Pennsylvania Coastal Resources Management Program

Sea Level Rise and Associated Effects in the Delaware Estuary Coastal Zone (DECZ)

Technical Report

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DELAWARE RIVER BASIN COMMISSION

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LIST OF ACRONYMS/ABBREVIATIONS

ADCIRC	Advanced Circulation Model and related Database
ADCP	Acoustic Doppler Current Profiler
CMIST	NOAA’s Currents Measurements Interface for the Study of Tides
C&D Canal	Chesapeake & Delaware Canal
DRBC	Delaware River Basin Commission
DRB	Delaware River Basin
DNREC	Delaware Department of Natural Resources and Environmental Control
EFDC	Environmental Fluid Dynamics Code
EPA	U.S. Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FNC	Federal Navigation Channel
GIA	Glacial Isostatic Adjustment
GM	Glacial melting
GMSL(R)	Global Mean Sea Level (Rise)
GVC	Generalized Vertical Coordinate (Grid)
IPCC	Intergovernmental Panel on Climate Change
NCDC	NOAA's National Climatic Data Center
NJCAA	New Jersey Climate Adaptation Alliance
NOAA	National Oceanic and Atmospheric Administration
PACZM	Pennsylvania Coastal Zone Management Program,
PADEP	Pennsylvania Department of Environmental Protection
QA/QC	quality assurance/quality control
RM	River Mile
LRSL(R)	Local Relative Sea Level (Rise)
MSL	Mean Sea Level
SC	Specific Conductance
SF	Salt Front (also referred to as Salt Front River Mile)

SLR	Sea Level Rise
NJCAA(STAP)	The New Jersey Climate Adaptation Alliance Science and Science and Technical Advisory Panel
USGS	U.S. Geological Survey
USACE	U.S. Army Corps of Engineers
VLM	Vertical land motion
WOA	NOAA Ocean Climate Lab’s Product World Ocean Atlas Database

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1. BACKGROUND

The Delaware Estuary is experiencing the relative sea level rise rate of 3.48 mm/year (1.14 feet in 100 years) at Lewes, Delaware and 4.63 mm/year (1.52 feet in 100 years) at Cape May, New Jersey based on long-term sea level data[1]. It is anticipated that the local sea level rise rate will accelerate in coming decades and by 2100, range from 0.52 to 1.53 m (1.71 to 5.02 feet) based on technical workgroup established by Delaware Department of Natural Resources and Environmental Control (DNREC) in 2017[2].

Sea level rise will increase the size and extent of the tidal prism and alter flow circulation patterns and other hydrodynamic processes in the Delaware Estuary. In addition, the effective mixing volume of water in the estuary will increase. More salt water from the ocean will enter the estuary relative to the incoming freshwater flows, resulting in less dilution and higher salinity water.

The Delaware River Estuary is habitat to the Atlantic Sturgeon, an endangered species listed by the National Oceanic and Atmospheric Administration Fisheries Service. Critical spawning habitat was identified near Marcus Hook and Chester Island. Oysters are harvested from the lower estuary and bay areas in New Jersey and Delaware. Both species are sensitive to the salt content of water (salinity) and sea level rise may have a negative impact on their respective habitats.

In 2018, the Commonwealth of Pennsylvania, Department of Environmental Protection (DEP or PADEP) engaged the Delaware River Basin Commission (DRBC) to evaluate the effects of sea level rise on salinity in the Delaware Estuary Coastal Zone (DECZ). DRBC applied its three-dimensional hydrodynamic model, known as the Salinity Model, to simulate the effects of sea level rise on salinity and determine the potential impacts to Atlantic Sturgeon and oyster habitats.[3] This report summarizes the analyses performed with the model and documents the potential impacts from sea level rise on salinity and habitat.

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[1] Sea Level Trends. https://tidesandcurrents.noaa.gov/sltrends/

[2] DNREC Sea Level Rise Technical Workgroup (2017): https://southbethany.delaware.gov/files/2018/11/Attachment-6-to-February-2018-Mayor-Report-Technical-Report-Regarding-SLR-Planning-Scenarios.pdf[3] Callahan, John A., Benjamin P. Horton, Daria L. Nikitina, Christopher K. Sommerfield, Thomas E. McKenna, and Danielle Swallow, 2017. Recommendation of Sea-Level Rise Planning Scenarios for Delaware: Technical Report, prepared for Delaware Department of Natural Resources and Environmental Control (DNREC) Delaware Coastal Programs. 114 pp.

[4] Susan Love, Tricia Arndt, and Molly Ellwood, 2014. Recommendations for Adapting to Sea Level Rise in Delaware: Final Report of the Delaware Sea Level Rise Advisory Committee. http://www.dnrec.delaware.gov/coastal/Documents/SeaLevelRise/FinalAdaptationPlanasPublished.pdf

[5] David Bushek, Jason Morson, David Wong, Colby Hause, Chester Lindley, Danielle Kreeger, David Velinsky, Roger Thomas. 2016. Oyster and Water Quality Study for The Delaware River Main Channel Deepening Project. Prepared for U.S. Army Corps of Engineers, Philadelphia District.

[3] https://www.nj.gov/drbc/library/documents/3DSalinityModel.pdf and https://www.nj.gov/drbc/library/documents/3DSalinitySLR.pdf

1.1 The Delaware River and Estuary

The Delaware River extends 330 miles from the Catskill Mountains in New York to the mouth of the Delaware Bay where it enters the Atlantic Ocean between Cape May, New Jersey and Cape Henlopen, Delaware (Figure 1.1-1). It is the longest un-dammed river on the Atlantic coast of the United States. The entire Delaware River basin comprises 13,539 square miles in four states (New York, New Jersey, Pennsylvania, and Delaware), including the 782 square miles of the Delaware Bay itself. The East and West Branches of the Delaware River combine at Hancock, New York to form the mainstem Delaware River, which flows 200 miles south to the head of tide at Trenton, New Jersey. Below Trenton, the river is tidally influenced for 133 miles down to the mouth of the Delaware Bay. The drainage area at Trenton, New Jersey is approximately 6,780 square miles. The total watershed downstream of Trenton to the mouth of the bay is 6,060 square miles, including the Schuylkill River (1,911 square miles) and Christina River (755 square miles) basins; these are the second and third largest tributaries (behind the Delaware River itself) in terms of freshwater flow contributed to the mainstem. The hydrodynamics and water quality model domain extends from the head of tide at Trenton to the mouth of the bay into the Atlantic Ocean. Locations along the river are described by the River Mileage System, established by DRBC in 1969 and revised periodically. The mouth of the Bay is at River Mile (RM) 0 and Trenton NJ is at RM 134.[4]

The Delaware Estuary is a typical coastal plain estuary with a relatively homogeneous shallow depth of about 26 to 33 feet (Figure 1.1-2). Eighty percent of the estuary has a depth of less than 30 feet, except for the Federal Navigation Channel (FNC), which was dredged in sections between 2012 and 2018 to a depth of 45 feet below Mean Lower Low Water (MLLW) level. The width of the Delaware Bay at its mouth is 11 miles, and the widest part of the bay is about 27 miles. The width decreases from the bay area toward the land: 2.4 miles wide in the reach from Delaware City just inland of the C&D Canal (RM 60); 1/2 -mile wide in Philadelphia at the Ben Franklin Bridge (RM 100); about ¼-mile wide at Burlington (RM 117.5); and less than 1,000 feet wide at Trenton (RM 134).

1.2 Salinity

Salinity is a measure of the salt concentration in water. Salinity intrusion occurs when the salty water in the Estuary of a specific salinity moves into the Bay and upstream into the tidal river. In the Delaware Estuary, the salt front is used an indicator of salinity intrusion and represents the location along the tidal river where the salinity is 0.45 ppt on average over seven days.[5] Upstream of the salt front, the salinity is less than 0.45 ppt. The salt front, also referenced as the salt front location, is expressed as River Mile (RM). The salt front is monitored and recorded by DRBC.[6]

[4] https://www.nj.gov/drbc/basin/river-mileage-sys.html

[5] The salt front is calculated with chlorides and represents the 250 mg/l 7dma isochlor. The Salinity Model output is reported as salinity. A chloride concentration of 250 mg/l is approximately equivalent to 0.45 ppt salinity. See hydrosnap.drbc.net for a description of how the salt front location is determined.

[6] https://www.nj.gov/drbc/programs/flow/salt-front.html

Figure 1.1-1 Delaware River and Bay

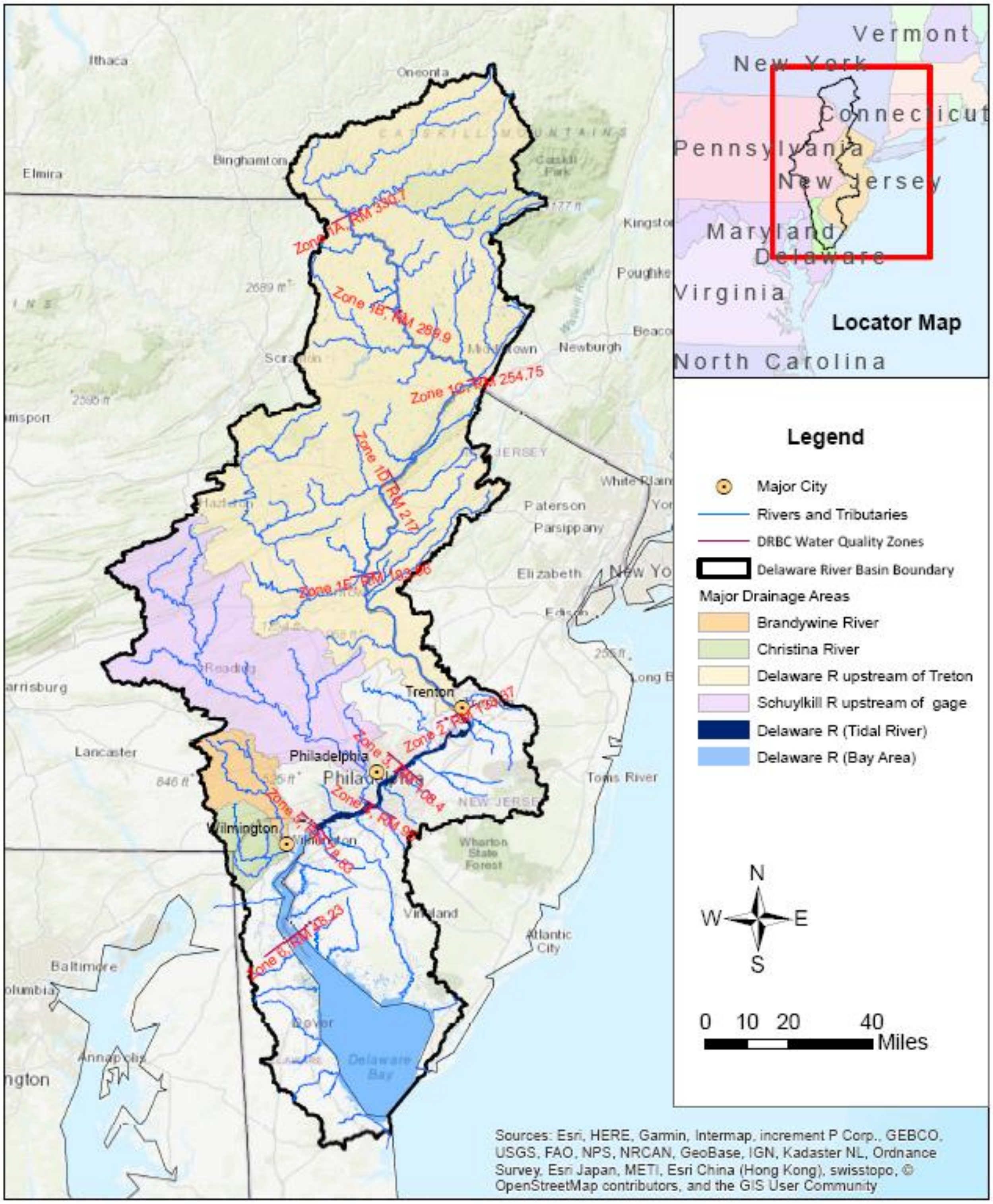
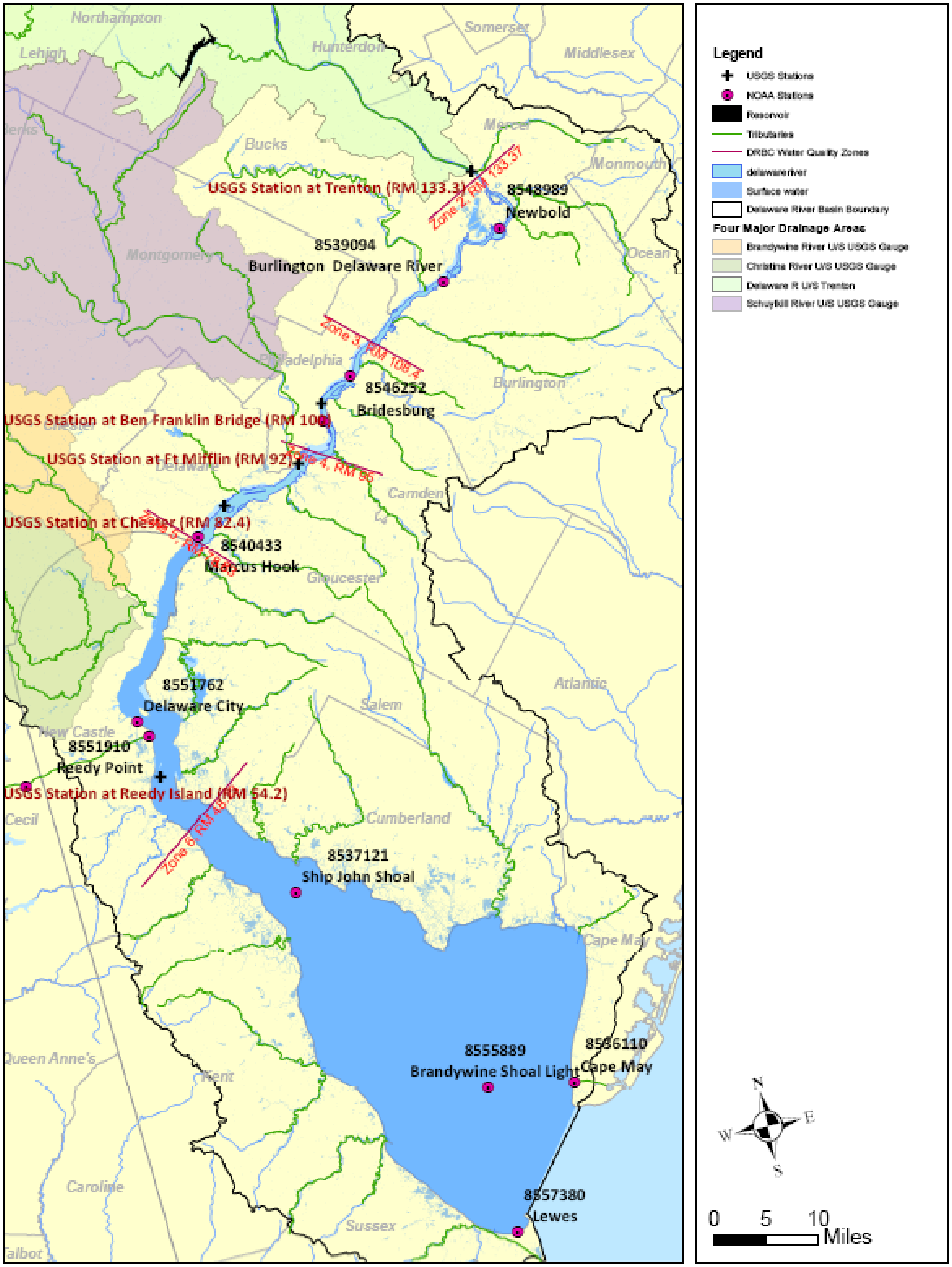


Figure 1.1-2 Delaware Estuary and Location of NOAA and USGS Gages



2. Habitat in the Delaware River Estuary

The Delaware Estuary provides habitat for a large variety of aquatic life and plant species. Criteria defining suitable habitat is specific to each species and may include the concentration of various water quality parameters including salinity, type of sediment and/or substrate, velocity and current, temperature, the presence of other species, among others. SLR has the potential to impact many habitat features. The focus of this project is limited to predicting the possible changes to salinity as the result of SLR.

2.1 Atlantic Sturgeon Habitat

The Delaware Estuary once supported the largest and most profitable Atlantic sturgeon fishery along the Atlantic Coast. The fish can reach 60 years of age, 15 ft (4.6 m) in length and weigh more than 800 pounds (360 kilograms). Along with other sturgeon, Atlantic sturgeon are considered living fossils. When the first European settlers came to North America, Atlantic Sturgeon were abundant in the Estuary, but overfishing, water pollution, and habitat impediments resulted in population collapsed by the end of the 1800s.

In 1998 a coast-wide moratorium on the fishery was established by the Atlantic Sturgeon Fishery Management Plan of the Atlantic States Marine Fisheries Commission (ASMFC) to restore Atlantic sturgeon spawning stocks and create a sustainable fishery and viable spawning populations. The National Marine Fisheries Service (NOAA Fisheries) followed with a moratorium on the harvest of Atlantic sturgeon within the Exclusive Economic Zone (3 mile to 200-mile limit) along the Atlantic coast. Neither moratorium resulted in sufficient recovery of the species, and in February 2012, the Atlantic sturgeon was listed as an endangered by the National Oceanic and Atmospheric Administration Fisheries Service under the Endangered Species Act (ESA). Portions of the Delaware River were identified as critical habitat in 2017 (DNREC Division of Fish and Wildlife).

The Atlantic Sturgeon are anadromous fish that migrate upstream to freshwater to spawn. In the Delaware Estuary, Atlantic Sturgeon of all life stages are present throughout the freshwater portion of the river. Juvenile Atlantic Sturgeon have been observed year-round as far upstream as Trenton, NJ (Brundage and O'Herron, 2009; Hale, et. al. 2016; Lazzari, O'Herron and Hastings, 1986). Atlantic sturgeon spawn in freshwater with salinities less than 0.5 ppt (Bain et al. 2000, Atlantic Sturgeon Status Review 2007). The egg and larval life stages have a low tolerance for salinity with suitable habitat typically occurring where the salinity is less than 0.45 ppt (Van Eenennaam 1996). However, larval stages of Atlantic sturgeon were documented in habitats with salinity concentrations between 0 and less than 12 ppt (Shirey et al. 1999). Sea level rise may result in higher salinity water persisting farther upstream more often. As a result, the availability of suitable freshwater habitat for spawning and successful propagation may be significantly reduced.

2.2 OYSTER HABITAT

Delaware Bay supports commercially important oyster beds in New Jersey and Delaware state waters. Oysters thrive in salinity that ranges from 14-28 ppt but can survive in water that contains 5-35 ppt. The greatest level of oyster productivity occurs when salinities are more than 20 ppt. In addition to health and productivity, the taste of an oyster is also affected by salinity (Box 1).

Figure 2-2 shows the location of oyster beds in the estuary. Table 2.2-1 lists the locations monitored for USACE conducted channel dredging project from 2012 to 2018 to deepen the Federal Navigational Channel from 40 feet to 45 feet MLLW. Dredging may impact the Eastern oyster *Crassostrea virginica* and by altering not only the salinity regime, dissolved oxygen, and other factors that affect oyster habitat quality.

The Eastern oyster is highly susceptible to the diseases *Haplosporidium nelsoni* (MSX) and *Perkinsus marinus* (Dermo), which thrive in high salinity waters, but are less prevalent at lower salinities. In addition, several oyster predators, such as drills (e.g., *Urosalpina cinerea* and *Eupleura caudata*) that prey on small oysters, prefer higher salinity. Changes in the spatial and vertical distribution of salinity may negatively impact the health of oyster beds by increasing favorable conditions for oyster diseases and oyster predators farther upstream into the estuary. In response, oysters may migrate upstream to lower-salinity habitats, but the space for new beds is limited as the bay narrows and transitions into the tidal river (Versar, Inc. 2018).

Table 2.2-1 Coordinates of Oyster Bed and Water Quality Stations Monitored in 2012-2015 and 2018

	Station ID	Latitude	Longitude	Notes
Arnolds	(ARN)	39 23.000'	75 27.000'	New Jersey Sites
Bennies	(BEN)	39 15.000'	75 18.200'	
Cohansey	(C)	39 19.200'	75 22.200'	
Hope Creek	(HC)	39 26.500'	75 31.100'	
Nantuxent	(NAN)	39 16.333'	75 15.097'	
New Beds	(NEW)	39 14.900'	75 15.200'	
Shell Rock	(SR)	39 17.700'	75 20.700'	
Over the Bar	(OB)	39 15.571'	75 22.572'	Delaware Sites
Ridge	(R)	39 12.549'	75 21.753'	

Figure 2.2-1 Map of Oyster Bed Monitoring Locations

Notes: The red points represent the center of the oyster bed not the entire oyster bed area

Box 1. Salinity Affects More than Just Habitat.

In addition to the health and productivity of oysters, salinity affects the way they taste, an important consideration for the oyster industry. Delaware Bay Oysters are known for the delicate flavor and firm, plump meat. The Bay is home to two types of oysters, one coming from the Cape Shore, and the other from the inner bay. The oysters from the Cape Shore have briny, sweet, and nutty flavors, while those from the inner bay have a milder flavor (World Food Atlas, 2022).

Although not specific to oysters in the Delaware Bay, the table below, developed by the Virgina Aquaculture Oyster Growers, indicates salinity ranges and taste profile of oysters in various locations throught the Chesapeake Bay. The table below expresses the salinity of the growing region, as well as providing a scale rating for saltiness, sweetness, and buttery/creaminess (1=barely perceptible, 9=strong).

Salinity and Taste Characteristics of Oysters in the Chesapeake Bay

Region	Salinity Range	Saltiness	Buttery/Creamy	Sweetness	Comments
#1 Seaside	28-32	9	3	3	Initial bold saltiness mellowing into a taste of sweet butter/cream at the finish.
#2 Upper Bay Eastern Shore	16-18	5	1	3	Classic Virginia bay oyster flavor with balanced salt and sweet with a savory finish.
#3 Lower Bay Eastern Shore	18-22	7	3	3	Salty and Creamy with mellow sweetness and a quick finish.
#4 Upper Bay Western Shore	10-17	5	2	2	Sweetwater oyster with a light cream taste.
#5 Middle Bay Western Shore	16-18	5	3	3	Lightly salty with easily distinguished cream or butter and a pleasant slight minerality.
#6 Lower Bay Western Shore	16-18	5	2	2	Mild saltiness moving to a sweet finish.
#7 Tidewater	16-30	8	2	2	Salty oyster with a sweetness and a smooth finish.
#8 Tangier/Middle Chesapeake Bay	16-18	5	5	4	Traditional Virginia Bay Oyster flavor with a balance of salt and sweet, and a savory butter/cream finish.

Source: Virgina Aquaculture Oyster Growers (2022)

3. SEA LEVEL RISE (SLR)

The Delaware River Estuary has experienced sea level rise throughout the 20th century. Locally, the rate of sea level rise is anticipated to accelerate over the next several decades. Figure 3.1-1 and Figure 3.1-2 show the monthly variation and long-term trend of sea level at NOAA tidal gage stations: Lewes, Cape May, Reedy Point tide gauges to Philadelphia. The periods of record range from 47 to 119 years and the rates range from 3.02 mm/year to 4.73 mm/year. The historical rate of sea level rise for each location and the associated confidence intervals are presented in Table 3.1-1. Locations of the tidal gage stations were shown in Figure 1.1-2.

