbridge
31	-75.947233	36.685175	Central North Bay above islands
32	-75.946838	36.648423	North Central Back Bay below islands
33	-75.908295	36.605649	Middle East Back Bay
34	-75.945372	36.605275	Middle Central Back Bay
35	-75.909983	36.561773	North of Knotts Channel
36	-75.907532	36.521585	Southern Knotts Island Channel
37	-75.907707	36.474687	Knotts Island Bay at Currituck Sound
38*	-75.836557	36.371526	White Head Bay
39*	-75.865353	36.307471	Wells Bay
40*	-75.833944	36.242511	Dowdys Bay

** Observation locations 38, 39, and 40 are located in Currituck Sound and are not shown in Figure 13.*

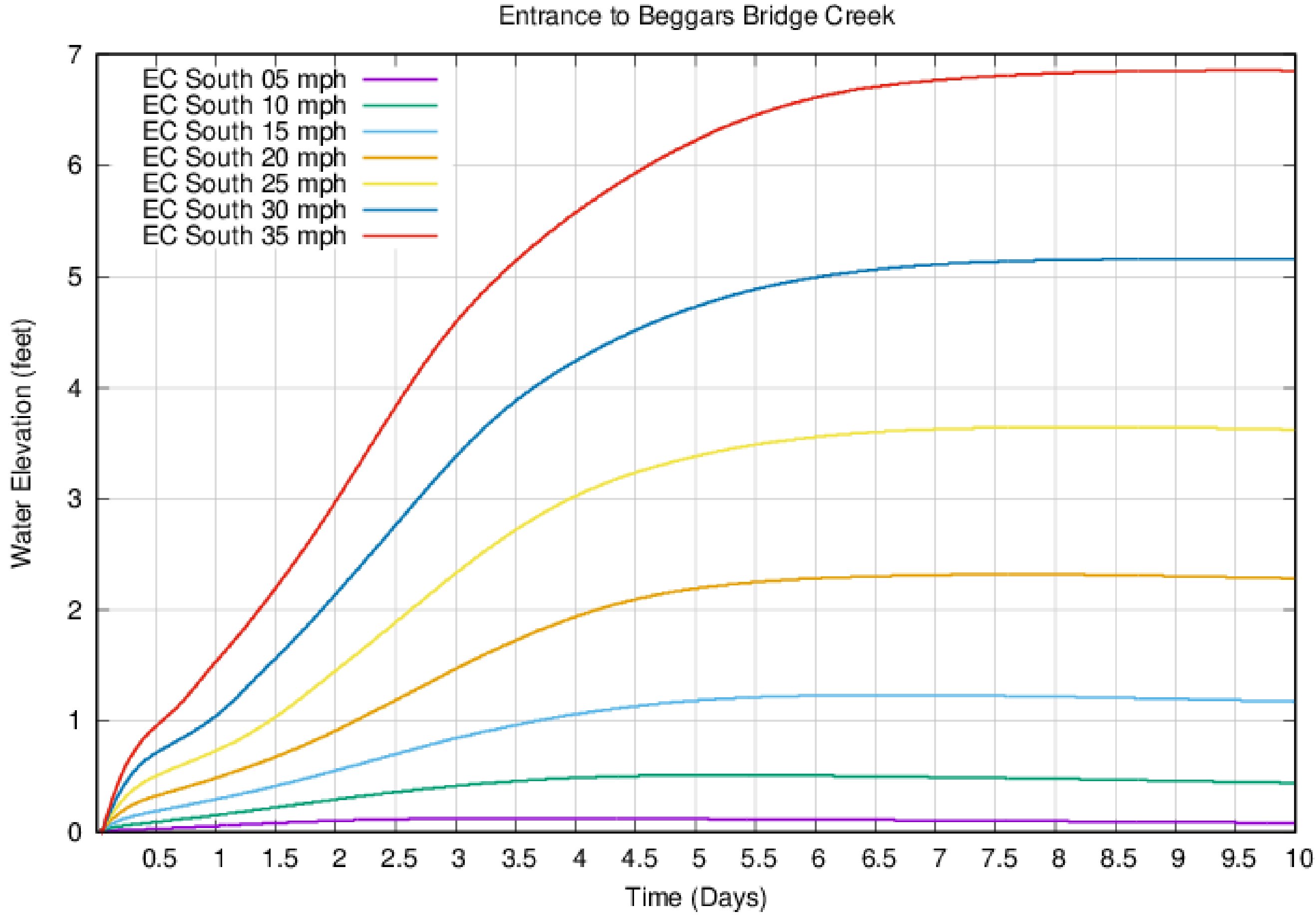


Figure 14: Example output plot showing time versus water elevation.

3. RESULTS

3.1. Water Level Response to Sustained Winds

The Back Bay region has an overall geographic orientation of south to north and would indicate that winds from the south would produce the overall greatest water levels. In addition, the hydrodynamic connection between Back Bay and Currituck Sound around Knotts Island is orientated in a north to south direction. Prior to modeling, one could deduce that a southerly wind would produce the largest water levels within Back Bay, due to both the long fetch of Back Bay in the north/south direction and the ability of water to flow from Currituck Sound to Back Bay.

The final results prove this to be true, with winds from the south southwest, south, and south southeast produced the highest water levels within the bay, with a southerly wind producing the greatest water level. For example, at Location 31 in Figure 15 (Central North Bay), a southerly wind at 35 mph reaches a maximum water level of 6.9 feet, a south southeasterly reaches approximately 6.8 feet, and a south southwest reaches 6.25 feet. Both the southwest and southeast simulations are below 6 feet. Figure 15 shows the plots for this location.

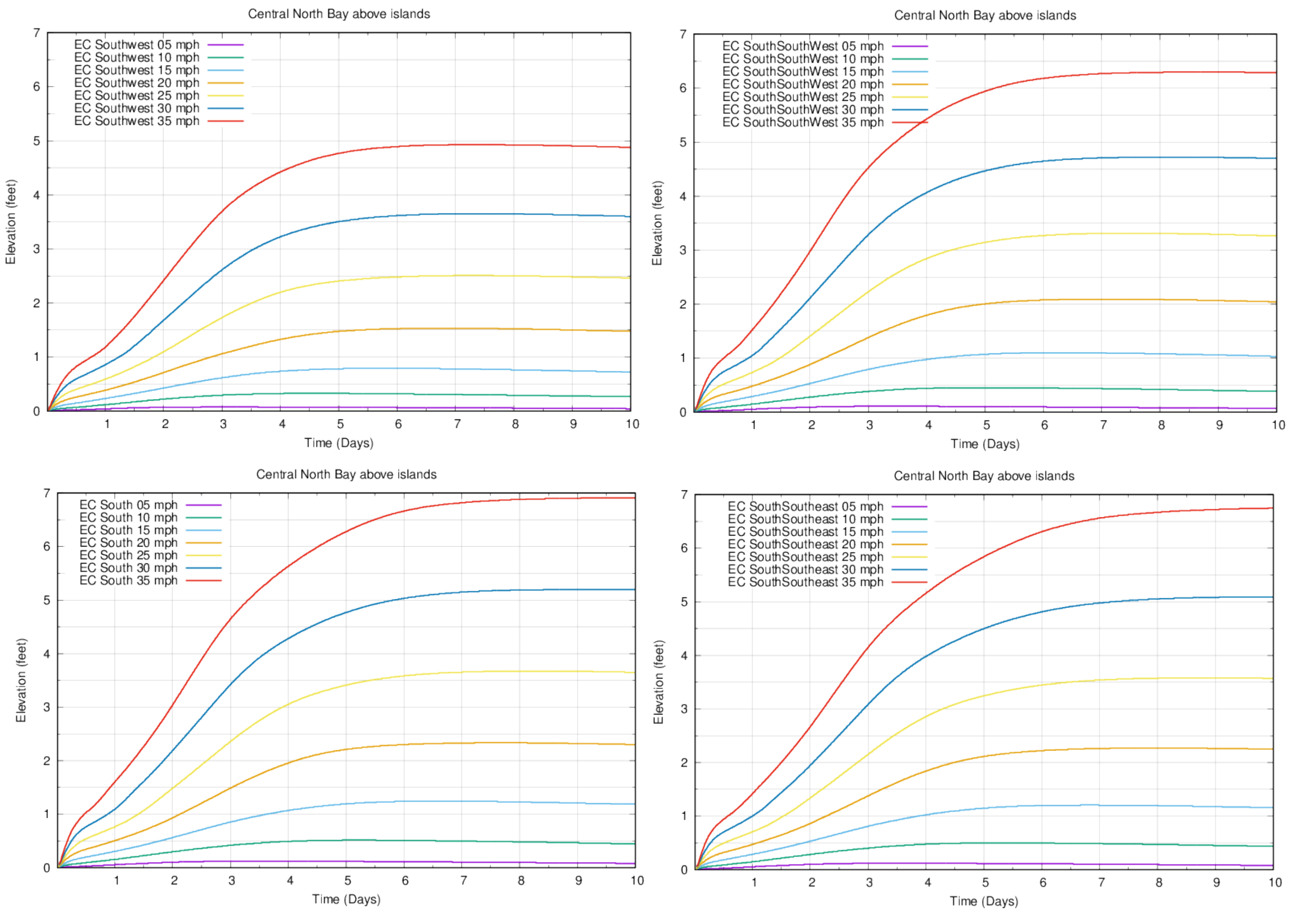
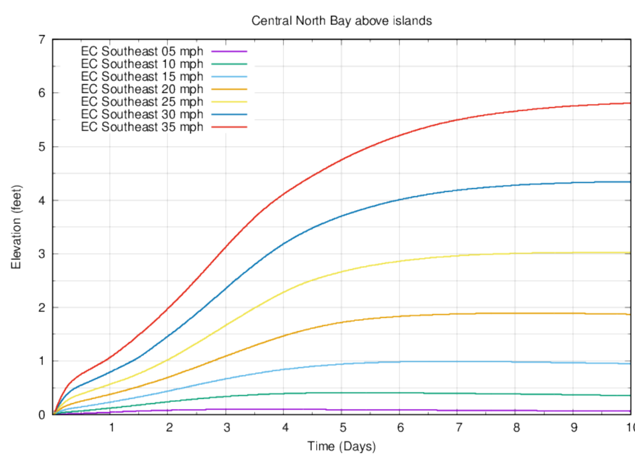


Figure 15: Example water level response plots for each of the simulated wind directions and wind speeds.



The above plots were produced for each of the observation locations shown in Figure 13. In addition, five separate locations were chosen to produce look-up tables providing the water surface elevation for a given wind speed in 12 hour increments, an example of which is provided in Table 2. Tables for the following location are provided in Appendix A:

- Northern Back Bay (near East Big Bend Point)
- Southern Back Bay (just north of Knotts Island)
- Entrance to Beggars Creek
- Entrance to Nawney Creek
- West Neck Road at West Neck Creek

Table 2: Water surface elevation for a given wind speed from the south in 12 hour increments.