Table 3.1-1 Observed Local SLR Rates and Confidence Intervals for Locations in and near the Delaware Estuary

NOAA Station	Station Name	Period of Record	Number of Years	Linear Trend and 95% Confidence Interval (mm/yr)
8534720	Atlantic City, NJ	1911-2019	108	4.12 +/1 0.15
8536110	Cape May, NJ	1965-2019	54	4.73 +/- 0.49
8557380	Lewes, DE	1919-2019	100	3.53 +/- 0.23
8545240	Philadelphia, PA	1900-2019	119	3.02 +/- 0.19
8551910	Reedy Point, DE	1956-2019	63	3.69 +/- 0.46
8573927	Chesapeake City, MD	1972-2019	47	4.07 +/- 0.67
Stations are listed approximately from north to south. Source: NOAA Tides and Currents Sea Level Trends website, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html				

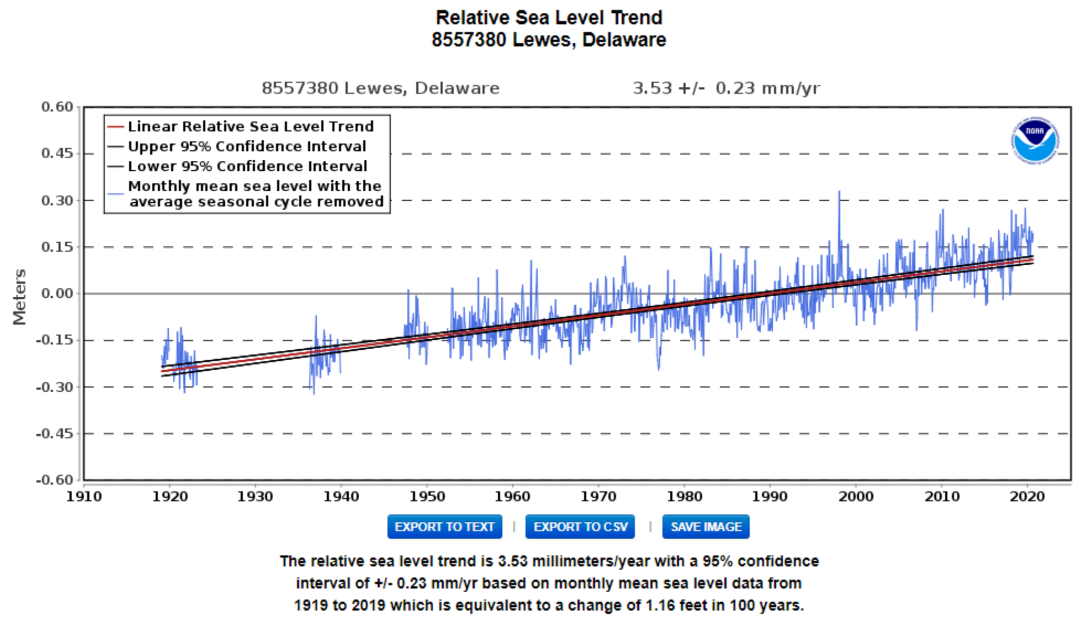
SLR projections are reported in reference to a datum because sea level varies seasonally and has increased over time. NOAA uses a 19-year tidal cycle, called an epoch, to calculate tidal datums. The present National Tidal Datum Epoch (NTDE) is based on observations from 1983 through 2001 (centered at 1992). Projections of SLR in the literature are often referenced to the year 2000, so the reference tidal datum for this study, was adjusted to the year 2000 to be consistent with the literature. The projections were converted to the year 2000 by adding 3.25 cm or 1.28 inch, which is the difference between the 1992 Epoch and the average sea level for 1991 – 2009 (centered on 2000).

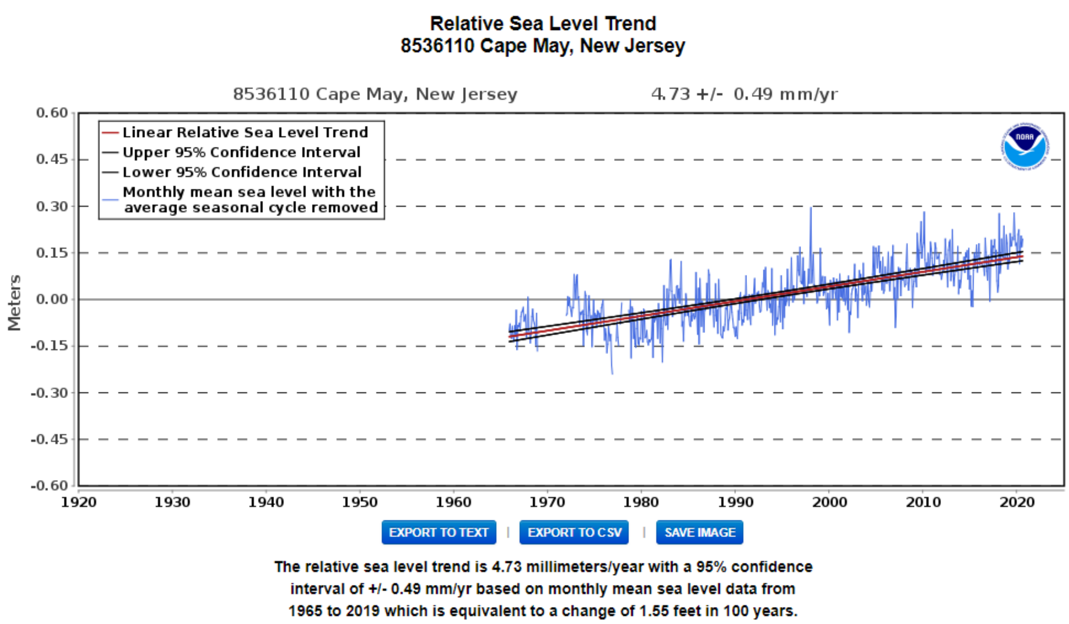
Three SLR projections were specified for this study: 0.5 m, 1.0 m and 1.6 m (1.64, 3.28 and 5.25 ft, respectively). The values were recommended by DNREC (2017) and shown in Figure 3.1-3. For a worst-case climate scenario, SLR will be approximately 0.5, 1,0, or 1.61 m by 2100 for the low, intermediate and high SLR projection rates. A value of 0.5 is also possible by 2060 for the intermediate scenario. NOAA released new projections in 2022[7] (Table 3.1-2) based on a revised methodology for estimating different components of SLR (discussion of which is outside the scope

[7] NOAA Sea Level Rise Report (2022): https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

of this report). The new projections, adjusted to the year 2000 baseline indicate that 0.5 m SLR may occur by 2060 under the intermediate scenario, 1.6 m SLR by 2100 with the intermediate-to-high scenario, and 1.0 m by 2070 with the high scenario.

Figure 3.1-1 Relative Sea Level Trend for Selected NOAA Stations

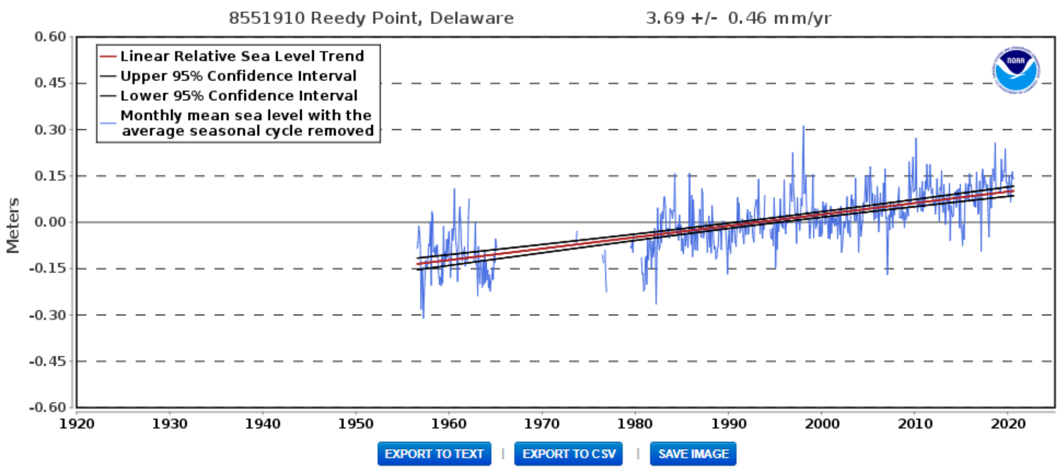




Linear MSL trend and 95% confidence interval shown in red and black, respectively. Data referenced to NTDE 1983-2001 MSL. Source: NOAA CO-OPS Tides and Currents SLR Trends website, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

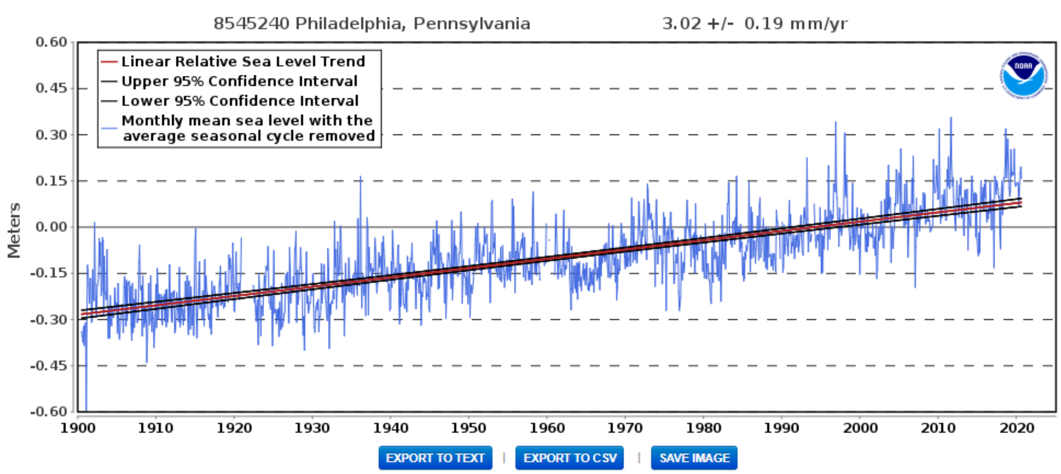
Figure 3.1-2 Relative Sea Level Trend for Selected NOAA Stations

Relative Sea Level Trend
8551910 Reedy Point, Delaware



The relative sea level trend is 3.69 millimeters/year with a 95% confidence interval of +/- 0.46 mm/yr based on monthly mean sea level data from 1956 to 2019 which is equivalent to a change of 1.21 feet in 100 years.

Relative Sea Level Trend
8545240 Philadelphia, Pennsylvania



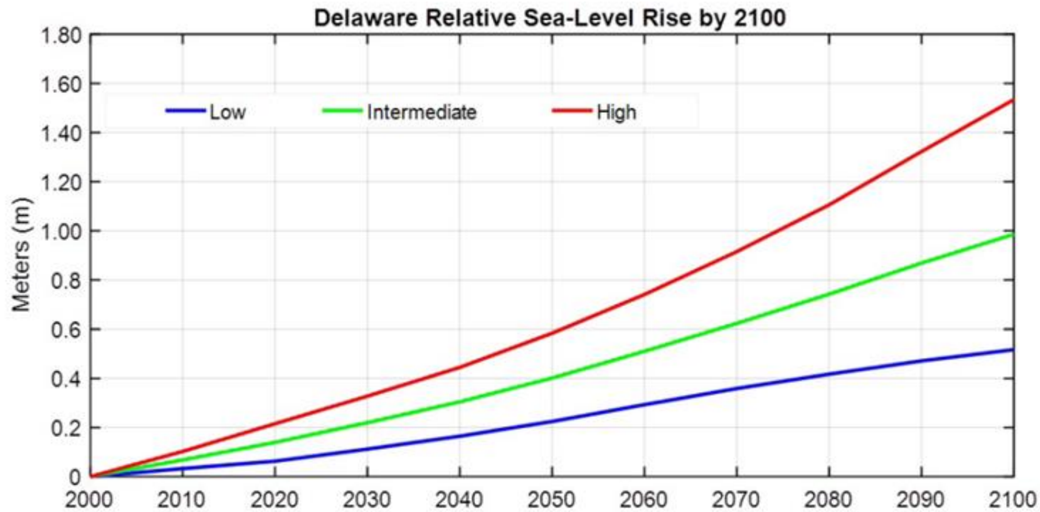
The relative sea level trend is 3.02 millimeters/year with a 95% confidence interval of +/- 0.19 mm/yr based on monthly mean sea level data from 1900 to 2019 which is equivalent to a change of 0.99 feet in 100 years.
Earlier data stored in database as station 8545530

Linear MSL trend and 95% confidence interval shown in red and black, respectively. Data referenced to NTDE 1983-2001 MSL. Source: NOAA CO-OPS Tides and Currents SLR Trends website, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

Table 3.1-2 NOAA (2022) SLR Projection at Station 8557380, Lewes, DE

Year	NOAA (Int-Low)	NOAA(Int.)	NOAA (Int-High)	NOAA (High)
	(m)	(m)	(m)	(m)
2000	0.00	0.00	0.00	0.00
2030	**0.22**	**0.23**	**0.24**	**0.24**
2040	**0.30**	**0.32**	**0.35**	**0.36**
2050	**0.39**	**0.42**	**0.48**	**0.53**
2060	**0.47**	**0.54**	**0.65**	**0.75**
2070	**0.56**	**0.67**	**0.85**	**1.04**
2080	**0.63**	**0.82**	**1.07**	**1.36**
2090	**0.71**	**1.02**	**1.33**	**1.71**
2100	**0.79**	**1.23**	**1.61**	**2.08**
Year	NOAA (Int-Low)	NOAA(Int.)	NOAA (Int-High)	NOAA (High)
	(ft)	(ft)	(ft)	(ft)
2000	0.00	0.00	0.00	0.00
2030	**0.72**	**0.75**	**0.78**	**0.79**
2040	**0.98**	**1.05**	**1.15**	**1.18**
2050	**1.28**	**1.38**	**1.57**	**1.74**
2060	**1.54**	**1.77**	**2.13**	**2.46**
2070	**1.84**	**2.20**	**2.79**	**3.41**
2080	**2.07**	**2.69**	**3.51**	**4.46**
2090	**2.33**	**3.35**	**4.36**	**5.61**
2100	**2.59**	**4.04**	**5.28**	**6.82**

Figure 3.1-3 The 2017 Delaware SLR planning scenario curves to the year 2100 (Delaware Sea-Level Rise Technical Committee report for DRNEC, 2017)



SLR Planning Scenario	SLR by 2100	
Low Scenario (5%)	**0.52 m**	**1.71 ft**
Intermediate Scenario (50%)	**0.99 m**	**3.25 ft**
High Scenario (95%)	**1.53 m**	**5.02 ft**

The Low, Intermediate and High planning scenarios correspond with the 5%, 50%, and 95% probability levels. It is the recommendation of the SLR Technical Committee to use the 5, 50, and 95 percent probability levels of sea-level rise in Delaware, determined by the Kopp et al. (2014) methodology under the IPCC AR5 RCP 8.5 emission scenario, as the Low, Intermediate, and High SLR planning scenarios, respectively. This equates to 0.52 m, 0.99 m, and 1.53 m of SLR by 2100, relative to year 2000 MSL. Depending on time horizon and sensitivity to coastal flooding, projects also may benefit by planning for SLR scenarios greater than the High (95%) planning scenario.

4. Analytical Approach and Salinity Model

Estuary hydrodynamics, including circulation and salinity transport, are three-dimensional in nature and often affected by complicated geometry and bathymetry. Near the mouth of the bay, a typical two-layer current and salinity structure exists (also known as tidal exchange flow structure) as the result of competing forcings from upstream inflows and ocean tidal forcing. Fresher, less dense water from inflows to the Estuary are flushed seaward on the surface layer, and saltier, denser ocean water is pushed landward along the bottom layer. The phenomenon is known as the estuary exchange flow. As a result, a relatively strong vertical stratification of salinity is often observed in the lower bay area. Moving upstream from the mouth of the bay, the vertical stratification becomes weaker. Vertical stratification affects the mixing processes and consequent salinity transport in the estuary. Near Marcus Hook (RM 79), the tidal river becomes well-mixed with a uniform vertical salinity profile.

To capture the complexity of the vertical structure correctly, A three-dimensional model is necessary to capture the effects of the complex hydrodynamics affecting the vertical salinity structure and transport. Moreover, a full three-dimensional numerical realization allows for the representation of many physical processes, including buoyancy, density differences related to temperature, tidal forcing, climatological/meteorological factors, surface heat exchange, wind forcing (local and remote), wind-wave induced current, and other processes. The interplay among these physical make it necessary to use a three-dimensional model to simulate the salinity transport.

4.1 Salinity Model

DRBC's Salinity Model is a three-dimensional (3D) hydrodynamic model of the Delaware Estuary developed to evaluate issues related to salinity, including SLR. The Salinity Model was reviewed by technical experts and deemed appropriate for the intended purpose of evaluating the impacts to salinity from SLR. Key aspects of the Salinity Model and its calibration are presented herein. The development of the Salinity Model and its application for estimating the impacts to salinity from SLR are documented in separate reports and posted on the DRBC website. (Chen, F. and Shallcross, A. 2022a, 2022b)[8].

4.1.1 Model Development

DRBC's Salinity Model was developed with the Environmental Fluid Dynamics Code (EFDC), software designed for the simulation of time-variable flow in rivers, lakes, reservoirs, estuaries, and coastal areas. The model solves multiple state equations for the fundamental processes affecting the movement of water in an estuary, including conservation of mass, momentum, transport, and the interplay between temperature and salinity (e.g., density-driven circulation due

[8] https://www.nj.gov/drbc/library/documents/3DSalintyModel.pdf and
https://www.nj.gov/drbc/library/documents/3DSalinitySLR.pdf

to spatial and temporal gradients in temperature and salinity). The effects of vertical turbulence on mixing and transport in the water column are also simulated.

EFDC is maintained by Tetra Tech and supported by the U.S. Environmental Protection Agency (USEPA) and has a history of extensive use in the United States and worldwide (e.g., Wool et al., 2003; Sucsy and Morris, 2002; SJRWMD 2012; Ji et al., 2007). A complete description of EFDC is provided in Hamrick (1992).

The tasks involved in developing the salinity model included developing a numerical model grid, processing bathymetric data, assigning initial hydrodynamic conditions in the water column, defining meteorological boundary conditions at the water surface, assigning inflow boundary conditions from upstream rivers and streams, determining the lateral inputs from point sources, and configuring the downstream open boundary condition in Delaware Bay. A summary of the model development provided herein. Detailed information about the Salinity Model is available in the model development and calibration report (DRBC 2022)1.

4.1.2 Model domain and Numerical Grid

The foundation of a hydrodynamic model is representation of the water body. A boundary-fitted, curvilinear numerical grid was used to represent the geometry of the Estuary. The geographical extent of the model numerical grid encompasses the entire 218 km (or 133 miles) tidal river and Delaware Bay from the water fall 2 km north of Trenton to the bay mouth. The grid also extends from the bay to approximately 68 km (or 42 miles) into the Atlantic Ocean on the continental shelf, where the depth is approximately roughly along with the 60 meters isobath.[9] The northern and southern boundaries of the coastal zone are located 96 and 100 km (60 and 62 miles) from the mouth of Delaware Bay, respectively. In addition, the Chesapeake and Delaware Canal (C&D Canal) from the Estuary to its western near the NOAA tide gauge station at Chesapeake City was included. The net flux of water in the Canal is into the Delaware. The numerical grid with projected bathymetry is shown in Figure 4.1-1

It is common practice to set hydrodynamic model boundaries in tidal systems away from the area of interest, to ensure that the numerical methods used to specify inputs at model boundaries do not influence model predictions within the area of interest. Although the area of interest for this study is the Estuary, the grid includes a portion of the coastal area surrounding the Bay to minimize uncertainty in specifying the model boundary conditions. The salinity at the mouth of the bay is highly time and spatially variable. After large flow events, a freshwater plume can float more than 10 miles into the ocean, creating a stratified salinity structure at the mouth of the Bay. Whereas the salinity of the ocean is more uniformly distributed spatially and in the water column farther from the mouth. In addition, expanding the grid so more stable boundary conditions can be specified limits the propagation of numerical uncertainty into the area of interest. In addition, it is easier to perform sensitivity testing with stable boundary conditions by increasing and decreasing their values.

[9] An isobath an imaginary line or a line on a map or chart that connects all points having the same depth below a water surface (as of an ocean, sea, or lake). The edge of the continental self is 145 km (90 miles), where the depth is approximately 100 meters.

Two versions of the model grid were developed to investigate the sensitivity of salinity predictions to the spatial extent of the riverbanks and marsh area of the grid. The first, named Grid v2.1 includes a limited amount of low-lying marshes surrounding the bay area. Grid v2.1 is representative of hardscaping around the marshes, such as levees or sea walls. The second version, named Grid v4.1, includes more of the low-lying marshes. The model was calibrated for both grids. Background information about hydrodynamics and the inclusion of additional marsh area and the results of the sensitivity testing are provided in Section 5.2.

Grid v2.1 contains 2510 grid cells: 1260 cells upstream of RM 70 near City of Wilmington) of the tidal river in the horizontal plane, and 1250 grid cells for the bay area. The tidal river was delineated with four to six grid cells in the cross-channel direction. The average grid cell size in the river channel upstream of RM 70 was 540 m and 240 m in the longitudinal and lateral directions, respectively. Grid cells in in the bay area are much larger with the average length in longitudinal and lateral directions of 1984 m and 1962 m (approximately 2 kilometers), respectively. Up to 20 vertical layers were assigned to cells near the ocean boundary, and eight vertical layers were used in most of the cells in the Federal Navigation Channel (FNC) to adequately capture the vertical structures of salinity and the current.

4.1.3 Bathymetry

The bathymetry data was obtained from Federal Emergency Management Agency (FEMA) Region III Storm Surge Study in 2011, formatted as a GIS raster surface, developed from the Digital Elevation Model (DEM).[10] The FEMA 2011 DEM was produced by merging the latest in coastal Lidar and other topographic survey data sets with the most reliable bathymetric datasets of the region. The bathymetry data includes the Delaware Bay and extends offshore to include the continental shelf and a portion of the deeper ocean. The horizontal datum is the North American Datum of 1983 (NAD83) and vertical datum is the North American Vertical Datum of 1988 (NAVD88). The raster grid resolution is 1/3 arc-seconds (~10 meters).

Related to the bathymetry is the Federal Navigation Channel (FNC). The U.S. Army Corps of Engineers (USACE) completed a channel deepening project in 2016 (with a small section finished in 2017-2018). The project involved dredging, where needed, along 102.5 miles of the existing 40-foot channel to 45 feet in the 102.5mile area between Philadelphia Harbor, PA. and Beckett Street Terminal, Camden, N.J. To reflect the dredged channel, the bathymetry in navigation channel cells was adjusted to 45 ft below MLLW for simulations after 2016 (e.g., 2017-2019 period) and 40 ft below MLLW for simulations of earlier years for model calibration and simulations under historical conditions. The current bathymetry (i.e., with the dredged 45 ft channel) was used for the SLR simulations. It was assumed that the FNC will be maintained as a 45 ft deep channel in the future. The bathymetry in C&D Canal was set to 35 ft below MLLW. The bathymetry was examined and adjusted manually based on NOAA nautical charts (12277, 12304, 12311 to 12314). The final bathymetry projected on the numerical grid is shown in Figure 4.1-1.