Northern Back Bay	Wind Duration (hr)	Wind Speed (mph) from the South						
		5	10	15	20	25	30	35
Water Level (feet)	12	0	0.1	0.2	0.4	0.7	0.9	1.3
	24	0.1	0.2	0.3	0.6	0.9	1.3	1.8
	36	0.1	0.2	0.5	0.8	1.2	1.8	2.5
	48	0.1	0.3	0.6	1	1.6	2.3	3.3
	60	0.1	0.4	0.7	1.3	2	3	4.1
	72	0.1	0.4	0.9	1.6	2.5	3.6	4.8
	84	0.1	0.5	1	1.8	2.8	4.1	5.4
	96	0.1	0.5	1.1	2	3.2	4.4	5.8
	108	0.1	0.5	1.2	2.2	3.4	4.7	6.2
	120	0.1	0.5	1.2	2.3	3.5	4.9	6.5

3.2. Evaluation of Wind Tide Response to Sea Level Rise

An aspect of this evaluation was to evaluate how both water levels and response times for wind tides would be affected by SLR. Two additional sets of simulations were completed using the same approach as described above for SLR conditions of 1.5- and 3.0-feet. These scenario values were sourced from the Comprehensive Sea Level Rise and Recurrent Flood Planning Study and correspond with anticipated conditions in the 2050s and 2070s, respectively. The ADCIRC starting water surface elevation was adjusted to 1.5 –and 3.0-feet for each set of runs. Two additional sets of response plots, as previously discussed, were produced for each condition.

Comparison of the water levels to existing conditions found that water elevations rose more quickly with increased sea level. An example of this is provided in Figure 16, which shows the response water level curve at Location 31 (Central North Bay) for existing conditions, 1.5- and 3.0-feet SLR scenarios for a 15 mph sustained southerly wind. The three lines in the figure represent the water level response to the sustained wind for each sea level. Time to maximum water level is reduced by approximately two days from the existing condition to the 1.5-foot SLR curve, and another one and a half days from the 1.5- to 3.0-feet SLR curve. This effect can be attributed mainly to the reduced friction in the water column from the increased water depth, which allows water to move more quickly through key hydraulic pathways.

The results were notable in that as sea levels continue to rise, a shorter duration wind event will produce more wind induced flooding in less time. In turn, this will reduce response times while increasing expected potential damage to homes, businesses and infrastructure. The results from these SLR conditions can also be related to expected response times given a starting water level elevation in the Currituck and Back Bay. At times when water levels are elevated for various reasons, the City should expect that water levels will increase faster.

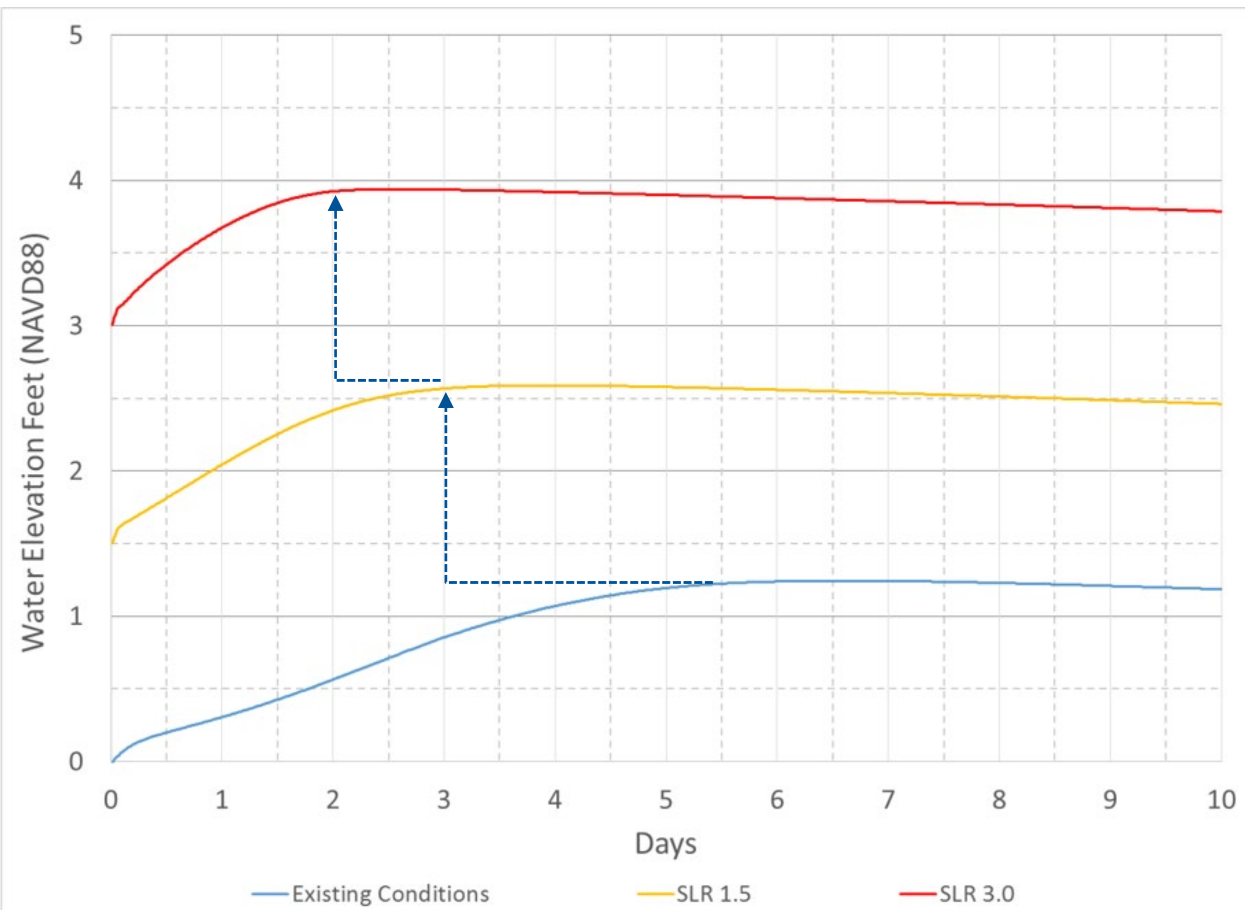


Figure 16: Plot of water level response to a sustained southerly wind of 15 mph for starting water level conditions of 0, 1.5, and 3.0 feet in central Back Bay. The time it takes to reach the maximum water level is decreased when the additional water levels are introduced, as indicated by the dashed arrows.

3.3. Great Bridge Lock

An exploratory study was conducted with the model to assess the effects of the Great Bridge Lock on water levels in the Southern Watershed. The lock is located on the western end of the Albemarle and Chesapeake Canal (Figure 17). According to City stakeholders, the Great Bridge Lock impounds water in the Southern Watershed during wind tide events, resulting in increased flood levels along the North Landing River and Back Bay.

Figure 17: Great Bridge lock is located in Chesapeake, VA, to the southeast of Virginia Beach. The lock separates the Albemarle and Chesapeake Canal from the Southern Branch Elizabeth River (Bing Maps, 2019).

Model setup parameters and input wind conditions were kept the same as those used for the wind tide simulations. Lock-open and lock-closed conditions were evaluated. All previous simulations kept the Albemarle and Chesapeake Canal open. To represent lock-closed conditions, model node elevations across the canal at the location of the lock were set to +15 feet NAVD88 (Figure 18). Simulations were conducted with a southerly wind at speeds from 5- to 35-mph at 5 mph increments. The southerly wind was chosen as it produces the highest wind tide levels and is therefore the most conservative for evaluation purposes.

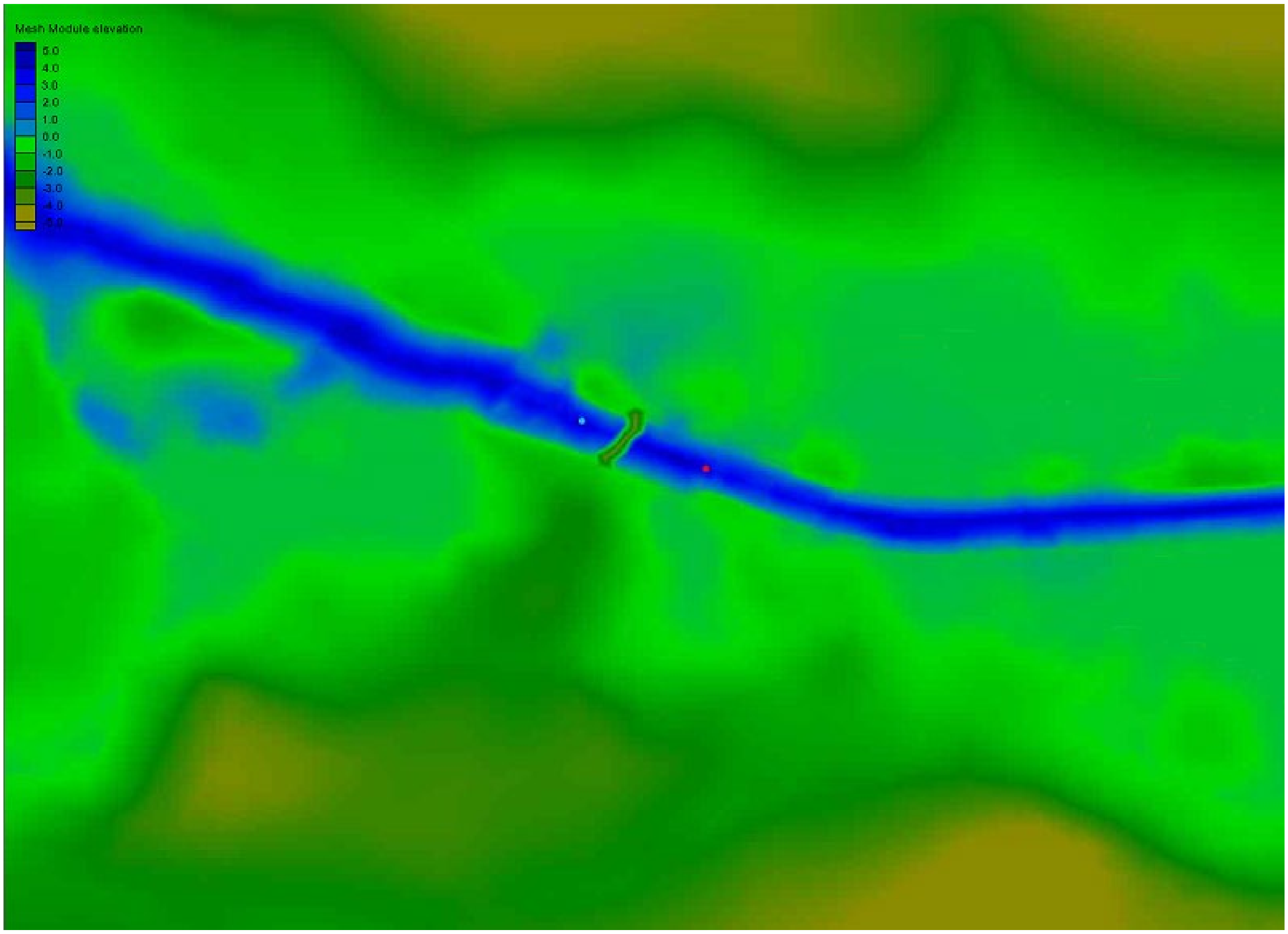


Figure 18: ADCIRC model representation of the "lock closed condition. The small points visible represent water level "save" stations for output from the 2D simulation.