[10] *Coastal Storm Surge Analysis System Digital Elevation Model* (FEMA 2011)

4.1.4 Boundary Conditions

The Salinity Model required specification of the following boundary conditions:

- Flow rate at the upstream boundary (Delaware River at Trenton, N.J.);
- Inflows from tributaries, point source discharges, and major water withdrawals;
- Water surface elevation at the ocean open boundary;
- Water surface elevation at the western end of the C and D Canal; and
- Climate/meteorological information (air temperature, pressure, dew point, precipitation, wind speed and direction, and solar radiation).

Specification of key boundary conditions are briefly described in this section for reference. Details about model development and boundary conditions were documented in a the model calibration report (DRBC, 2021a).

4.1.4.1 Water Surface Elevations

The water surface elevation (total tide) is composed of the astronomical tides and a sub-tidal signal, which depends on meteorological forcings. The astronomical tides were be calculated by with a series of harmonic functions extracted from the Advanced CIRCulation (ADCIRC) (Szpilka C. et al., 2016). The dominant tidal constituent is the principal lunar semi-diurnal (M2). In addition to M2, eight other constituents (S2, N2, K2, K1, O1, Q1, M4 and M6) are included in the tidal boundary condition. The tidal harmonics cover total of 52 ocean open boundary cells. Tidal database "*Western North Atlantic, Caribbean and Gulf of Mexico Tidal Databases*" are available from website: http://adcirc.org/products/adcirc-tidal-databases/. DRBC added one subroutine to the EFDC source code based on the algorithm from ADCIRC to calculate the nodal factors and equilibrium arguments, which allows the code to specify the tidal forcing at ocean open boundary correctly using the information extracted from the Advanced CIRCulation (ADCIRC) database.

The sub-tidal signals at the ocean boundary are unknown and were assumed to be similar to those at Lewes, DE (NOAA Station (8557380). The sub-tidal signals (meteorological forcing) were calculated as the total tide (verified hourly data) minus the NOAA predictions (astronomical tide) at the station location. NOAA hourly verified tide data at Station (8573927) Chesapeake City, MD were used at the western end of the C&D Canal. For time periods that verified data were not available, the total tide was specified as predicted tide at Chesapeake City provided plus the sub-tidal fluctuations observed at the nearest NOAA Station (8551910) at Reedy Point, DE (eastern end of C&D Canal). All water surface elevation data were converted to the vertical datum of NAVD88 in meters to be consistent with the bathymetry. For simulations under future SLR conditions, the amount of SLR was added to the water surface elevation at ocean open boundary and the western end of the C&D Canal (assumed to be similar).

4.1.4.2 Freshwater Inflows

Based on an analysis by DRBC using data collected from January 2018 through June 2019, the contributions of freshwater to the total water inflow budget from the mainstem at Trenton, Schuylkill River, the combined Christina and Brandywine Rivers, and the remaining tributaries are

52, 15, 4, and 12 percent, respectively. Point source discharges contribute 3 percent, and direct watershed contributions from non-point source (NPS), including Municipal Separated Storm Sewer System (MS4) and Combined Sewer Overflows (CSOs), contribute 5 percent. Direct precipitation onto the Delaware Estuary contributes another 9 percent of the total water load.

Flows from the Delaware River and 31 major tributaries were specified using available USGS data (Table 4.1-1). Hourly flow data were utilized for the Delaware River at Trenton and Schuylkill River because of their significant contributions to the total freshwater input. Daily flows were utilized for the remainder of the tributaries. Missing streamflow values were replaced by fitting a structural time series model to the data followed with a smoothing function. Gaging stations are typically located at or above the head of tide, often leaving substantial portions of the tidal river watershed ungaged. Flow rates for ungaged tributaries and tidal areas below gages were estimated based on data from similar watersheds. Flows were specified for 71 point source dischargers (DRBC 2022). Flows from NPS, groundwater and surface water interaction were not explicitly considered due to their relatively small contribution. Eight major withdrawals were included. The monthly withdrawal rates were based on DRBC Water Use database and assumed unchanged for the future SLR simulations.

Table 4.1-1 Summary of Tributaries in the Salinity Model

Count	Tributaries	RM	USGS Gauge
1	Delaware River at Trenton	134.3	USGS01463500
2	Assunpink Creek	133.8	USGS01464000
3	Crosswicks Creek	128.4	USGS01464500
4	Neshaminy Creek	115.6	USGS01465500
5	Rancocas Creek North Branch	111.1	USGS01467000
6	Rancocas Creek South Branch	111.1	USGS01465850
7	Poquessing Creek	111.7	USGS01465798
8	Pennypack Creek	109.8	USGS01467048
9	Pennsauken Creek South Branch	105.4	USGS01467081
10	Pennsauken Creek North Branch	105.4	N/A
11	Frankford Creek	104.6	USGS01467087
12	Cooper River	101.6	USGS01467150
13	Big Timber Creek	95.5	N/A
14	Schuylkill River	92.5	USGS01474500
15	Mantua Creek	89.7	N/A
16	Darby Creek	85.3	N/A
17	Crum Creek	84.9	USGS01475850
18	Ridley Creek	84.2	USGS01476480
19	Chester Creek	82.9	USGS01477000
20	Raccoon Creek	80.7	USGS01477120
21	Oldman Creek	77.0	N/A

22	Christina River	70.7	USGS01478000
23	Brandywine Creek	70.7	USGS01481500
24	Salem River	58.4	USGS01482500
25	Alloway Creek	54.5	N/A
26	Appoquinimink River	51.2	N/A
27	Cohansey River	37.8	USGS01412800
28	Leipsic River	35.0	USGS01483500
29	St. Jones River	23.7	USGS01483700
30	Murderkill River	23.1	USGS01484000
31	Maurice River	20.0	USGS01411500
32	Mispilion River	13.0	N/A

River mile zero is the mouth of the Delaware Bay at the start point of the Federal Navigation Channel (FNC). River mile is measured along the FNC from the mouth upstream.

4.1.4.3 Water Temperature and Salinity

Temperature in the Delaware River at Trenton varies seasonally, with minimum temperatures of 1 to 5° C during winter and maximum temperatures of approximately 25° C during summer. Water temperature and specific conductance data collected at USGS gaging stations were used to specify the water temperature and salinity boundary conditions at upstream and all tributaries. For tributaries without the water temperature or specific conductance data available, the water temperature and salinity were assigned the values from the Delaware River at Trenton gage and the Schuylkill River for tributaries located upstream and downstream, respectively, of the Schuylkill River. Salinity was calculated based on specific conductance or from conductivity.[11] The salinity was set as 0.1 ppt for tributaries located downstream of Schuylkill River if specific conductance data were not available. The salinity from point source discharges was assumed to be zero.

The near-surface water temperature at the ocean open boundary was assigned as the observed water temperature from NOAA station (8557380) at Lewes, DE. The water temperature below the surface was adjusted based on the WOA13 monthly mean data near the mouth of the Delaware Bay. The average difference between near-surface and water temperature at 10-m depth ranged from -0.3 C in February to 4.3 C in July of the year. The salinity boundary conditions at the ocean boundary were based on World Ocean Atlas 2013 (WOA13) database (Locarnini, R. A. et al. 2013, and Zweng, M. M, et al 2013) and monthly statistics for data collected from 2005 to 2012. The monthly mean salinity from various of depths were applied to the model boundary. Values were assigned to the surface layer and linearly transitioned through three vertical layers to reach a value that reflects salinity at deeper depth, which was based on WOA13 monthly mean data at

[11] *"Standard Methods for the Examination of Water and Wastewater" 19th Ed. 1995* (American Public Health Association. 1995)

a depth of 30-meters. A uniform vertical profile was applied to the remaining vertical layers at the ocean boundary.

The water temperature and salinity boundary conditions at the C&D Canal were established based on water temperature and conductivity data collected at NOAA Station (8573927) Chesapeake City, MD. For periods when conductivity data were not available (e.g., 2012 and others), a rating curve was used to specify the salinity boundary conditions. The rating curve was developed using multiple-linear regression analysis of data from NOAA Station Chesapeake City, USGS Station at Reedy Island and USGS Station (01576000) at Susquehanna River Flow at Marietta, PA from 04-01-2017 to 05-31-2019 (DRBC, 2021a).

4.1.4.4 Climate / Meteorological Forcing

Climate/Meteorological forcing boundary conditions include air temperature and pressure, dew point, cloud conditions, wind speed, wind direction, precipitation, and net shortwave solar radiation. This information was used to calculate the heat flux at the water surface, and its effects on the vertical distribution of water temperature in the water column. Since surface heat flux was spatially variable over the large model domain, meteorological data collected at multiple NOAA National Climatic Data Center (NOAA-NCDC) weather stations were considered for the climate forcing boundary conditions. The five weather stations are given in Table 4.1-2. Shortwave solar radiation, which is required as model input, was calculated based on other parameters rather than direct measurement from these weather stations. The calculated net shortwave solar radiation values were used to fill the data gaps, with assumptions for dew point, relative humidity and cloud cover.

Table 4.1-2 NOAA NADC Weather Stations

Count	STATION	USAF	WBAN	LAT	LON
1	Trenton Mercer Airport	724095	14792	40.277	-74.816
2	Philadelphia International Air	724080	13739	39.873	-75.227
3	New Castle County Airport	724180	13781	39.674	-75.606
4	Dover AFB Airport	724088	13707	39.133	-75.467
5	Cape May County Airport	745966	03726	39.008	-74.908

For future SLR condition simulations, no changes were made to the meteorological boundary conditions. Effects of the changes to meteorological parameters due to climate change were outside the scope of this analysis.

4.1.5 Model Performance

Detailed calibration results for the Salinity Model are documented in the full model calibration report (DRBC 2021). Representative results are summarized herein to demonstrate model performance. The major calibration metrics shown (1) water surface elevation, (2) current velocity, (3) water temperature, (4) salinity.

4.1.5.1 Water Surface Elevation

Model calibration begins with water surface elevation (WSE). The astronomical tide and total tide are compared to evaluate how well the model simulated the WSE.

4.1.5.1.1 Astronomical tide

Evaluating model performance for water surface elevation (WSE) was the first step of model calibration. The tide wave enters the estuary at the mouth near Cape May and progresses upstream to the head of tide at Trenton. The measured WSE (total tide) is the sum of astronomical tide and subtidal fluctuations at given location. According to NOAA, the total tidal amplitude observed at the mouth of the estuary (RM 0) is 4 feet (1.3 m) and increases to a local maximum of 6 feet (1.8 m) at the Ship John Shoal (RM 37) and a maximum of 6.5 feet (2 m) at Trenton (RM 134). Tidal harmonic analyses were performed with the observed data and model predictions for 2-year (2017-2018) period. The amplitude and phase of major harmonic constituents were compared. The principal lunar semidiurnal (M2, 12.42-hour period) is the dominant harmonic constituent throughout the estuary. Model reproduced the amplification of tidal amplitude for the dominant harmonic constituent M2. The tidal amplitude of M2 increased from 0.6 m at the mouth to 0.88 m at RM 37, decreased to 0.8 m at RM 79 near Marcus Hook, The M2 amplitude at Newbold is 1.1 m (RM 126). The maximum error in predicted M2 tidal amplitude is 8.8 cm at the NOAA Station Ship John Shoal. The spatial distribution of the amplitude of shallow water constituents M4 and M6 are also investigated and compared with the observations (not shown in this report). M4 and M6 reflect the influence of river inflows as well as impact from bathymetry. A complete model-to-data comparison of the amplitude of nine major harmonic constituents at nine NOAA tide stations were given in DRBC (2011a).

4.1.5.1.2 Total Tide

The model simulated the water surface elevation (total tide) with adequate accuracy to meet the objectives of this study. The statistics used to quantify the model performance are summarized in Table 4.1-3. The predicted tide has minimal bias (typically less than 0.1 m) and low ubRMSD (ranged from 0.09 to 0.26 m). The model Bias and ubRMSD error at Philadelphia are -0.04 m and 0.13 m, respectively. The model skill score ranged from 0.976 to 0.991. These statistical measures demonstrate that the model accurately predicted tidal water surface elevation throughout the Estuary.

Table 4.1-3 Model Performance Predicting Water Surface Elevation (2017-2018)

Station	State	NOAA ID	N	R^2	Bias (m)	RMSE (m)	ubRMSD (m)	Skill Score
Lewes	DE	8557380	17519	0.968	0.080	0.121	0.090	0.985
Cape May	NJ	8536110	17514	0.976	0.059	0.109	0.091	0.991
Ship John Shoal	NJ	8537121	17514	0.947	-0.016	0.174	0.173	0.984
Reedy Point	DE	8551910	17071	0.937	-0.041	0.162	0.157	0.983
Delaware City	DE	8551762	17514	0.937	-0.024	0.163	0.162	0.983
Marcus Hook	PA	8540433	16753	0.953	-0.049	0.146	0.138	0.986
Philadelphia	PA	8545240	17514	0.963	-0.040	0.138	0.132	0.990
Burlington	NJ	8539094	17514	0.931	-0.116	0.255	0.227	0.976
Newbold	PA	8548989	17514	0.920	-0.047	0.263	0.259	0.978

Notes: definition of these statistical measures were provided in the DRBC Salinity Model calibration report (DRBC 2022)

4.1.5.2 Current Velocity

Limited current velocity measurements from a few NOAA stations (db0201 at Reedy Point, db0501 and db0502 at Brown Shoal Light) during 2012 and 2018-2019 period were used for model calibration.

A representative comparison of observed and predicted depth-averaged along and cross-channel current velocity at Reedy Point at NOAA station db0201, located at 58 miles from the bay mouth on the main stem that near the eastern end of the C&D canal. For period of January 30 to February 5, 2012, the statistical measures for predicted depth-averaged current velocity at db0201 are ubRMSE (16.5 cm/s), bias (5.8 cm/s), and skill score of 0.98. The values indicate that the model adequately predicted depth-averaged current velocity magnitude at this location for 2012. Similarly, agreement between predicted and observed depth-averaged current velocity at db0501 was reasonable. For example, the comparisons of the depth-averaged current velocity at db0501 showed good agreement between predicted and observed depth-averaged current velocity at db0501 for June 2012 period. Similar model-to-data comparisons of depth averaged current velocity at station db0502 for the period of November 5 to 11 2018. Detailed comparisons were presented in DRBC hydrodynamic model calibration report (DRBC 2011b).

From April 8 to June 27, 2011, Rutgers University deployed a bottom mounted Acoustic Doppler Current Profiler (ADCP) mooring stations in the middle reach of Delaware Bay located at 68 and 54 km (DRBC RM 42 and RM 33) from the entrance of the bay. Model-to-data comparisons of longitudinal and cross-sectional channel current velocity at Station C5 from April 18 through June 30, 2011 were performed. Detailed comparisons were presented in DRBC hydrodynamic model calibration report (DRBC 2011b). An example of model predicted vertical profile of current velocity compared to the ADCP data is presented in Figure 4.1-2. The model was able to adequately capture the vertical structure of the current velocity at this location. The statistical measures for predicted along-channel depth-averaged current velocity at four ADCP station locations are summarized in Table 4.1-4. The model skill score for predicted depth-averaged current velocity ranged from 0.979 to 0.991 and with unbiased error ubRMSE ranging from 8.97 to 18.34 cm/s. These statistical measures indicate that the hydrodynamic model simulates current velocity with sufficient accuracy to meet the objectives of this study.

Table 4.1-4 Model Performance Predicting Depth-Averaged Current Velocity

Station	Source	ID	Period of Records	N	R^2	Bias (cm/s)	RMSE (cm/s)	ubRMSE (cm/s)	Skill Score
Brown Shoal Light	NOAA	db0501	06-01-2012 to 06-30-2012	718	0.963	0.64	8.97	8.95	0.991
Delaware Bay Channel LB 10	NOAA	Db0502	09-06-2018 to 02-25-2019	4075	0.936	-1.33	11.50	11.43	0.982
Reedy Point	NOAA	db0201	01-01-2012 to 05-05-2012	2811	0.963	5.54	18.34	17.48	0.982
Station C5	2011 Survey	C5	04-18-2011 to 06-30-2011	1729	0.929	3.60	16.41	16.01	0.979

4.1.5.3 Water Temperature

The model over-predicted water temperature near the surface during the summer in the bay area down stream of Reedy Island (RM 54), and it preformed reasonably well for stations in the upper portion of the tidal river (i.e., upstream of Chester at RM 83). The model was able to simulate the seasonal variation in temperature at all stations, with average bias from -1.03 to 1.37 degree Celsius. A summary of the statistical measures is presented in Table 4.1-5

Table 4.1-5 Model Performance Predicting Water Temperature (2018 Period)

Agency	Station	State	NOAA (or USGS) ID	N	R^2	Bias (C)	RMSE (C)	ubRMSE (C)	Skill Score
NOAA	Lewes	DE	8557380	8717	0.985	-0.11	1.32	1.31	0.994
NOAA	Cape May	NJ	8536110	8751	0.980	-0.12	1.46	1.45	0.993
NOAA	Ship John Shoal	NJ	8537121	4524	0.996	-1.03	1.28	0.75	0.996
NOAA	Reedy Point	DE	8551910	7971	0.993	-0.44	0.93	0.82	0.998
NOAA	Delaware City	DE	8551762	8754	0.991	1.37	1.71	1.03	0.992
NOAA	Marcus Hook	PA	8540433	8671	0.984	-0.79	1.37	1.12	0.994
NOAA	Philadelphia	PA	8545240	8614	0.993	-0.48	0.96	0.83	0.997
NOAA	Burlington	NJ	8539094	8684	0.995	-0.18	0.66	0.64	0.999
NOAA	Newbold	PA	8548989	8751	0.996	-0.17	0.57	0.55	0.999
USGS	Reedy Island	DE	USGS01482800	8663	0.994	-0.63	1.00	0.78	0.997
USGS	Chester	PA	USGS01477050	7999	0.983	-0.38	1.22	1.16	0.995
USGS	Ben Franklin Bridge	PA	USGS01467200	6284	0.994	-0.37	0.70	0.60	0.997

4.1.5.4 Salinity

Prediction of salinity intrusion and adequately capturing the longitudinal and vertical salinity structure in the estuary is essential because salinity is used as a tracer to evaluate conservative constituent transport. The model was calibrated with data from 2017-2018 years and validated using data from other years and multiple sources. They include continuous salinity (conductivity or specific conductance) measurements from NOAA and USGS monitoring locations, discrete sampling of along-channel salinity profiles from DRBC's Boat Run[12], and a 2011 survey of near-surface and near-bottom salinity performed by Rutgers University (Aristizabal and Chant 2014[13]).

In the Estuary from the mouth of the Bay to Reedy Island (RM 54), salinity transport is primarily driven by the tidal forcing from the ocean. Predicted hourly-averaged and 32-hour-low-pass-filtered salinity at NOAA stations at Ship John Shoal (RM 37) and at USGS station at Reedy Island (RM 54) and Chester (RM 83.6) are presented in Figures 4.1-3 through 4.1-5 for 2017 to 2018. Salinity varied widely during the data collection period and fluctuated over the tidal cycle. The 32-hour-low-pass filter was used to remove tidal oscillations from the hourly dataset. The tidally filtered salinity demonstrated a clearer response to the freshwater inflows. The results indicate that the model adequately predicted salinity near Ship John Shoal and at USGS gage at Reedy

[12] https://www.nj.gov/drbc/programs/quality/boat-run_explorer-app.html

[13] Marıa Aristizabal and Robert Chant (2014), Mechanisms driving stratification in Delaware Bay estuary. Ocean Dynamics (2014) 64:1615–1629. DOI 10.1007/s10236-014-0770-1

Island. Model performance of predicted near-surface 32-hour-low-pass-filtered salinity is summarized in Tables 4.1-6 for periods of 2017 to 2018.

The model results reflected the observed salinity for Ship John Shoal (RM 37) and Reedy Island (RM 54). The long-term average salinity was reproduced with a small bias (-0.18 to 0.13 during 2017 to 2018 period) for both locations. The standard deviation of the predicted salinity was similar to that of the data. Overall model performance for predicted salinity is reasonable with skill scores from to 0.88 to 0.94 (2017-2018 period). At Lewes, DE, near the mouth, the model has less skill at predicting the salinity. The grid cell size near Lewes is too large for the salinity to be predicted with a high degree of accuracy because the bathymetry lacks the needed detail for the complex hydrodynamics being simulated. However, the areas under investigation are well upstream from the mouth of the Bay. Overall, the results demonstrate that the model adequately predicts salinity at the Ship John Shoal area inside the Delaware Bay.

Table 4.1-6 Model Performance for Predicted 32-hr-LPF Surface Salinity at NOAA and USGS Stations (2017-2018)

Agency	Station	State	Station ID	N	R^2	Bias (psu)	RMSE (psu)	ubRMSE (psu)	Model Stdv. (psu)	Data Stdv. (psu)	Skill Score
NOAA	Lewes	DE	8557380	12726	0.448	0.023	1.910	1.910	2.565	1.618	0.767
NOAA	Ship John Shoal	NJ	8537121	8794	0.678	-0.179	2.395	2.388	4.116	2.893	0.875
USGS	Reedy Island	DE	01482800	17261	0.797	0.132	1.297	1.290	2.856	2.48	0.938

The Delaware Estuary water-quality monitoring program and boat run surveys have been performed since 1967. Samples were collected monthly during a short 4-to-5-hour time window at 22 locations along the river and provides a “snapshot” of the longitudinal salinity profile. The predicted tidally averaged salinity longitudinal profile agreed with the boat-run data over a wide range of flow and tidal conditions. Figure 4.1-6 through 4.1-8 present the comparison of the simulated and observed longitudinal salinity profile for August 7, 2017, October 7, 2017, and November 7, 2018, respectively. Comparisons from other years showed similar agreement between model predictions and the data.

During the September 16-17, 2011 survey conducted by Rutgers University, along-channel salinity and water temperature profile data were collected near the surface and near the bottom, over a 30-hour time span encompassing two tide cycles. The survey was conducted one week after a high-flow event when the maximum flow at Trenton was over 177,000 cfs on September

9th 2011 (a 10-year flood at Trenton.)[14] The observed salt front was located downstream of RM 50 during the survey. The model successfully reproduced the near-surface and near-bottom salinity as well as the water temperature longitudinal profiles. The predicted salinity profiles compared with the survey data are presented in Figures 4.1-9 and 4.1-10.

4.2 Assumptions for SLR Simulations

The purpose of most modeling studies is to test the response of a system to different inputs or stressors. Such analyses include the assignment of different boundary conditions. Future conditions in the Estuary are likely to be affected by multiple stressors but estimates of how those stressors will change in the future are unknown or of significant uncertainty. Examples of such stressors include changes to bathymetry from sedimentation, scour or dredging, meteorological parameters (wind, temperature, precipitation), among others. This study is limited to the specific impact of SLR in the Delaware Estuary to salinity with an additional assessment related to the extent of grid delineation into marsh areas. Additional assumptions were tested for a separate project and described separate reports (DRBC 2022). The assumptions used for the SLR simulations are summarized below.

- The Federal Navigation Channel (FNC) will be maintained to a depth of 45 ft.
- The bathymetry outside the navigation channel will not change as the result of SLR (e.g., not be substantially altered by sedimentation (e.g., the sedimentation rate and transport rate will keep pace with SLR).
- The amplitude and phase of astronomic tide (i.e., tidal harmonics) at the model ocean boundary will not change.
- SLR will be simulated by adding the value of the projection to the WSE in the calibrated Salinity Model at both the ocean boundary and western end of C&D Canal.
- The impacts from wind and wave action on salinity intrusion in the upper tidal river is not significant or persistent and thus wave induced current circulation was not simulated.
- The four-month low-flow period of July-October 2002 is representative of a critical condition for increased salinity in the Estuary.
- Point sources discharges and/or withdrawals will not increase or decrease significantly or have minor impacts (to salinity) due to their comparative net contribution of freshwater into or out of the Estuary.
- Groundwater-surface water interaction (volume and salinity) is insignificant relative to other forcings.