Water level response curves from the three locations studied on North Landing River are provided in this report. These include the location found immediately downstream of the lock, at the confluence of North Landing River with Salem Canal (approximately 10.5 miles downstream), and the confluence with West Neck Creek (approximately 14.5 miles downstream, Figure 19). Water level response plots for the sustained southerly wind simulations with the lock open and the lock closed are shown in Figure 20, Figure 21, and Figure 22. These figures demonstrate information found at the Salem Canal and West Neck confluences with North Landing River, respectively, and the data collected immediately downstream of the lock.

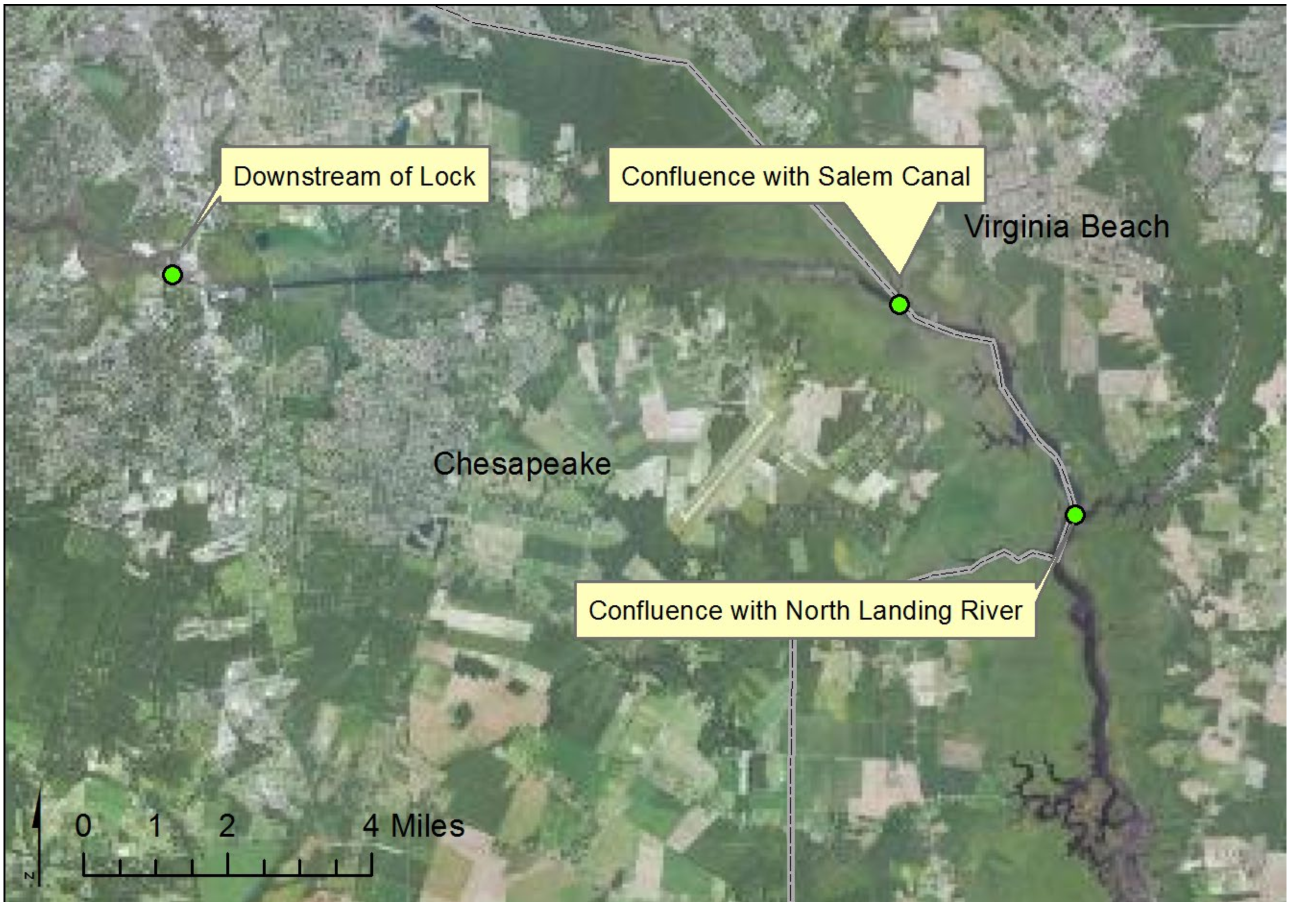


Figure 19: Locations of water level response plots for the Great Bridge Lock study.

The results show that the lock does increase water elevations immediately downstream and by several feet for higher wind speeds (Figure 20). Further downstream, the effects are minimal. Water levels with the lock closed are reduced to a couple inches at Salem Canal for most wind conditions (Figure 21), and differences are nominal at West Neck Creek (Figure 22). These results demonstrate that the lock minimally affects water levels in the Southern Watershed for wind tide conditions.