[14] Schopp, R.D., and Firda, G.D., (2008), Flood magnitude and frequency of the Delaware River in New Jersey, New York, and Pennsylvania: U.S. Geological Survey Open-File Report 2008–1203.

4.3 CAVEATS

Some classes of data (assumptions) and/or physical processes may be altered by climate change. The impacts to salinity from those changes are uncertain. For instance, higher flow events may occur, but may only affect the frequency or persistence of low-flow induced high salinity events. Evaluation of these changes was outside the scope of this study. Some examples include:

- meteorological forcings including wind, air temperature and pressure, solar radiation, intensity and frequency of the tropical storms, etc.
- freshwater inflows or hydrologic conditions (volume and timing) that may result from changes in precipitation, temperature, storm patterns, etc.

Figure 4.1-1 Numerical Grid and Projected Bathymetry, Gird v2.1 and Gird v4.1

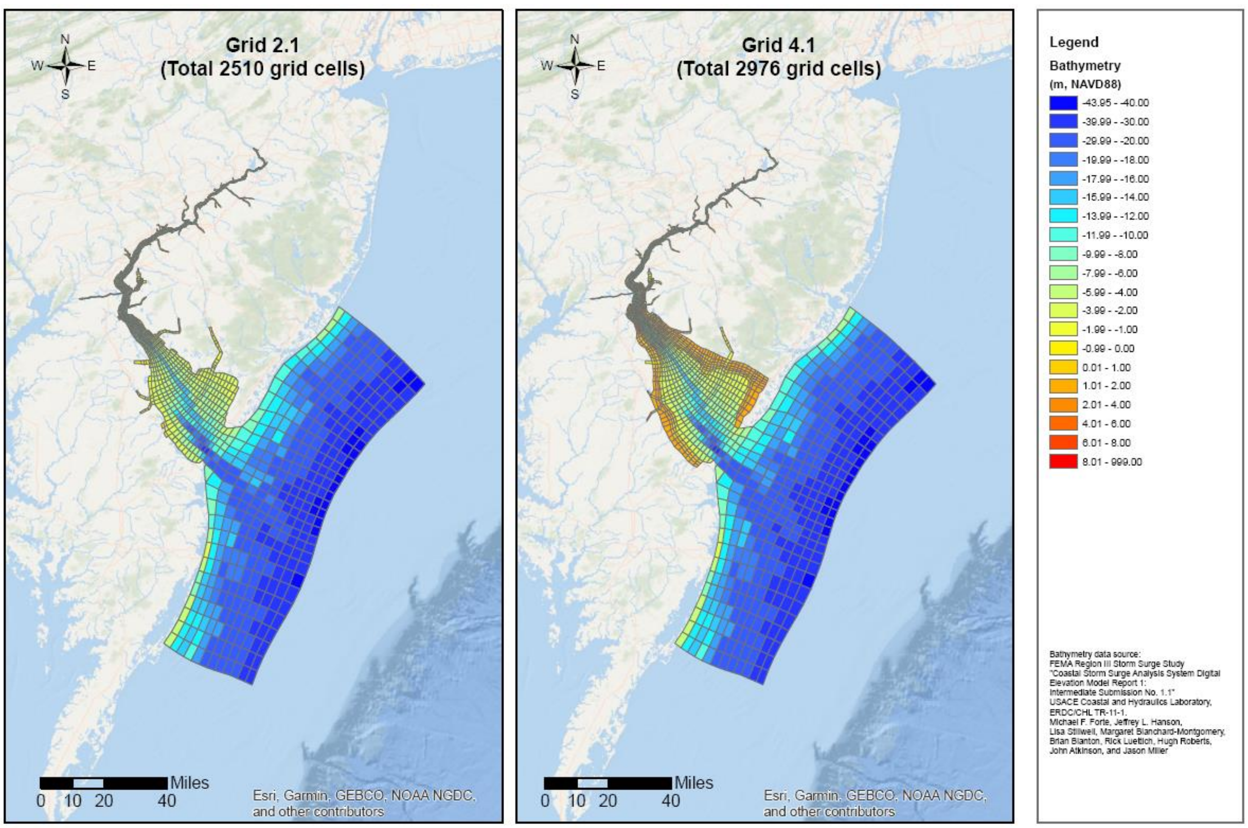


Figure 4.1-2 Vertical Profile of Observed and Predicted Along-Channel Current Velocity at C5 during 2011-05-01 02:00:00 to 2011-05-01 13:00:00 period

Note: 10-min ADCP current velocity measurements were averaged into a hourly window and compared to hourly average model outputs. ADCP survey data collected in 2011 were provide by Rutgers University.

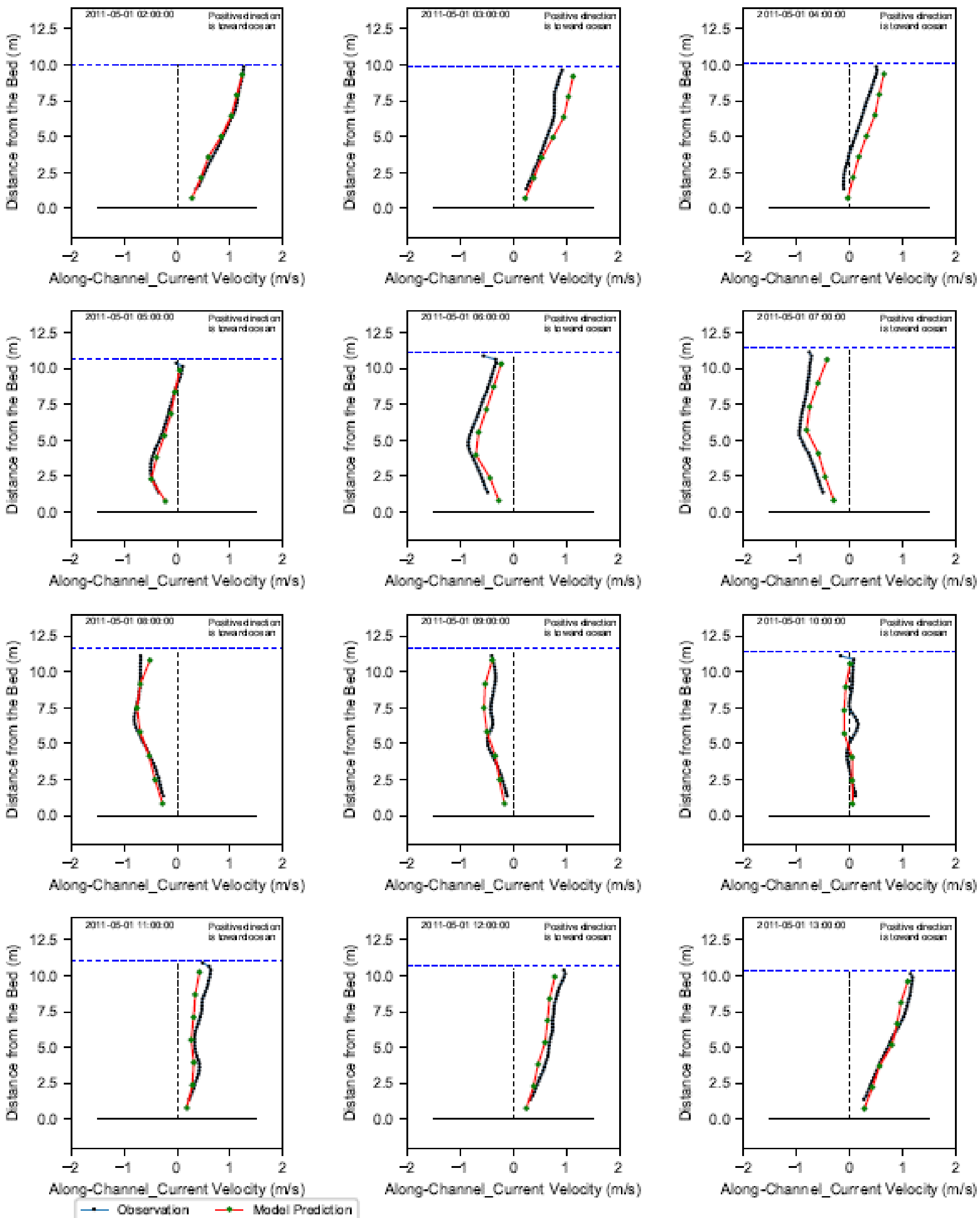


Figure 4.1-3 Observed and Predicted Near-surface Hourly and 32-hour-Lowpass-Filtered Salinity at NOAA Station at Ship John Shoal during 2017 to 2018 Period

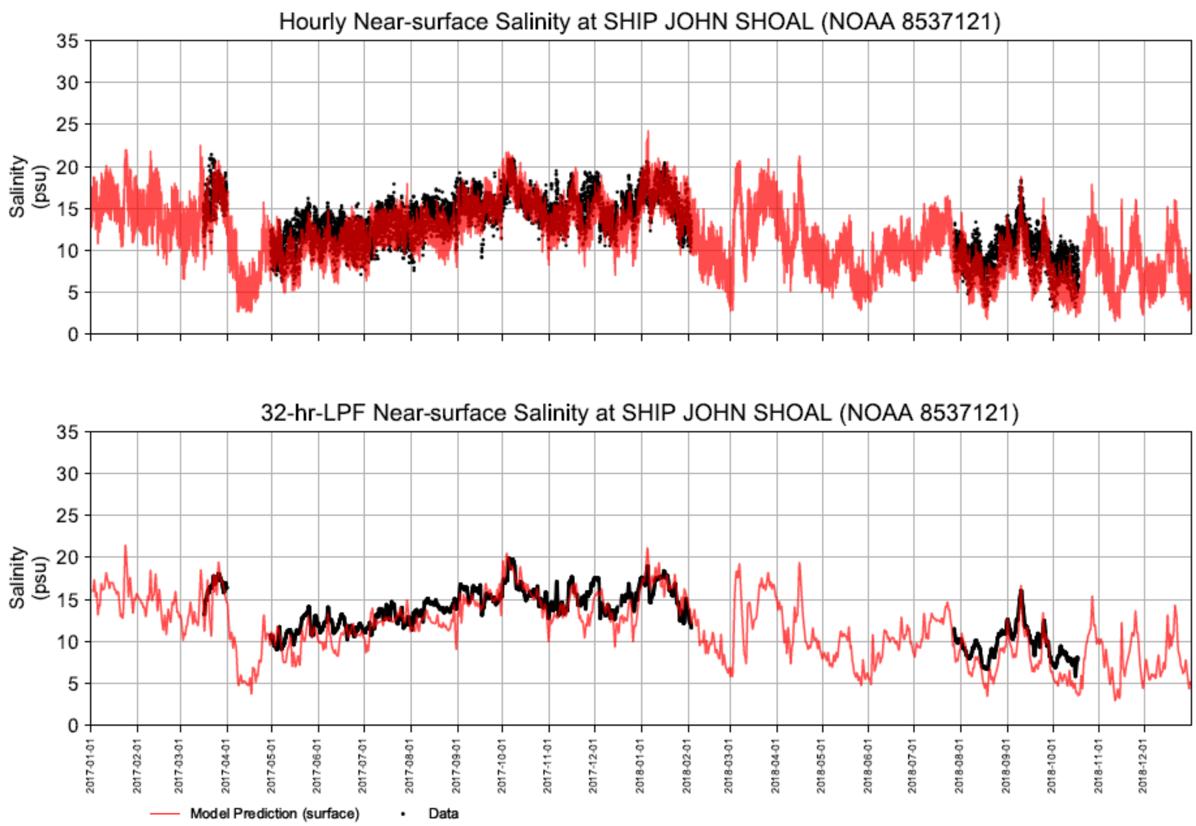


Figure 4.1-4 Observed and Predicted Near-surface Hourly and 32-hour-Lowpass-Filtered Salinity at USGS Gage at Reedy Island during 2017 to 2018 Period

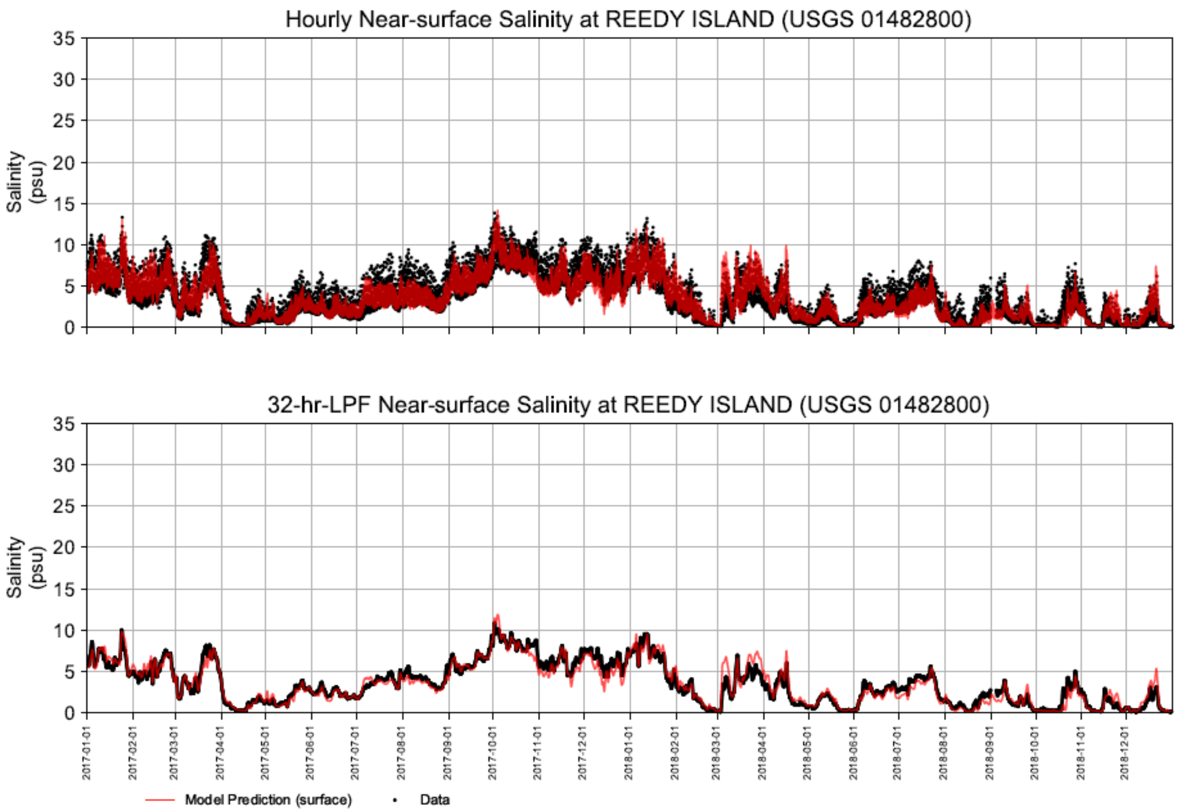


Figure 4.1-5 Observed and Predicted Near-surface Hourly and 32-hour-Lowpass-Filtered Salinity at USGS Gage at Chester during 2017 to 2018 Period

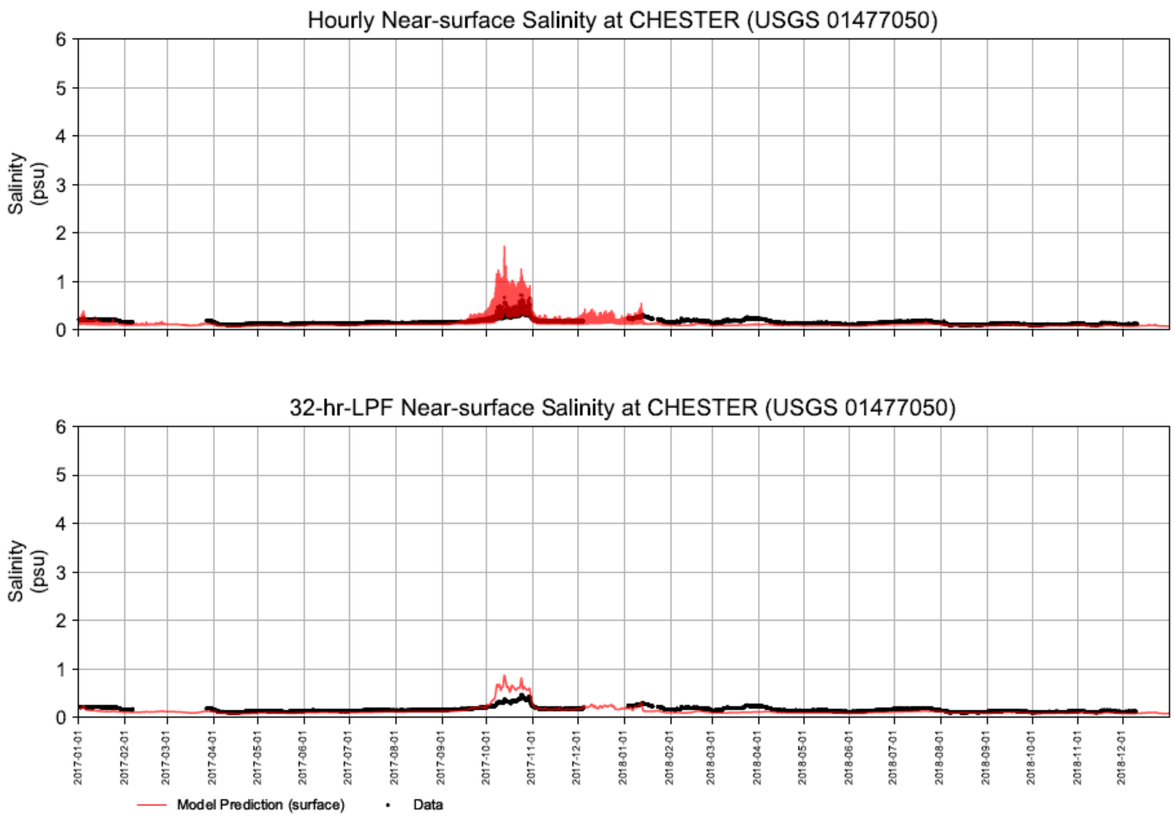
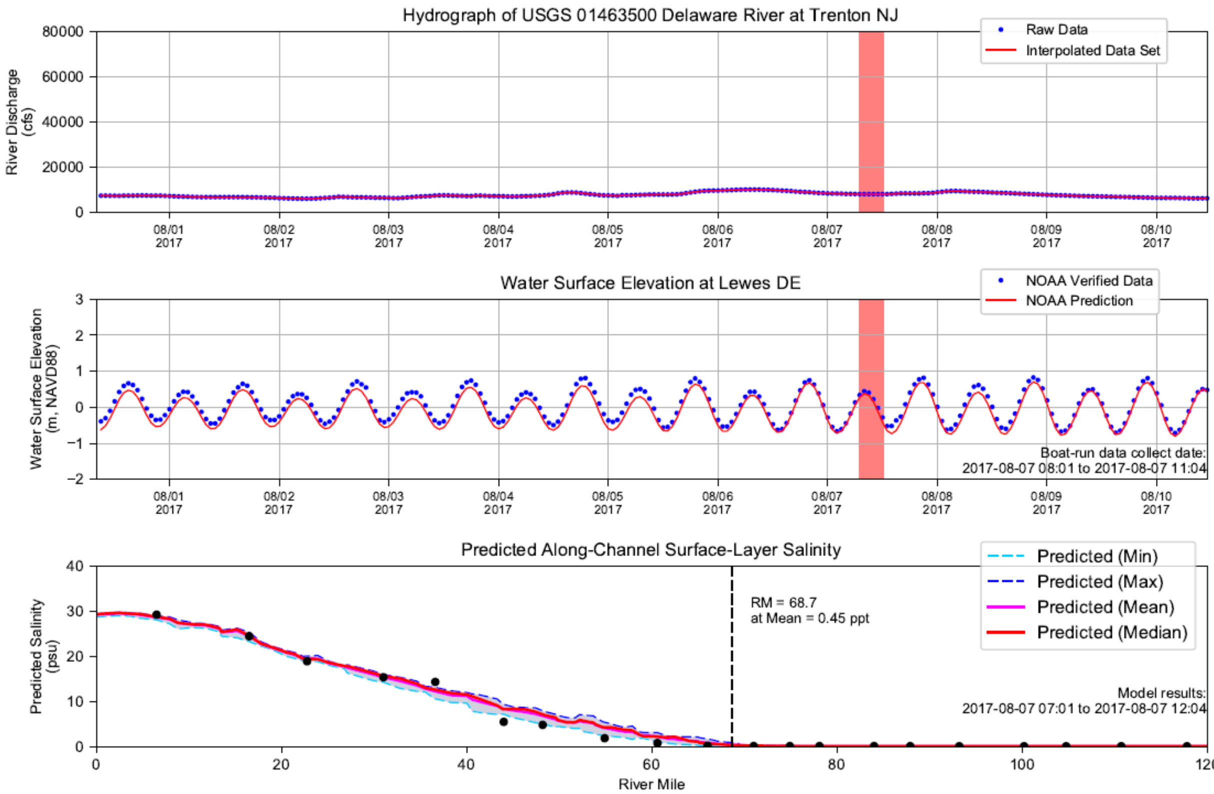
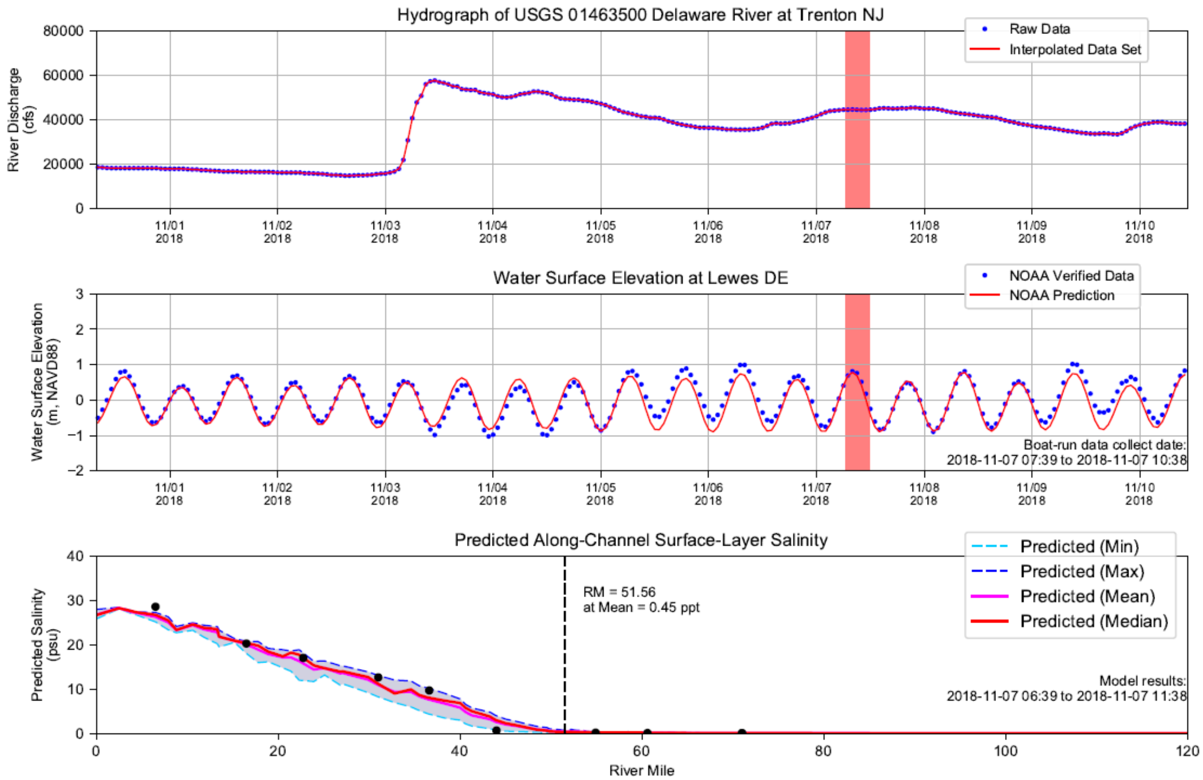


Figure 4.1-6. Simulated Longitudinal Profile of Salinity in Delaware Estuary.



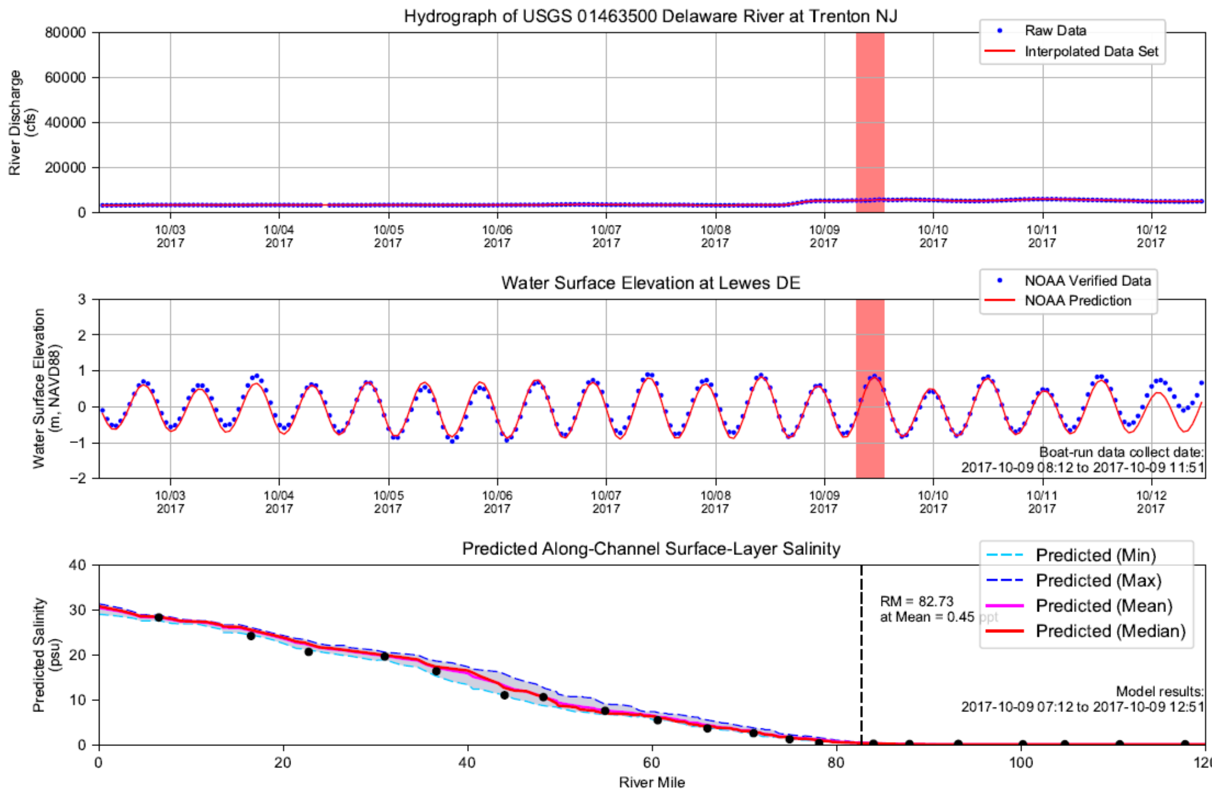
Notes: Data source: Boat Run Survey. Red shaded area indicates the timing of the boat run survey: 2017-08-07 08:01 to 2017-08-07 11:04. Model results along the navigation channel during period of 2017-08-07 07:01 to 2017-08-07 12:04 were used in this analysis.

Figure 4.1-7. Simulated Longitudinal Profile of Salinity in Delaware Estuary.



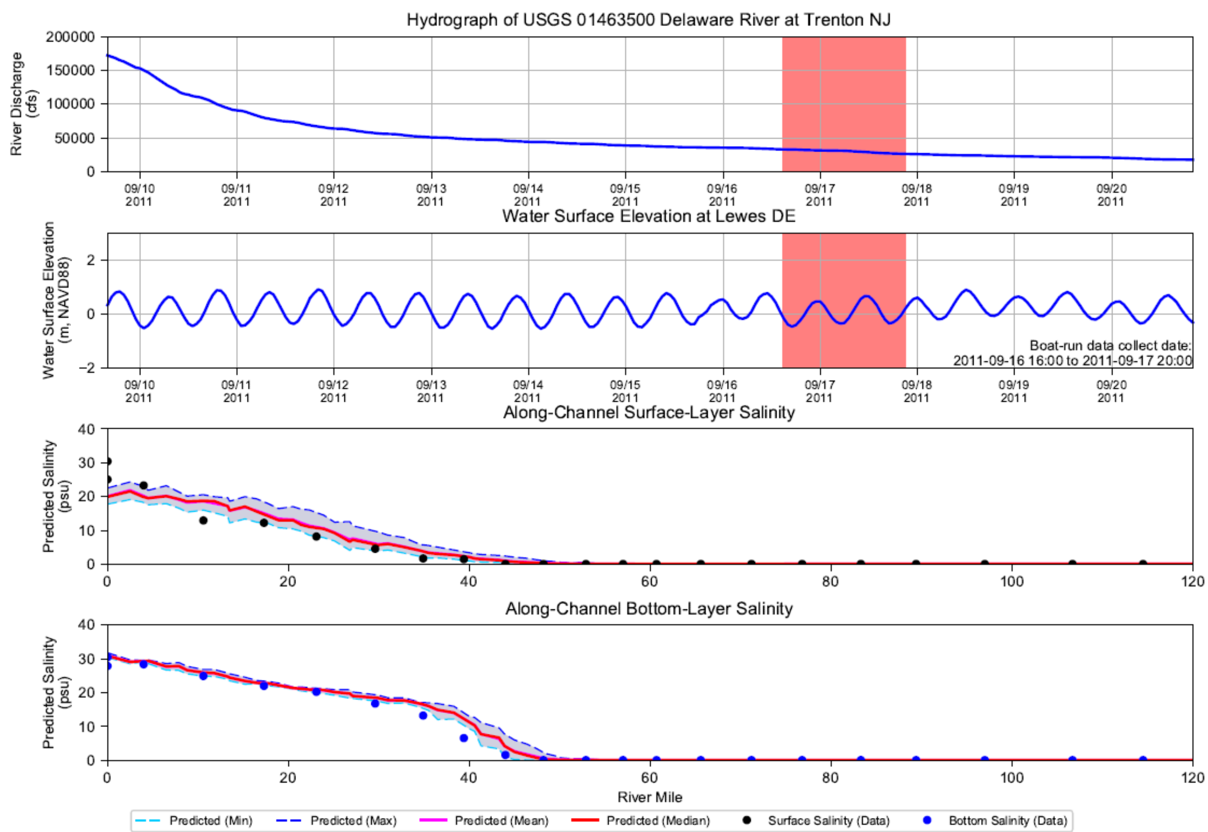
Salinity data collected by boat-run survey were used. Red shaded area indicates the boat run survey time period: 2018-11-07 07:39 to 2018-11-07 10:38. Model results along the navigation channel during period of 2018-11-07 06:39 to 2018-11-07 11:38were used in this analysis.

Figure 4.1-8. Simulated Longitudinal Profile of Salinity in Delaware Estuary.



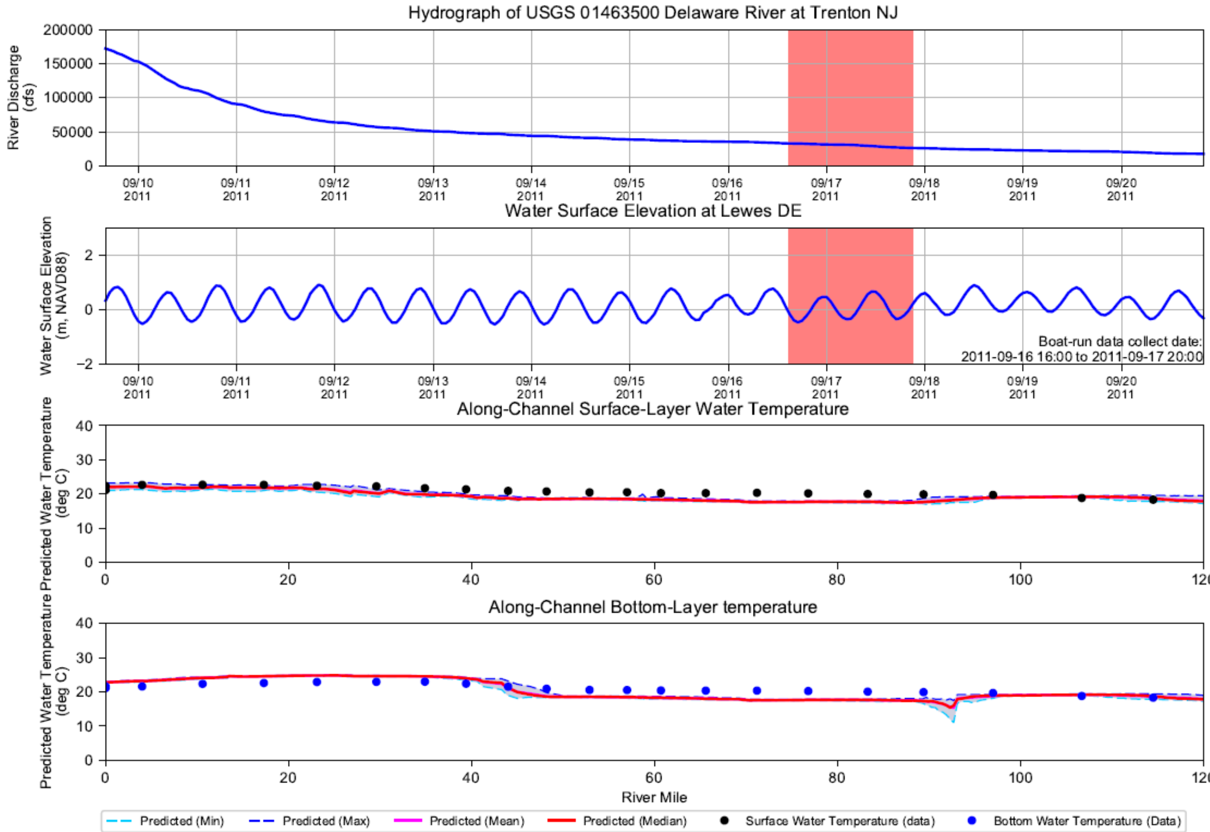
Salinity data collected by boat-run survey were used. Red shaded area indicates the boat run survey time period: 2017-10-09 08:12 to 2017-10-09 11:51. Model results along the navigation channel during period of 2017-10-09 07:12 to 2017-10-09 12:51 were used in this analysis

Figure 4.1-9 Predicted Longitudinal Profile of Salinity and 2011 Survey Data



Notes: 2011 Survey data were provided by Rutgers University to DRBC on June 4th, 2019.Red shaded area indicates the survey time period:2011-09-16 16:00 to 2011-09-17 20:00. Model results along the navigation channel during period of 2011-09-16 15:00 to 2011-09-17 21:00 were used in this analysis.

Figure 4.1-10 Predicted Longitudinal Profile of Water Temperature and 2011 Survey Data



Notes: 2011 Survey data were provided by Rutgers University to DRBC on June 4th, 2019. Red shaded area indicates the survey time period: 2011-09-16 16:00 to 2011-09-17 20:00. Model results along the navigation channel during period of 2011-09-16 15:00 to 2011-09-17 21:00 were used in this analysis.

5. RESULTS

The Salinity model was used to simulate the effects of SLR and test the sensitivity of model results based on the amount of marsh in the model domain. The first set of simulations, the SLR simulations, were performed with the version of the Salinity Model that contained a limited amount of marsh area, (Grid v2.1 - "without marshes"). The second set were performed with the Salinity Model that contained additional marsh area (Grid v4.1 - "with marshes") to evaluate the sensitivity of the model to the amount of marsh area. Freshwater flows used for the simulations were from the prolonged low-flow period of July-October 2002. A low-flow regime was selected because the highest persistent salinities are observed when inflows to the Estuary are low. Results are reported using tidally averaged and depth averaged along-channel salinity profiles and the salt front for the locations relevant to the potential Atlantic Sturgeon spawning habitat in the upper Estuary and the oyster beds in the Bay. For discussion of the Atlantic Sturgeon spawning habitat, the salt front, representing salinity less than 0.5 ppt, was used. Spawning habitat is expected to occur at locations above the salt front. For discussion of the oyster beds, salinity will be used. Unless noted otherwise, the results presented are the tidally averaged and depth-averaged salinity.

5.1 SLR SIMULATIONS

SLR projections of 0 m, 0.5 m, 1.0 m and 1.6 m of SLR, were simulated with 0 m representing the baseline for comparison. Change in the salinity structure can best be demonstrated by comparing the 0 m and 1.6 m SLR cases. Figure 5.1.1 presents a "snapshot" of the salinity structure in the FNC for one time-step in the simulation (3:00 am, October 6, 2020). The salt front, indicated by the 0.45 ppt transition, is approximately 15 miles farther upstream due to tidal amplification. For the baseline SLR of 0 m, the tidal and depth averaged along-channel salinity is 0.5 ppt near RM 85 (Figure 5.1-1). For 0.5, 1.0, and 1.6 m SLR, the salinity is 0.5 ppt, which was averaged over the four-month low-flow period of 2002, farther upstream by approximately 3, 5, and 12 miles, respectively (Figure 5.1-2). The implication is that the available spawning habitat, delineated only based on salinity will be farther upstream, the higher the amount of SLR.

The difference in salinity resulting from SLR is non-linear along the channel. The largest differences occur between RM 45 and RM 55, in the vicinity and upstream of the surveyed oyster beds (between RM 32-49). Figure 5.1-3 presents the differences in salinity with SLR between the tidal and depth averaged along-channel salinity and the tidally averaged near-bottom salinity for each projection. In this zone, the maximum differences in the tidal and depth averaged along-channel salinity are 1.1, 2.2, and 3.7 ppt, for SLR of 0.5, 1, 1.6 m, respectively. The maximum increase in tidally averaged and near-bottom salinity are 1.3, 2.7, 4.3 ppt for SLR of 0.5, 1, 1.6 m, respectively.

In addition to the change in longitudinal salinity structure along the navigation channel, the change in spatial distribution of salinity in the bay area is important. The lower Delaware Bay supports commercially important oyster beds in New Jersey and Delaware state waters and increases in salinity may adversely affect the quality of the habitat and health of the oysters. The spatial distribution of the predicted tidally averaged near bed salinity and the difference from baseline conditions over the four-month low flow period with SLR of 1.6 meter are presented in Figure 5.1-4. The predicted near-bed salinity maximum with SLR of 1.6 meter over the same period is presented in Figure 5.1-5. As in the FNC (Figure 5.1-3), the largest increase (by 1 to 4 ppt) in predicted salinity occurs near RM 45 to 55 by 1 to 4 ppt. Although the salinity may remain in the acceptable range and tolerable for oysters (14 to 28 ppt) with SLR, the taste, quality, and productivity of the oysters may be adversely impacted.

The time-series of the salt front location for the simulation period (July - October 2002) is presented in Figure 5.1-6. The ranges of predicted salt front river mile under various of SLR are provided in Table 5.1-1. For the SLR projections (0.5, 1.0, and 1.6 m), the maximum salt front location was upstream of the confluence of the Delaware and Schuylkill Rivers (RM 92.5).

Table 5.1-1 Range of Salt Front location (River Mile) for Different SLR Projections for the Simulation Period (July – October 2002).

SLR (m)	Min	Max	Average	Difference in the Average from 0 m baseline
0	60.53	89.47	80.69	-
0.5	62.6	93.19	84.18	3.49
1	64.39	97.56	87.83	7.14
1.6	67.14	104.30	93.40	12.71

Simulated salinity over selected oyster beds for 2012, 2013 and 2018 are presented in Appendix A. Simulated salinity distribution in selected oyster bed areas under SLR conditions are presented in Appendix B. Coordinates of oyster bed and water quality stations monitored in 2012-2015 and 2018 were provided in Table 2.2-1.

Simulated near-bottom salinity in the selected oyster bed areas under various SLR conditions and with the 2002 drought hydrology are summarized in Table B.1-1 and B.1-2. Change in the average salinity over four-month drought period with 0.5-meter SLR in three oyster beds, Ridge, Cohansey, and Hope Creek are 0.5, 1.1, and 1.0 ppt, respectively. Change in the average salinity over four-month drought period with 1.0-meter SLR in three oyster beds, Ridge, Cohansey, and Hope Creek are 1.2, 2.3, and 2.3 ppt, respectively. Change in the average salinity over four-month drought period with 1.6-meter SLR in three oyster beds, Ridge, Cohansey, and Hope Creek are 2.0, 3.8, and 3.9 ppt, respectively.

Hope Creek, just south of Artificial Island, is in low salinity water (5-15 ppt) region and is affected the most with the SLR in terms of both the absolute amount and relative percentage. Restricted by the geometry of the bay, the extent of area available shrinks for the affected low-salinity type of oyster bed might migrate further upstream. The oyster bed that located closer to the mouth of the bay may not affected very much, such as Ridge area. Those oyster bed usually experienced moderate salinity water (15-25 ppt), and the relative increase in salinity in Ridge bed ranged from 1.2 to 2.6 ppt with 0.5 m to 1.6 m SLR. The relative change in salinity is smaller compared to the relative change of salinity in oyster bed located farther upstream. The simulated salinity change in selected oyster bed areas are presented in Figure B.1-1 and B.1-2 as well as in Figure B.1-3 and B.1-5. The change in near-bed salinity for given habitat area is almost linearly with the SLR (shown in Figure B.1-5). The rate of increase with SLR tends to be slower at locations in the upstream tidal river portion of the estuary such as near Chester Island and Marcus Hook area.

5.2 Marsh Sensitivity Simulations

Much of the area along the coast of the Delaware Bay is considered tidal wetland and extends up to several kilometers inland. Near-shore low-lying marsh areas are flooded twice per day, where the elevation of the area is between the mean tide level and mean high water. With sea level rise, additional low-lying marsh areas are likely to be inundated more frequently. Both SLR and marsh inundation contribute to increase of tidal prism[15], which leads to a stronger salinity intrusion. Meanwhile, when the water flows into the marsh area, energy is lost due to the increase in drag friction. The larger the marsh area inundated and the frequency of inundation, the more energy is attenuated over the marsh areas from frictional drag, and less energy is available to propagate the tidal wave upstream. Moreover, the amplification caused by shoreline convergence (narrowing of the channel) is reduced. The sensitivity to amount of marsh area represented by the model is important because tidal forcing is one of the primary drivers of salinity transport.

Grid 4.1 (“with marshes”), a variation of Grid 2.1 (“without marshes”) that includes additional low-lying marsh area, represents a scenario in which the sediment load does not keep pace with sea level rise when the current bed elevation in marshes was used. The status of the salt marsh and the elevation change was reported by NJDEP (2020)[16]. Field observations (NJDEP SEB, 2020) indicate the sediment deposition rate in the marshes along the New Jersey side of the Delaware Bay is approximately the same rate of the current SLR. The rate of net bed elevation change in some marsh areas ranged from 1.19 to 6.89 mm/year and a rough estimate of the mean elevation change rate is 4.0 mm/year, which is just approximately the same or slightly greater than the current local SLR rate at the mouth of the Delaware bay (3.5 mm/year). Whereas Grid v2.1 represents scenarios that include shoreline protection measures (hard protection) or it may be possible that the net sedimentation rate will keep pace with the rate of SLR. It is more conservative to use the simulations with marsh excluded (e.g., “hard protection”) assumption under SLR conditions because the model will tend to over-estimate the salinity intrusion in the estuary. Simulations using G2.1 and G4.1 will provide a bounding estimation under future SLR conditions.

5.2.1 Sensitivity for Existing Conditions

With the additional marsh area included simulation of “wet-and-drying” process to reflect the wetting during the tidal flooding period and drying during the tidal ebbing period. Overall, under SLR conditions, more saline water from the ocean enters the estuary when marsh area is included. However, the loss of energy reduces the tidal force pushing saltwater upstream relative

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[15] The tidal prism is the amount of water that flows into and out of an estuary with the flood and ebb of the tide by removing the river freshwater contribution. It may be estimated by the water volume between mean high tide and mean low tide.

[16] NJDEP SAB (2020): Final Report the Status and Future of Tidal Marshes in New Jersey Faced with Sea Level Rise. https://dep.nj.gov/wp-content/uploads/sab/sab-salt-marsh.pdf

to the freshwater inflows. Simulations were performed using both grids using the same bathymetry and a 40 ft channel and hydrology from the year 2001-2002 to reflect the actual conditions during that time. Inclusion of the additional marsh area resulted in minor differences in the predicted SF RM. The range of the SF RM is 58.3 – 85.6 “without marshes” and is 59.0 – 85.1 “with marshes”.

For this study, the marsh simulations are for the testing of model sensitivity to marsh areas. For common features in both models, the same parameters were used. With additional resources, the model with marshes included (Grid v4.1) will be refined. For example, if hydrodynamic data from marsh areas become available (if collected), other parameters such as bottom roughness height could be better estimated and used, rather a universal value.

5.2.2 Marsh Area and SLR

Comparisons of the simulated tidally averaged longitudinal salinity profiles for SLR and the four-month dry period of 2002 inflows are presented in Figure 5.2-1. The salinity intrusion was not as far upstream with marsh areas included. The difference is more pronounced for SLR of 1.0 m and 1.6 m, than for 0.5 m. The differences in predicted salinity with and without marshes are shown in Figure 5.2-2. With marshes the impact on salinity is less. However, the zone of maximum difference is from RM 50 (without marsh) to RM 60 (with marsh) and the maximum increase in salinity is 1.5 and 2.2 ppt for 1.0 m and 1.6 m SLR conditions, respectively.

The predicted SF RM minimums, maximums, and averages for July through October 2002 are provided in Table 5.2-1. The time-series of the predicted SF RM is shown in Figure 5.2-3. The maximum salinity intrusion with and without marshes for SLR of 1.0 and 1.6 m are presented in Figure 5.2-4. With marsh areas, the maximum difference in salinity intrusion (SF RM) was 0.9, 3.1, and 4.7 less for SLR of 0.5, 1.0 and 1.6 m, respectively. The predicted SF RM becomes more sensitive to the marsh inundation if SLR is above one meter (Figure 5.2-5).