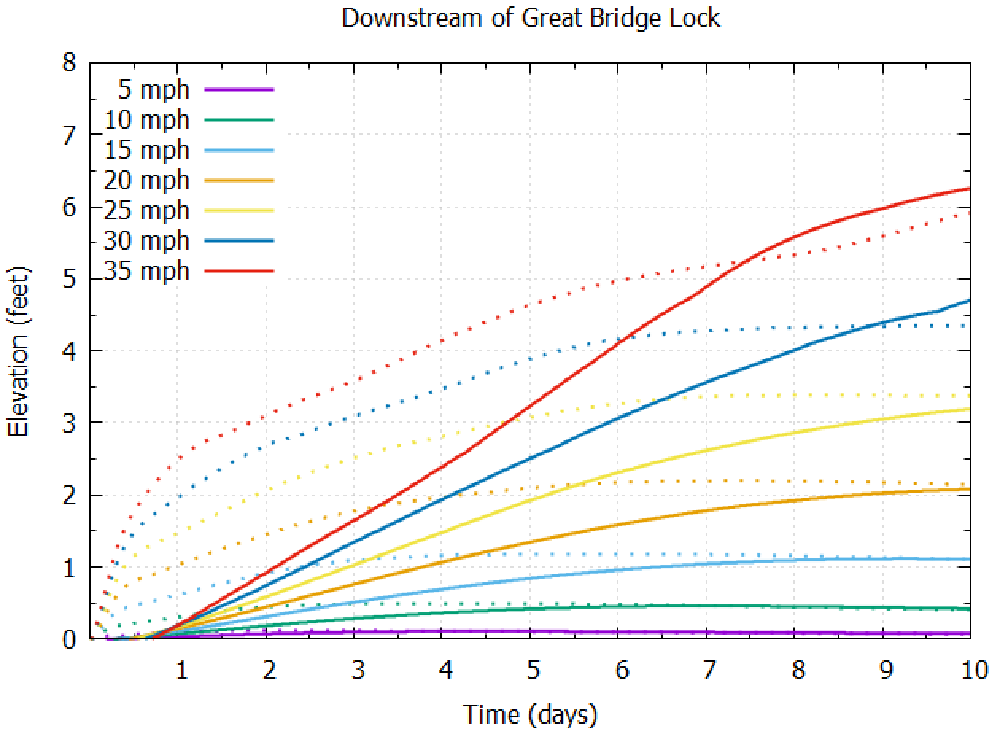


Figure 20: Plots show water surface elevation for a southerly wind downstream of the Great Bridge Lock. Solid lines represent the lock open scenario and dashed lines represent the lock closed scenario.

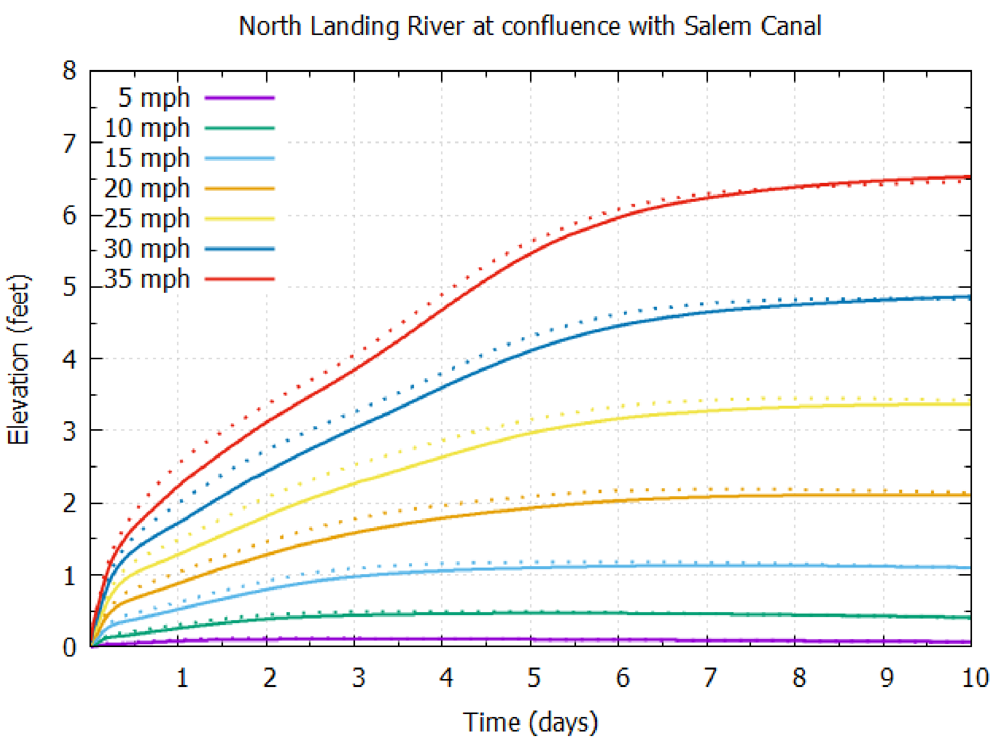


Figure 21: Plots show water surface elevation for a southerly wind at the confluence of the North Landing River and Salem Canal. Solid lines represent the lock open scenario and dashed lines represent the lock closed scenario.