Table 5.2-1 Range of Salt Front for Different SLR under 2002 Low-Flow Conditions, Grid v2.1 (marsh excluded) vs. Grid v4.1 (marsh included)

SLR (m)	Min	Max	Average
0	60.53 / 60.75	89.47 / 88.95	80.69 / 80.44
0.5	62.60 / 62.74	93.19 / 92.26	84.18 / 83.45
1.0	64.39 / 63.84	97.56 / 94.45	87.83 / 85.68
1.6	67.14 / 66.09	104.3 / 99.65	93.4 / 89.20

Left/Right = left is model result without marshes, and right is model result with marshes.
Note: SLR 0m was the baseline.

The spatial distribution of the predicted tidally averaged near-bottom salinity under SLR of 1.6 m and the difference with respect to baseline case are presented in Figure 5.2-6. Spatial distribution of predicted maximum near-bottom salinity under SLR of 1.6 m. The difference with respect to the baseline are presented in Figure 5.2-7. Most areas experienced salinity increases of 1 to 3 ppt for SLR of 1.6m.

Figure 5.1-1 A Snap-shot of Simulated Salinity Profile in the Federal Navigation Channel, 0 m SLR vs. 1.6 m SLR

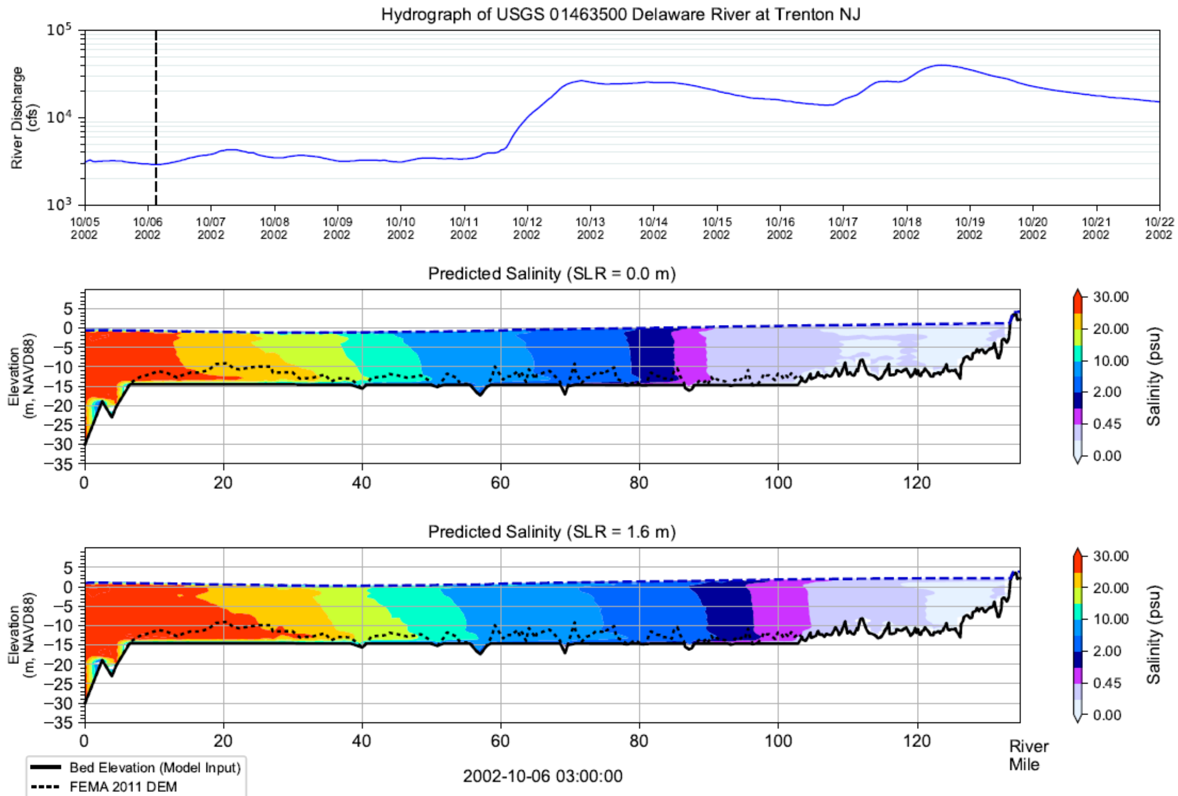


Figure 5.1-2 Tidally-Averaged Depth-Average Salinity Profiles under 2002 Low-flow Conditions

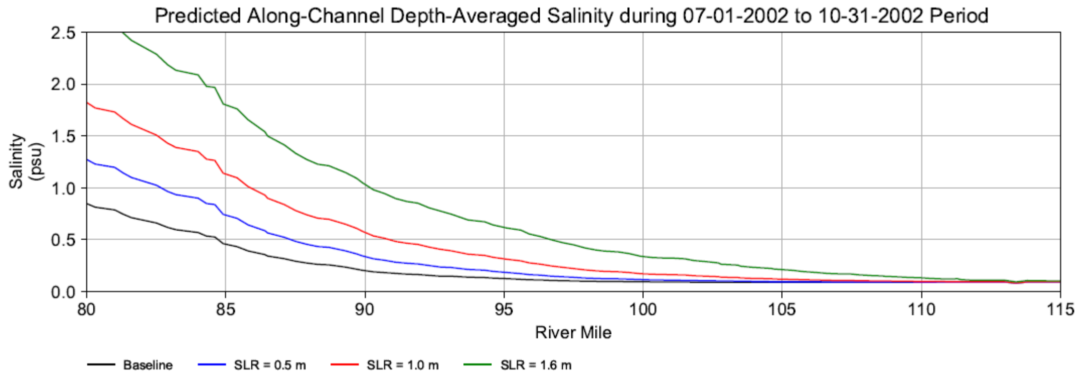


Figure 5.1-3 Relative change in tidally-averaged salinity profile under 2002 Low-flow Conditions

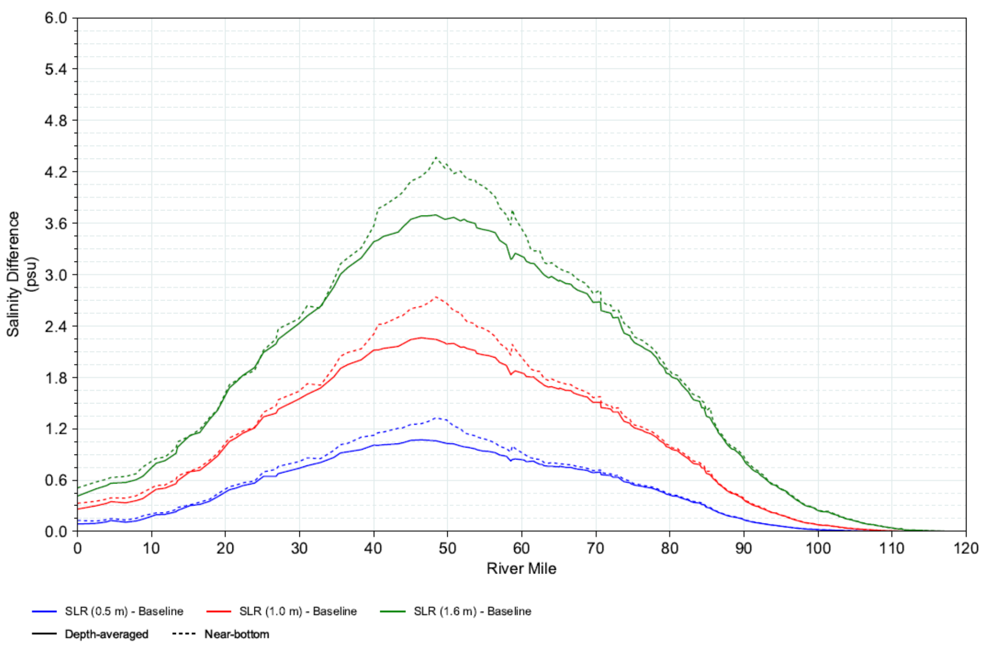


Figure 5.1-4 Predicted Tidally averaged Near-bottom Salinity over a Four-month Dry Flow Period. Inflows from July through October 2002 were applied, Grid v2.1 (Marsh Excluded)

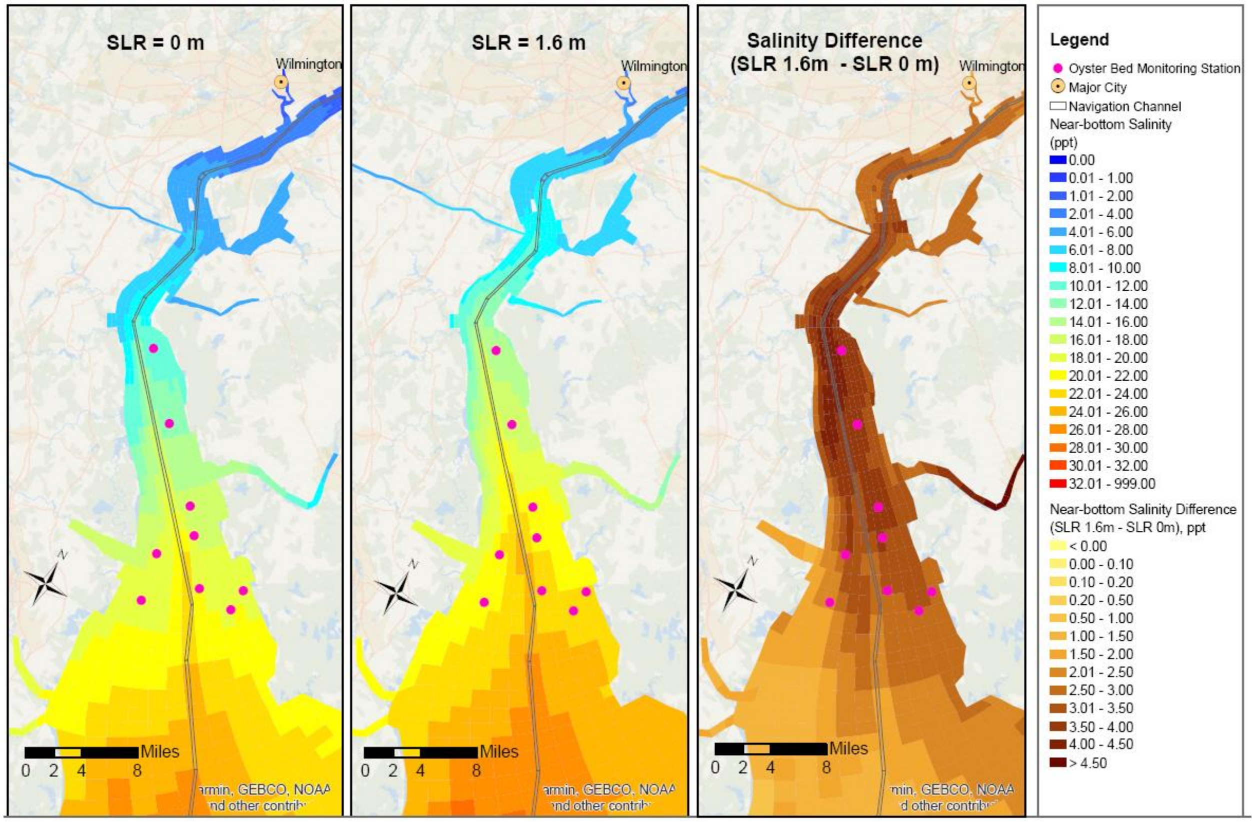


Figure 5.1-5 Predicted Near-bottom Salinity Maximum over a Four-month Dry Flow Period. Inflows from July through October 2002 were applied, Grid v2.1 (Marsh Excluded)

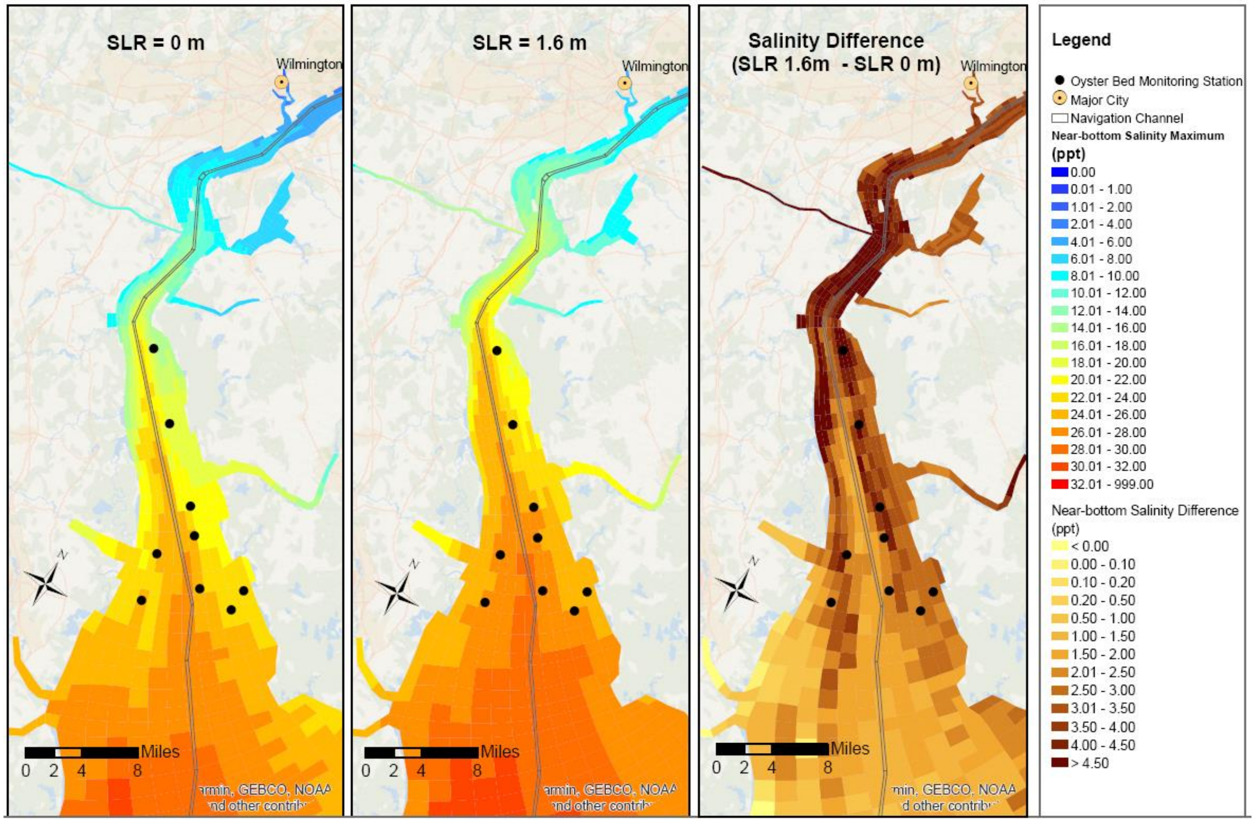


Figure 5.1-6 Time history of the Salt Front Location under 2002 Low-flow Conditions

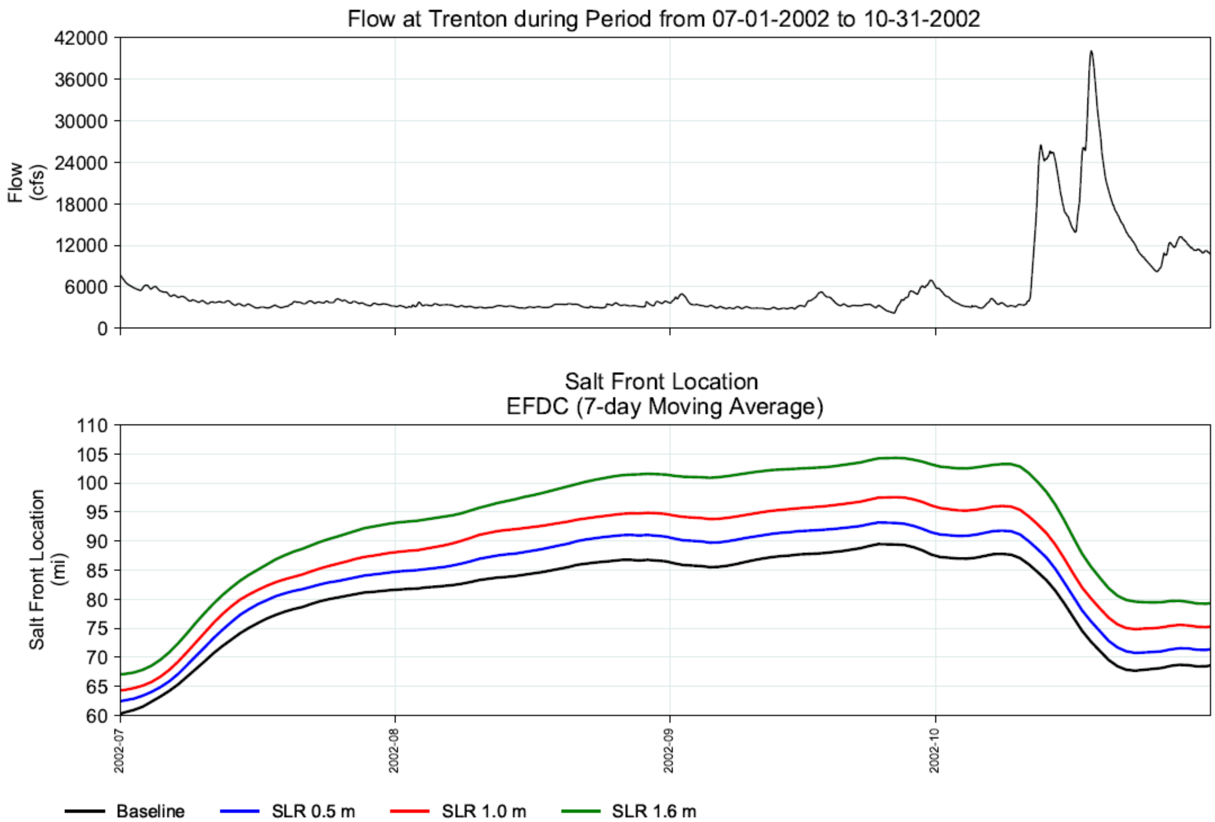


Figure 5.2-1 Comparisons of the Simulated Tidally-averaged Longitudinal Salinity Profiles from Various of SLR Scenarios with 2002 Dry Flow Conditions, Grid v2.1 (Marsh Excluded) vs. Grid v4.1 (Marsh Included)

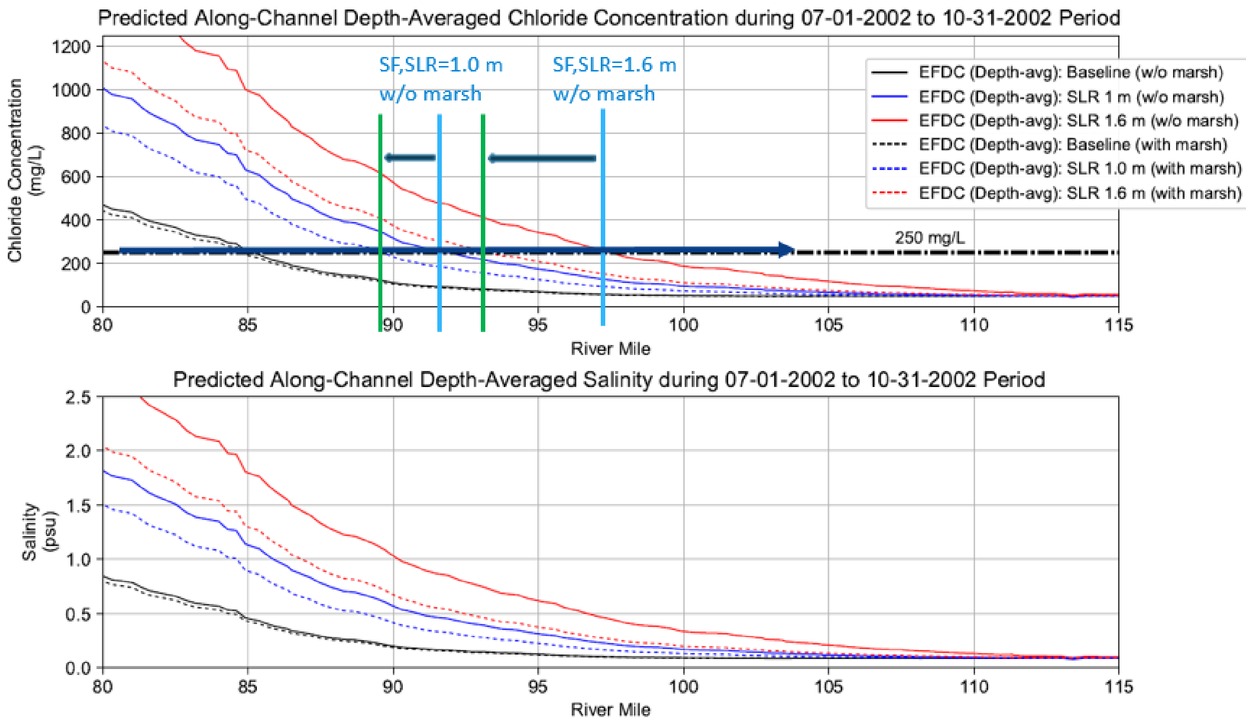


Figure 5.2-2 Comparisons of the Impact on Salinity Distribution from Various of SLR Scenarios with 2002 Dry Flow Conditions, Grid v2.1 (Marsh Excluded) vs. Grid v4.1 (Marsh Included)

Notes: The impact from the SLR on salinity transport is evaluated through the tidally averaged longitudinal salinity profile over a four-month dry flow period, in which inflow from July through October 2002 period was applied in combination of various of SLR conditions. The change in tidally averaged salinity profile along the navigation channel from the baseline case is shown. The area where experienced highest salinity increase is defined as the zone of maximum impact.