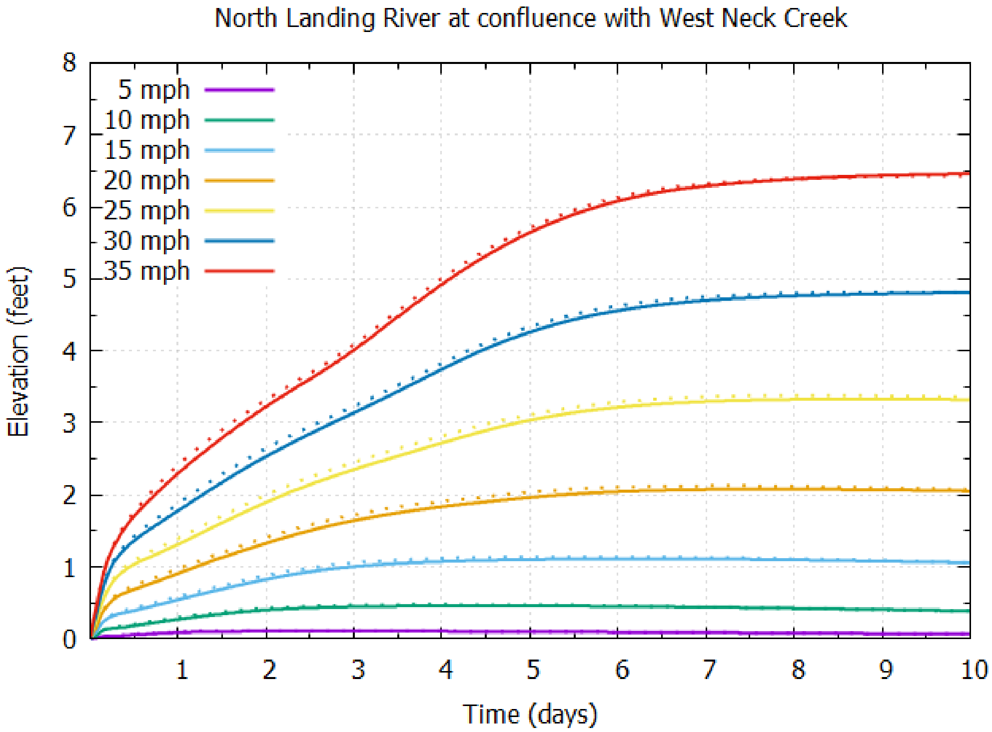


Figure 22: Plots show water surface elevation for a southerly wind at the confluence of the North Landing River and West Neck Creek. Solid lines represent the lock open scenario and dashed lines represent the lock closed scenario.

4. REFERENCES

"Great Bridge Lock." Bing Maps. Accessed January 18, 2019. https://www.bing.com/maps/.

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APPENDIX A: Water Level Response Tables for Sustained Southerly Winds

The following tables provide anticipated increases in water level for 12-hr increments given sustained southerly wind conditions for the following locations:

- Northern Back Bay (near East Big Bend Point)
- Southern Back Bay (just north of Knotts Island)
- Entrance to Beggars Bridge Creek
- Entrance to Nawney Creek
- West Neck Road at West Neck Creek

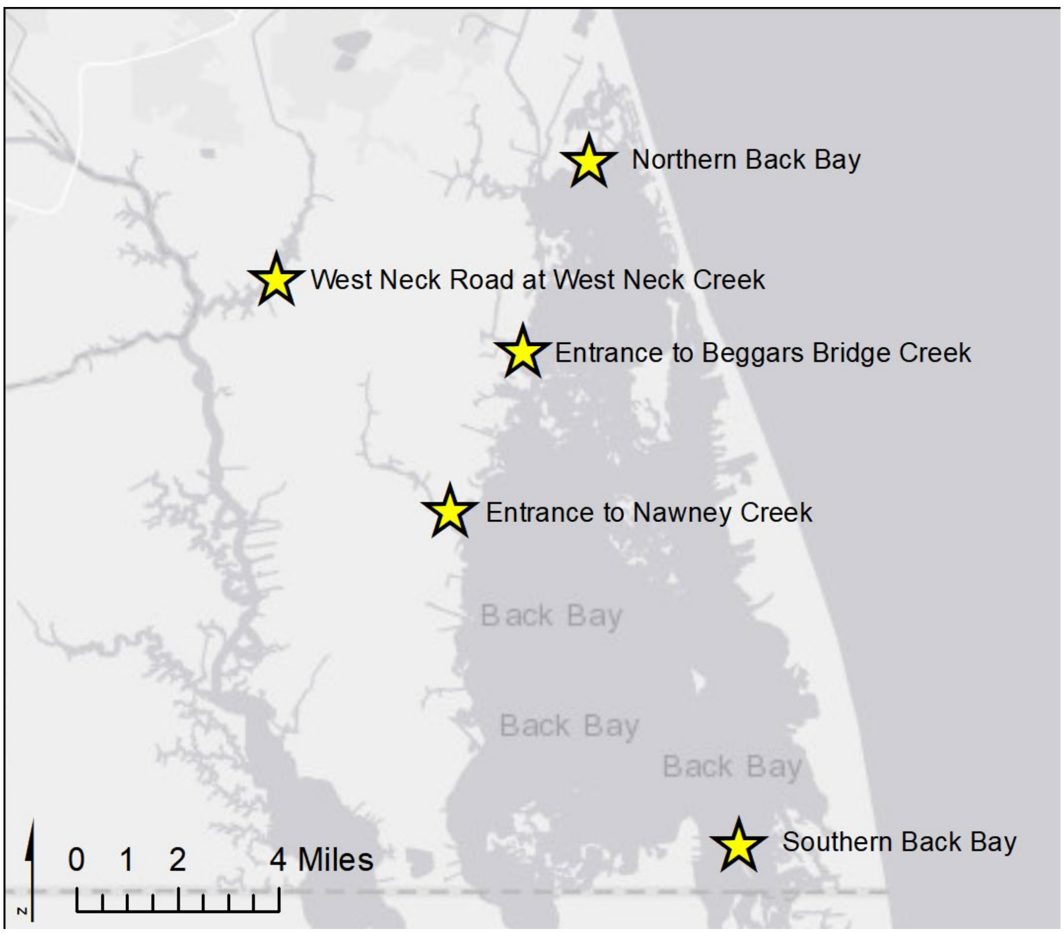

Figure A-1: Point locations for tables located in Appendix A.

Table A-1: Water level response times for Northern Back Bay.