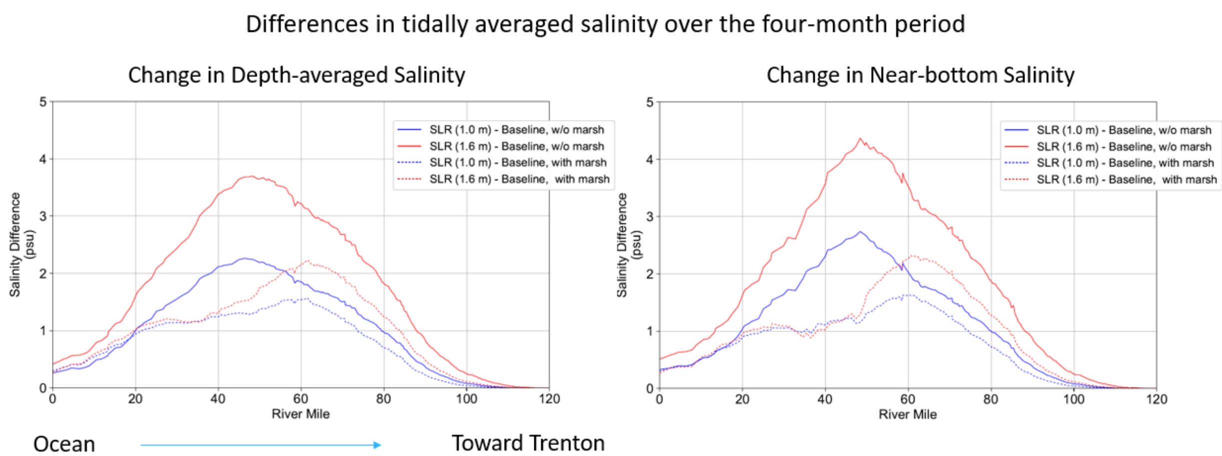


Figure 5.2-3 Comparisons of the Time History of Simulated Salt Front Location under 2002 Dry Flow Conditions, Grid v2.1 (Marsh Excluded) vs. Grid v4.1 (Marsh Included)

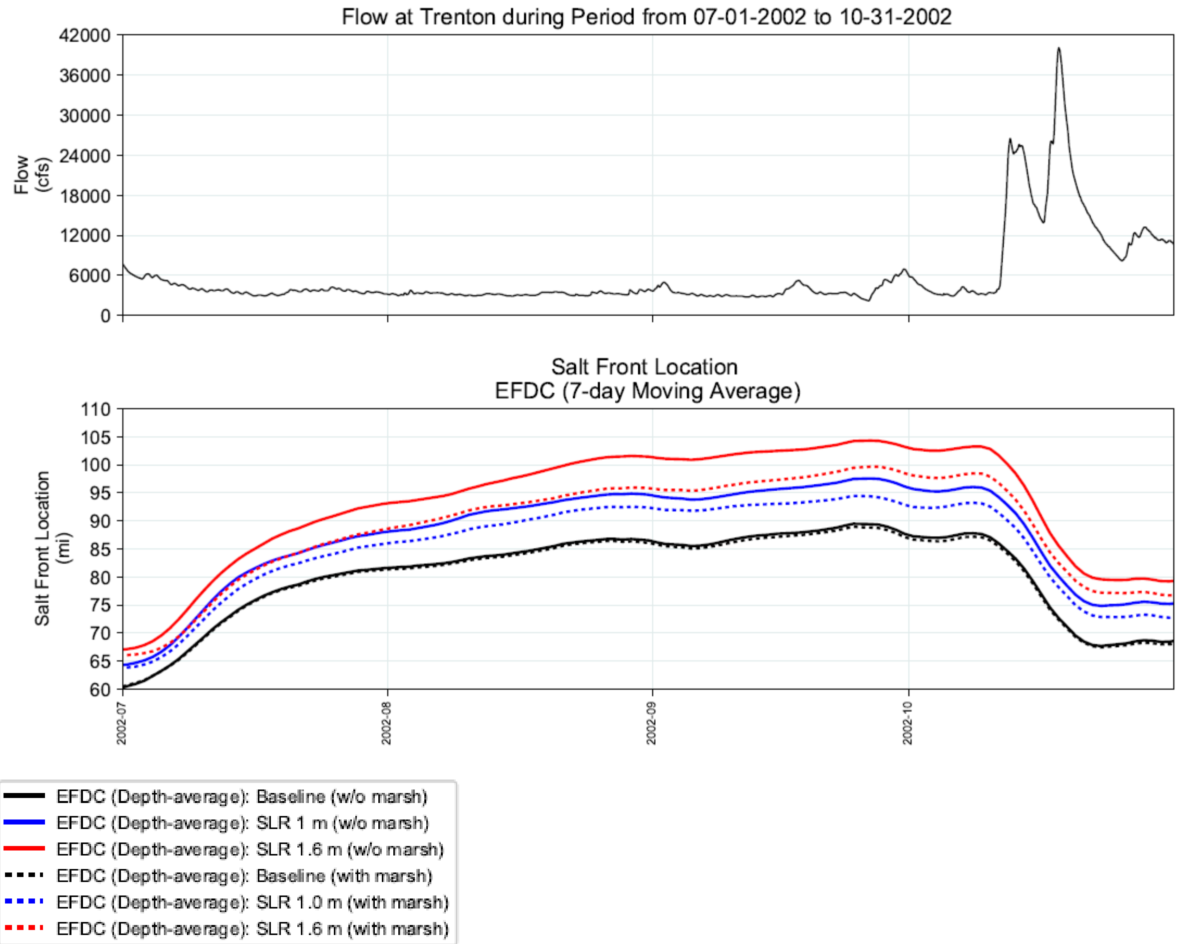


Figure 5.2-4 Comparisons of Simulated Maximum Location of the Salt Front under 2002 Dry Flow Conditions, Grid v2.1 (Marsh Excluded) vs. Grid v4.1 (Marsh Included)

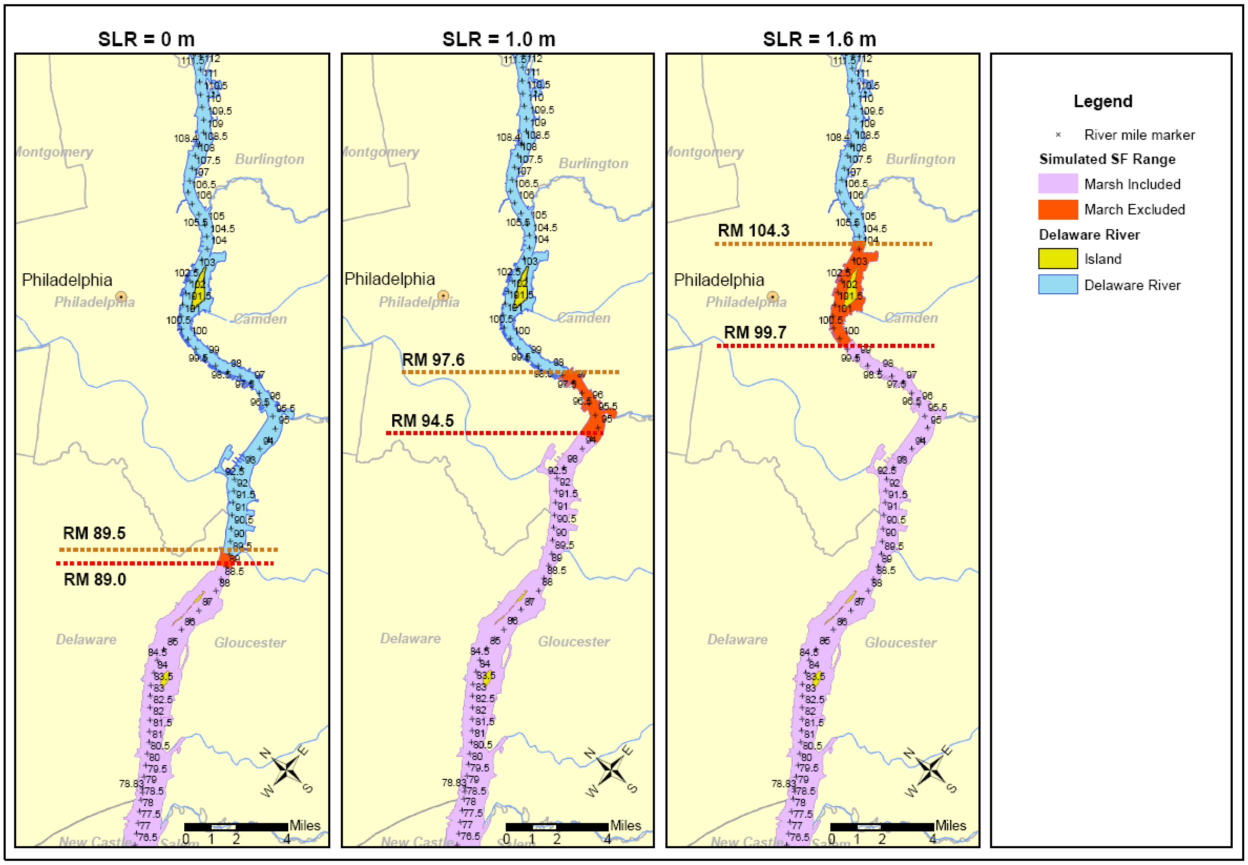
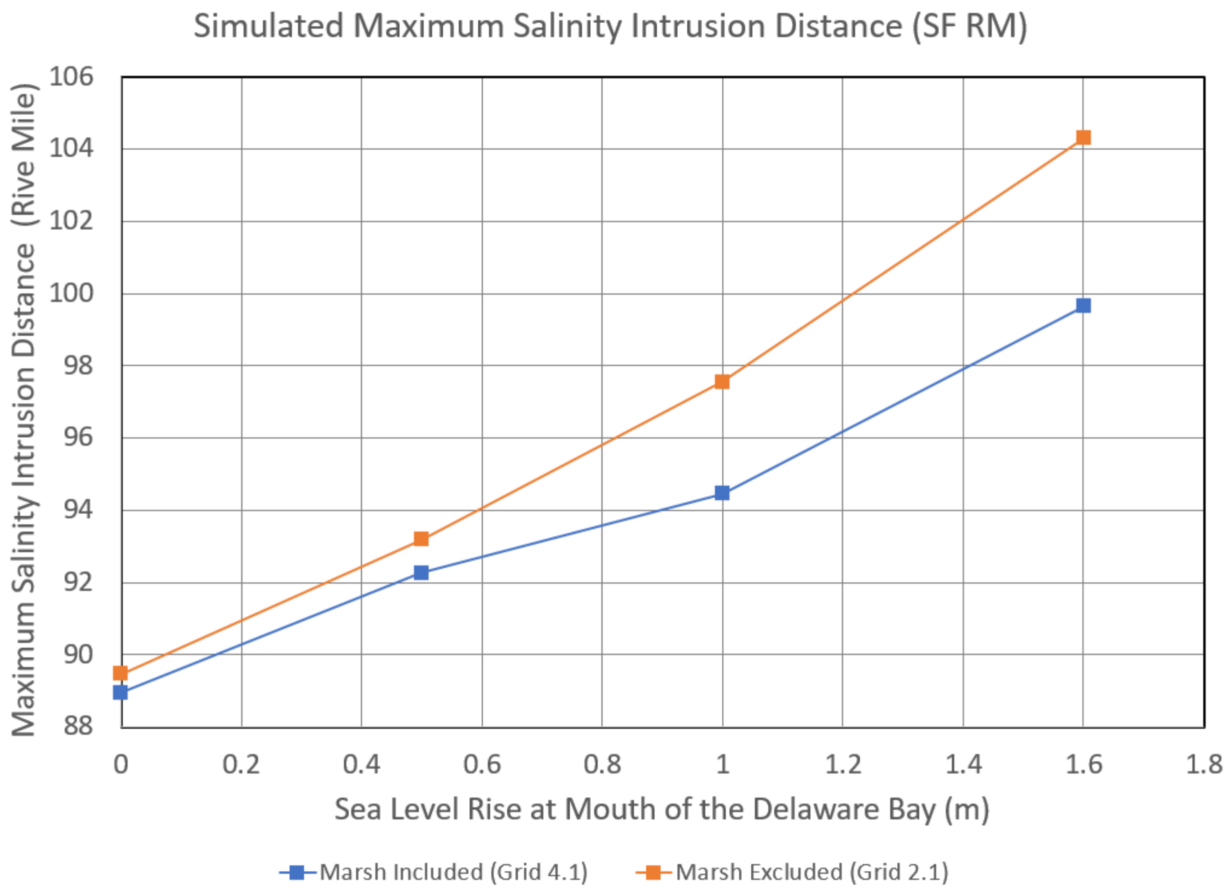


Figure 5.2-5 Comparisons of Simulated Maximum Location of the Salt Front under 2002 Dry Flow Conditions, Grid v2.1 (Marsh Excluded) vs. Grid v4.1 (Marsh Included)



6. SUMMARY

The quality of aquatic habitat for both the endangered Atlantic Sturgeon and oyster population depends, in part, upon salinity. Suitable spawning habitat for Atlantic Sturgeon is typically found in areas with low salinity (much less than 0.5 ppt). Other factors also affect the quality of habitat, and it is unclear which are limiting.

DRBC's salinity model was used to simulate the impacts of SLR on salinity. The model adequately reproduces the observed tidal water surface elevations, current velocity, water temperature and salinity. The calibration results indicate that the model has good performance and is suitable to assess the impact from SLR in selected key habitat areas for the Atlantic sturgeon and oysters.

A representative dry period (July-October 2022) was simulated because the highest values and most upstream location of the salt front occur during dry years and low flow conditions. Simulations indicate that SLR has a significant effect on salinity intrusion and reduces the suitable habitat for Atlantic Sturgeon spawning and oyster beds, in the upper tidal-river and Bay. As sea level rises, the changes to estuary hydrodynamics become more conducive to salinity transport. As the salinity distribution changes, Atlantic sturgeon spawning habitat area is likely experience higher salinity under the conditions of persistent low flows and SLR. The oyster populations may be more vulnerable to disease or experience changes in taste. Major findings from the simulations are summarized with respect to 2002 dry weather flows as follows:

- SLR is likely to cause an increase in salinity and its persistence (frequency and duration), which may affect the quality, location, and abundance of suitable habitats for Atlantic Sturgeon spawning and oyster populations.
- Simulations with limited marsh area ("without marshes"), indicate that salinity intrusion will occur farther upstream with SLR. With low flows similar to 2002, the maximum salinity intrusion may reach to RM 93.3, 97.6, 104.3, and 108.3 with SLR of 0.5, 1.0, and 1.6, respectively.
- The "with marshes" simulations result in salinity intrusion that is less severe than the "without marshes' simulations under low flow conditions. The "with marshes" simulations indicate that the maximum salinity intrusion may reach to RM 92.3, 94.5 and 99.7 with SLR of 0.5, 1.0, and 1.6 meters, respectively".
- The largest increase in predicted salinity (zone of maximum impact) from SLR (0.5-1.6 m) occurs near RM 45 to 55 with maximum increase in near bed salinity from 2 to 4 ppt "without marshes" and from 1 to 3 ppt "with marshes". The maximum salinity increase in the upper bay area.
- The "with marshes" simulations demonstrate that the zone of the maximum change in salinity is closer to RM 60, compared with the "without marshes" simulation (RM 50). This indicates that SLR may have significant impact on the health of the oyster habitats upstream of Ship John Shoal area.

The Salinity Model is a "living" model and, as time and resources allow, will be updated with new information to refine its predictive ability. Data are now becoming available to test additional assumptions and boundary conditions needed to simulate sea level. One example is the net flow from Chesapeake Bay to Delaware Estuary through the C&D Canal under future SLR conditions. USGS has established a new monitoring station inside the C&D Canal and began collecting data in late 2019[17]. In addition, the USGS established a monitoring station at Delaware Memorial Bridge.[18]. The new data from this station, including the current velocity, flow, water temperature and specific conductance, will provide more detailed information along the river for model testing.

[17] USGS Station in C&D Canal (01482695) https://waterdata.usgs.gov/nwis/uv?site_no=01482695

[18] USGS Station at Delware Memorial Bridge (01482100) https://waterdata.usgs.gov/nwis/uv?site_no=01482100

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Appendix A: Simulation Results for Salinity Over Selected Oyster Bed Areas For 2012, 2013, 2018

A.1 Model Results for 2012 Monitoring Period

Figure A.1-1 Time History of Observed and Predicted Daily-averaged Near Bed Salinity at Oyster Bed Monitoring Site at Ridge during June through November 2012 Period

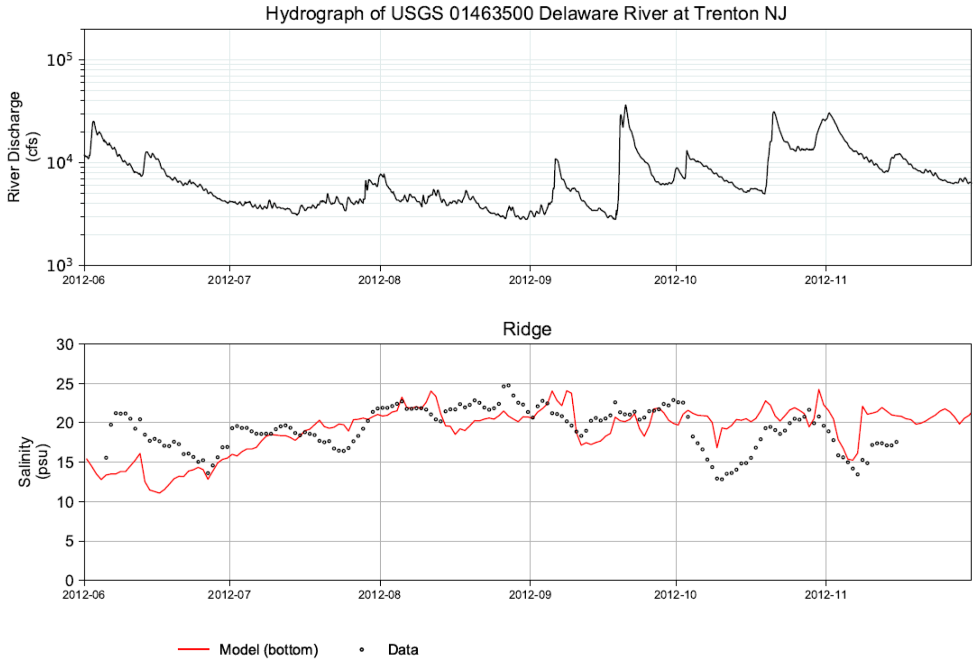


Figure A.1-2 Time History of Observed and Predicted Daily-averaged Near Bed Salinity at Oyster Bed Monitoring Site at Cohansey during June through November 2012 Period

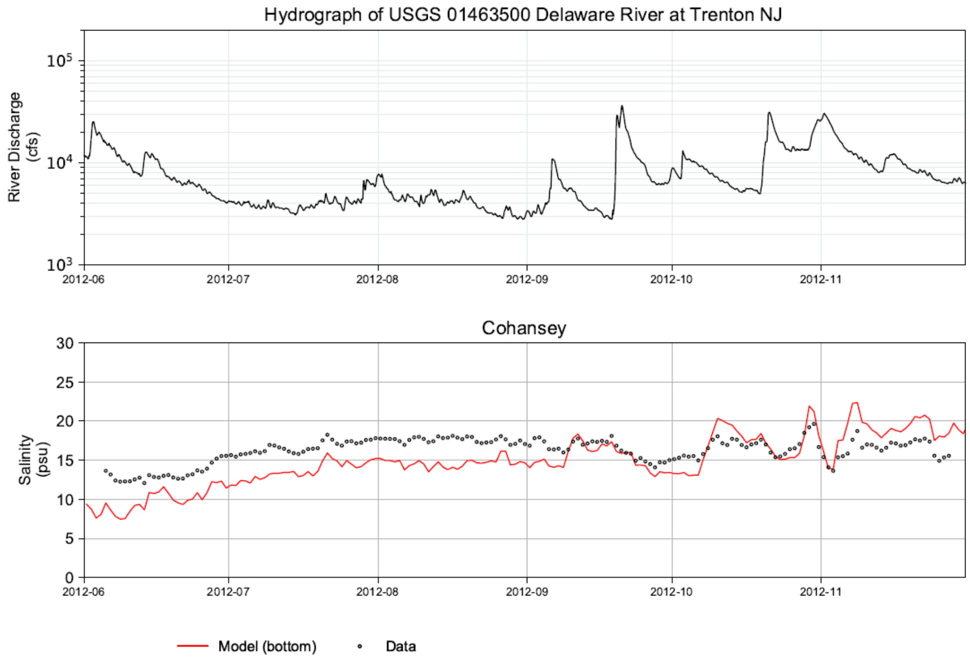


Figure A.1-3 Time History of Observed and Predicted Daily-averaged Near Bed Salinity at Oyster Bed Monitoring Site at Hope Creek during June through November 2012 Period

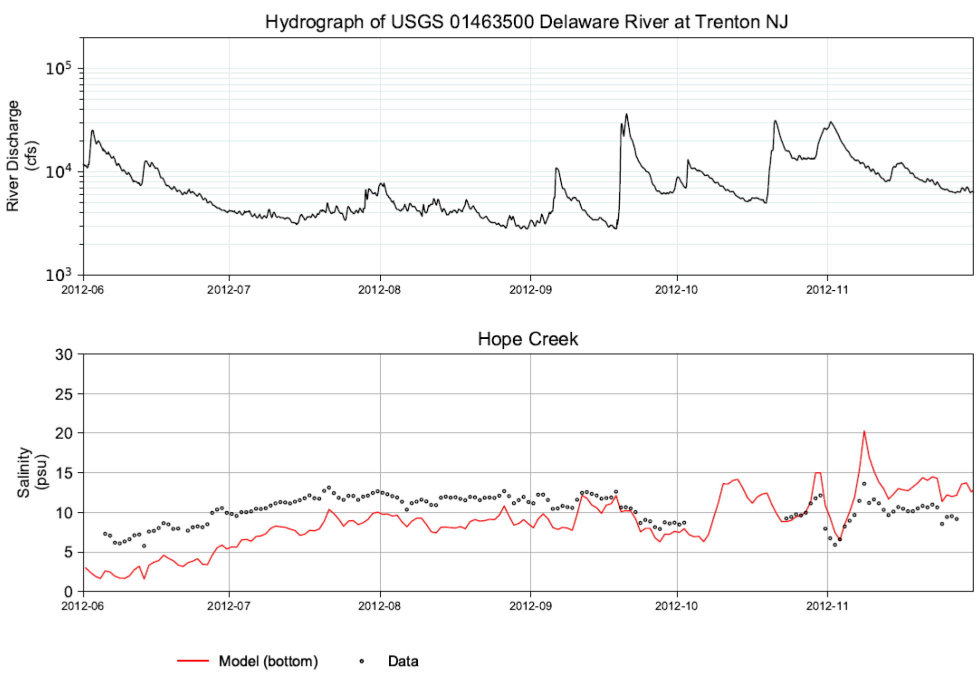


Figure A.1-4 Comparison of Observed and Predicted Daily-averaged Near Bed Salinity Distributions at Nine Oyster Bed Monitoring Sites during June through November 2012 Period

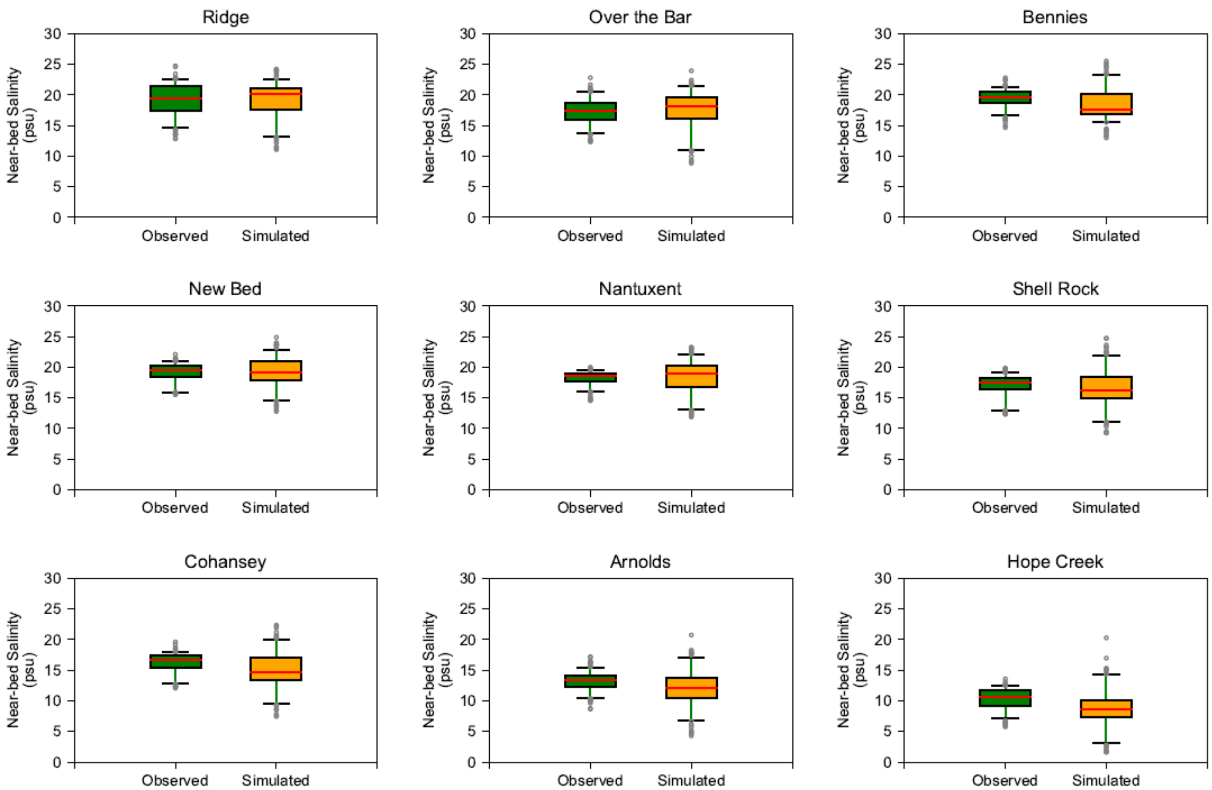


Table A.1-1 Summary of Observed and Predicted Daily-averaged Near Bed Salinity at Nine Oyster Bed Monitoring Sites during June through November 2012 Period