Northern Back Bay	Wind Duration (hours)	Wind Speed from the South (mph)						
		5	10	15	20	25	30	35
Time (Hours)	12	0	0.1	0.2	0.4	0.7	0.9	1.3
	24	0.1	0.2	0.3	0.6	0.9	1.3	1.8
	36	0.1	0.2	0.5	0.8	1.2	1.8	2.5
	48	0.1	0.3	0.6	1	1.6	2.3	3.3
	60	0.1	0.4	0.7	1.3	2	3	4.1
	72	0.1	0.4	0.9	1.6	2.5	3.6	4.8
	84	0.1	0.5	1	1.8	2.8	4.1	5.4
	96	0.1	0.5	1.1	2	3.2	4.4	5.8
	108	0.1	0.5	1.2	2.2	3.4	4.7	6.2
	120	0.1	0.5	1.2	2.3	3.5	4.9	6.5

Table A-2: Water level response times for Southern Back Bay.

Southern Back Bay	Wind Duration (hr)	Wind Speed from the South (mph)						
		5	10	15	20	25	30	35
Time (Hours)	12	0	0	0	0	0	0	0
	24	0	0.1	0.1	0.2	0.3	0.3	0.5
	36	0.1	0.2	0.3	0.4	0.6	0.9	1.3
	48	0.1	0.2	0.4	0.6	1	1.5	2.1
	60	0.1	0.3	0.6	0.9	1.5	2.2	3.1
	72	0.1	0.3	0.7	1.2	1.9	2.8	3.9
	84	0.1	0.4	0.8	1.5	2.3	3.4	4.5
	96	0.1	0.4	0.9	1.7	2.7	3.7	4.9
	108	0.1	0.4	1	1.8	2.9	4	5.3
	120	0.1	0.4	1	1.9	3	4.3	5.6

Table A-3: Water level response times for the Entrance to Beggars Bridge Creek.

Entrance to Beggars Creek	Wind Duration (hours)	Wind Speed from the South (mph)						
		5	10	15	20	25	30	35
Time (Hours)	12	0.1	0.1	0.2	0.3	0.5	0.7	1
	24	0.1	0.2	0.3	0.5	0.7	1.1	1.6
	36	0.1	0.2	0.4	0.7	1	1.6	2.2
	48	0.1	0.3	0.6	0.9	1.5	2.2	3
	60	0.1	0.4	0.7	1.2	1.9	2.8	3.8
	72	0.1	0.4	0.8	1.5	2.3	3.4	4.6
	84	0.1	0.5	1	1.7	2.7	3.9	5.1
	96	0.1	0.5	1.1	1.9	3	4.2	5.6
	108	0.1	0.5	1.1	2.1	3.2	4.5	5.9
	120	0.1	0.5	1.2	2.2	3.4	4.7	6.2

Table A-4: Water level response times for Entrance to Nawney Creek.

Entrance to Nawney Creek	Wind Duration (hours)	Wind Speed from the South (mph)						
		5	10	15	20	25	30	35
Time (Hours)	12	0	0.1	0.1	0.1	0.2	0.3	0.4
	24	0	0.1	0.2	0.3	0.5	0.7	0.9
	36	0.1	0.2	0.3	0.5	0.8	1.2	1.7
	48	0.1	0.3	0.5	0.8	1.2	1.8	2.5
	60	0.1	0.3	0.6	1	1.6	2.4	3.4
	72	0.1	0.4	0.8	1.3	2.1	3.1	4.2
	84	0.1	0.4	0.9	1.6	2.5	3.6	4.8
	96	0.1	0.4	1	1.8	2.8	4	5.3
	108	0.1	0.5	1	1.9	3	4.3	5.6
	120	0.1	0.5	1.1	2	3.2	4.5	5.9

Table A-5: Water level response times for West Neck Road at West Neck Creek.

West Neck Road at West Neck Creek	Wind Duration (hours)	Wind Speed from the South (mph)						
		5	10	15	20	25	30	35
Time (Hours)	12	0	0.2	0.4	0.7	1.1	1.4	1.7
	24	0	0.3	0.6	0.9	1.3	1.8	2.3
	36	0.1	0.4	0.7	1.1	1.6	2.2	2.8
	48	0.1	0.4	0.8	1.3	1.9	2.6	3.3
	60	0.1	0.4	0.9	1.5	2.2	2.9	3.6
	72	0.1	0.5	1	1.7	2.4	3.2	4
	84	0.1	0.5	1.1	1.8	2.6	3.5	4.5
	96	0.1	0.5	1.1	1.9	2.7	3.8	4.9
	108	0.1	0.5	1.1	1.9	2.9	4	5.3
	120	0.1	0.5	1.1	2	3.1	4.3	5.7

APPENDIX B: Water Level Response Plots

Water level response plots were generated for all 40 stations illustrated in Figure 13 for each of the five wind directions, as well as each sea level state (existing condition [0], and SLR conditions of 1.5- and 3.0-feet above existing). Due to the large number of figures (600), a digital deliverable has been provided in place of inserting all figures into this document. Files are organized by water level condition and direction (Figure B-1). Individual image files are provided for each station and condition under the sub-folder structure.

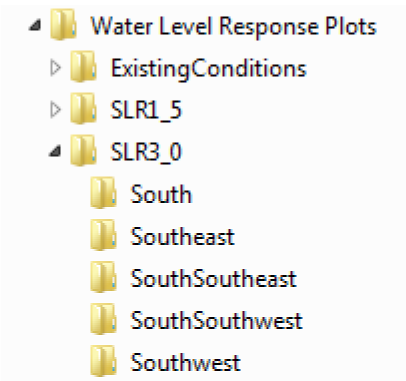

Figure B-1: Directory structure for response plots.