STATION	STATION ID	NOBS	Data Mean	Model Mean	Data Median	Model Median	DATA STDEV	Model STDEV	Bias
Ridge	RID	164	19.2	19.1	19.4	20.1	2.6	3.0	-0.1
Over the Bar	OTB	159	17.3	17.4	17.4	18.2	2.1	3.1	0.2
Bennies	BEN	161	19.5	18.5	19.6	17.6	1.5	2.5	-1.0
New Bed	NEW	175	19.2	19.1	19.6	19.2	1.5	2.6	-0.1
Nantuxent	NAN	175	18.3	18.4	18.6	19.0	1.1	2.7	0.2
Shell Rock	SR	175	17.0	16.6	17.4	16.2	1.8	3.1	-0.4
Cohansey	COH	176	16.2	14.9	16.7	14.7	1.6	3.1	-1.3
Arnolds	ARN	176	13.2	12.1	13.3	12.1	1.5	3.1	-1.1
Hope Creek	HC	155	10.4	8.6	10.7	8.6	1.8	3.2	-1.7

A.2 Model Results for 2013 Monitoring Period

Figure A.2-1 Time History of Observed and Predicted Daily-averaged Near Bed Salinity at Oyster Bed Monitoring Site at Ridge during April through November 2013 Period

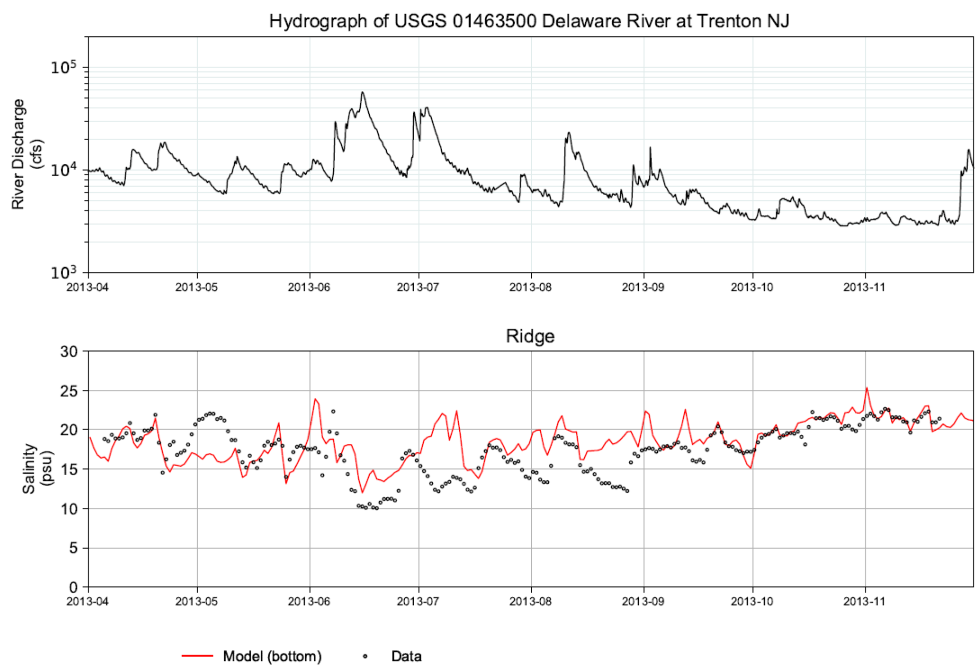


Figure A.2-2 Time History of Observed and Predicted Daily-averaged Near Bed Salinity at Oyster Bed Monitoring Site at Cohansey during April through November 2013 Period

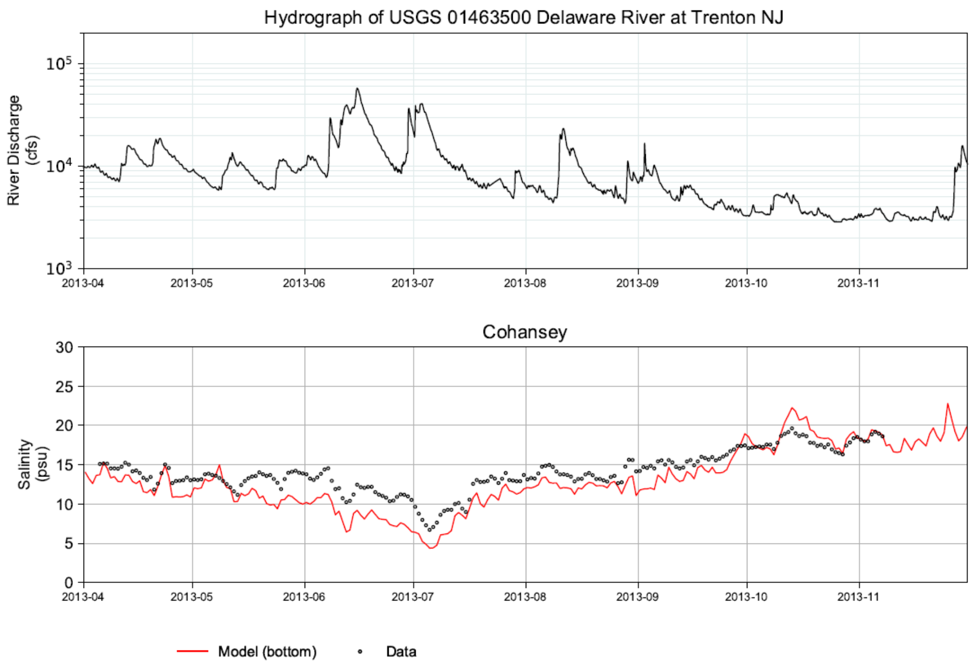


Figure A.2-3 Time History of Observed and Predicted Daily-averaged Near Bed Salinity at Oyster Bed Monitoring Site at Hope Creek during April through November 2013 Period

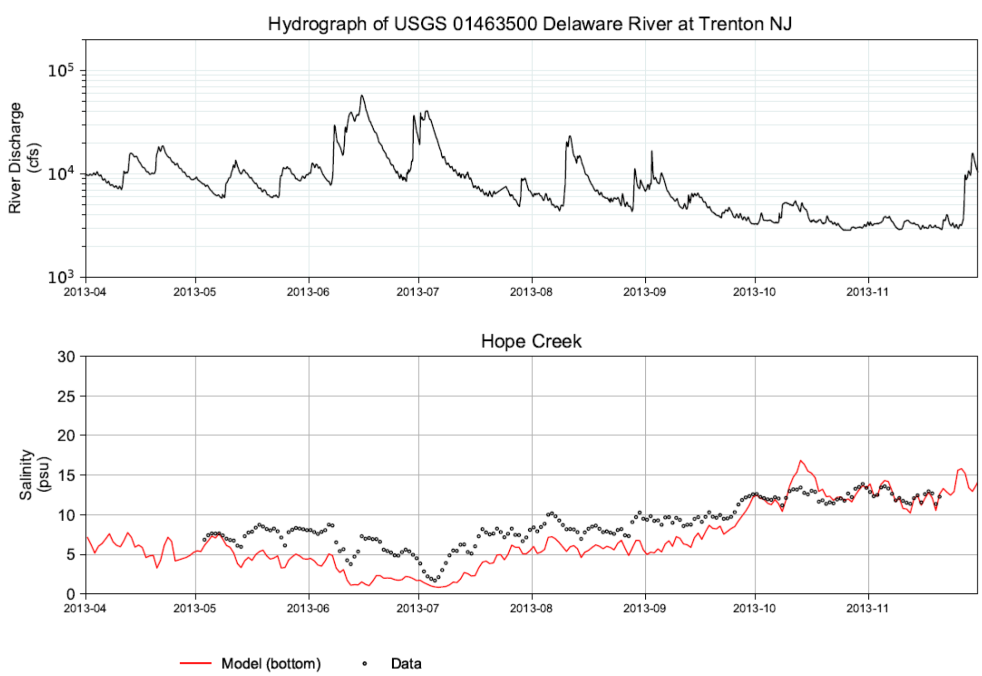


Figure A.2-4 Comparisoon of Observed and Predicted Daily-averaged Near Bed Salinity Distributions at Nine Oyster Bed Monitoring Sites during April through November 2013 Period

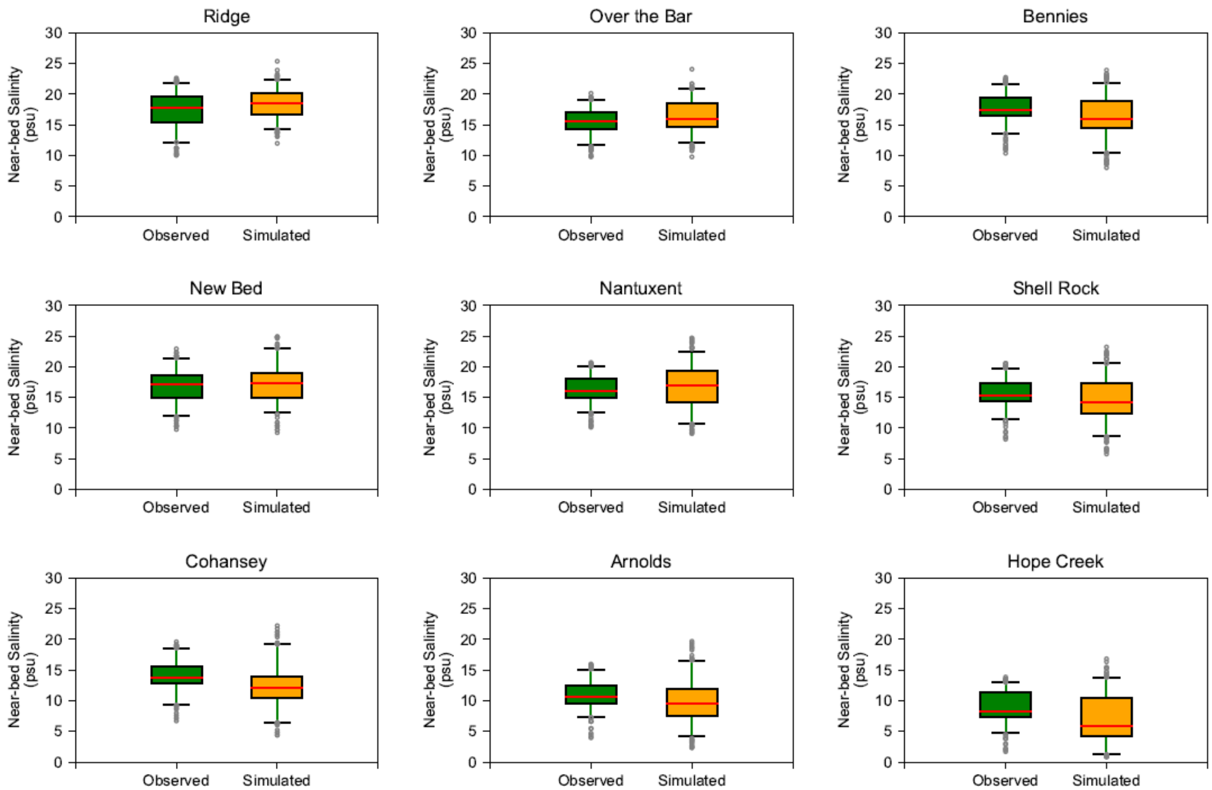


Table A.2-1 Summary of Observed and Predicted Daily-averaged Near Bed Salinity at Nine Oyster Bed Monitoring Sites during April through November 2013 Period

STATION	STATION ID	NOBS	Data Mean	Model Mean	Data Median	Model Median	DATA STDEV	Model STDEV	Bias
Ridge	RID	231	17.4	18.5	17.7	18.5	3.1	2.5	1.1
Over the Bar	OTB	231	15.6	16.4	15.6	16.0	2.2	2.7	0.8
Bennies	BEN	231	17.7	16.4	17.4	16.0	2.5	3.4	-1.4
New Bed	NEW	216	16.8	17.2	17.2	17.4	2.7	3.2	0.4
Nantuxent	NAN	229	16.4	16.8	16.1	17.0	2.3	3.5	0.5
Shell Rock	SR	224	15.5	14.6	15.2	14.2	2.5	3.7	-0.9
Cohansey	COH	217	14.0	12.6	13.8	12.1	2.6	3.7	-1.4
Arnolds	ARN	230	11.0	9.9	10.7	9.5	2.4	3.9	-1.1
Hope Creek	HC	202	8.8	6.8	8.3	5.9	2.7	4.0	-2.0

A.3 Model Results for 2018 Monitoring Period

Figure A.3-1 Time History of Observed and Predicted Daily-averaged Near Bed Salinity at Oyster Bed Monitoring Site at Ridge during June through December 2018 Period

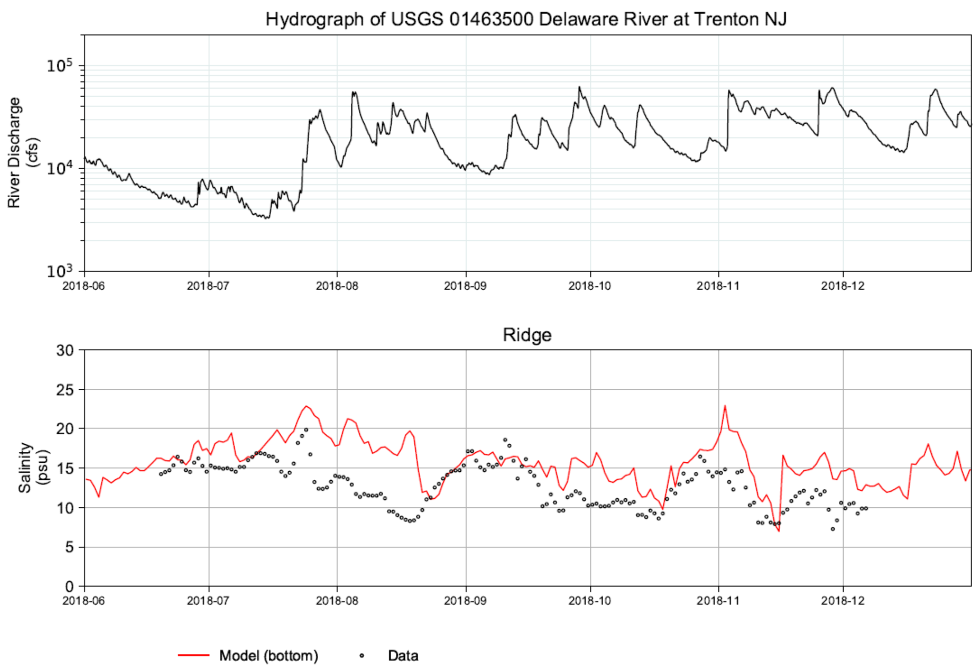


Figure A.3-2 Time History of Observed and Predicted Daily-averaged Near Bed Salinity at Oyster Bed Monitoring Site at Cohansey during June through December 2018 Period

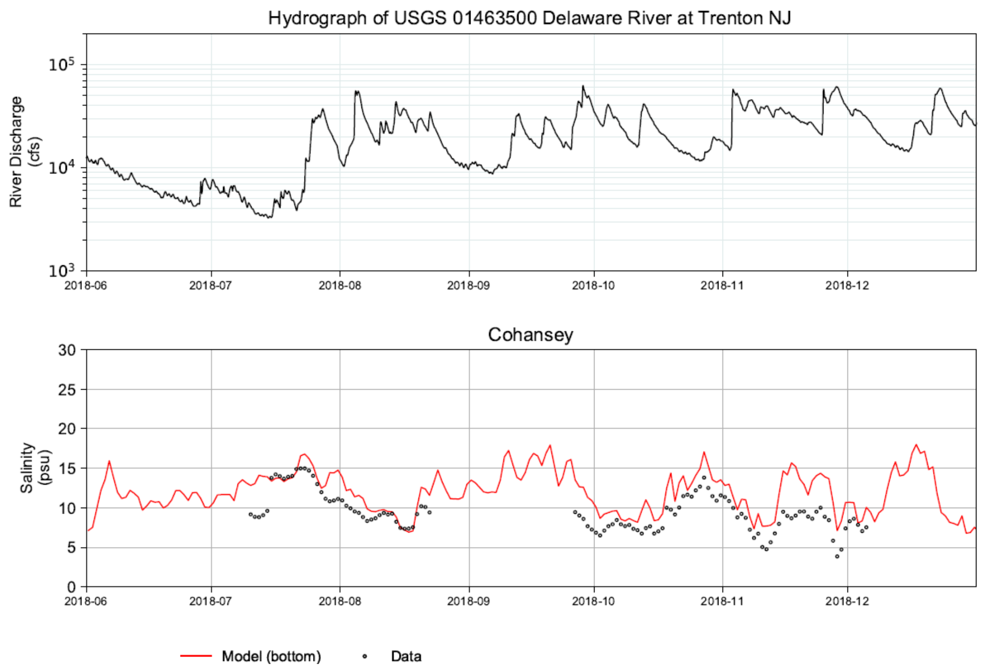


Figure A.3-3 Time History of Observed and Predicted Daily-averaged Near Bed Salinity at Oyster Bed Monitoring Site at Hope Creek during June through December 2018 Period

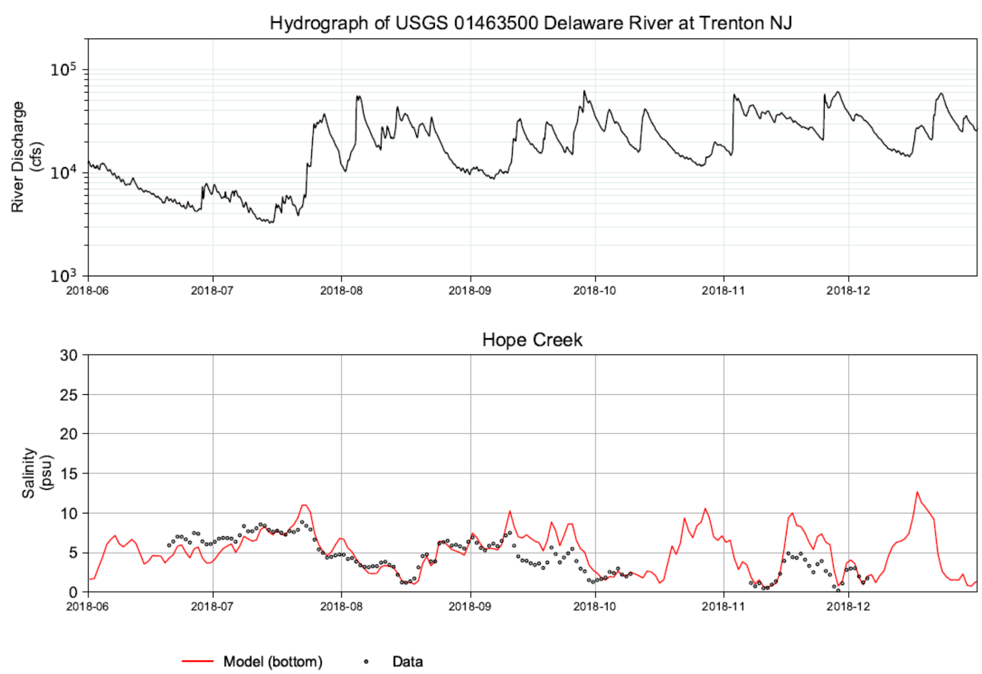


Figure A.3-4 Comparison of Observed and Predicted Daily-averaged Near Bed Salinity Distributions at Nine Oyster Bed Monitoring Sites during June through December 2018 Period

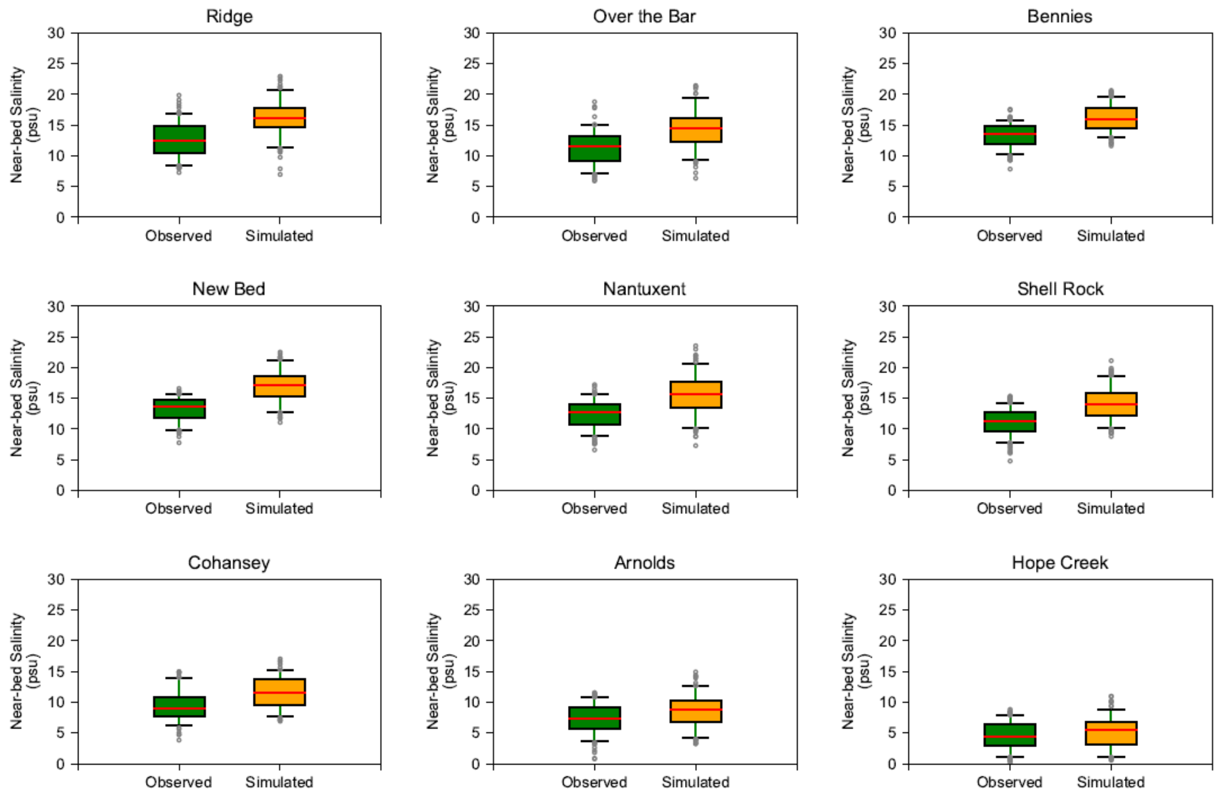
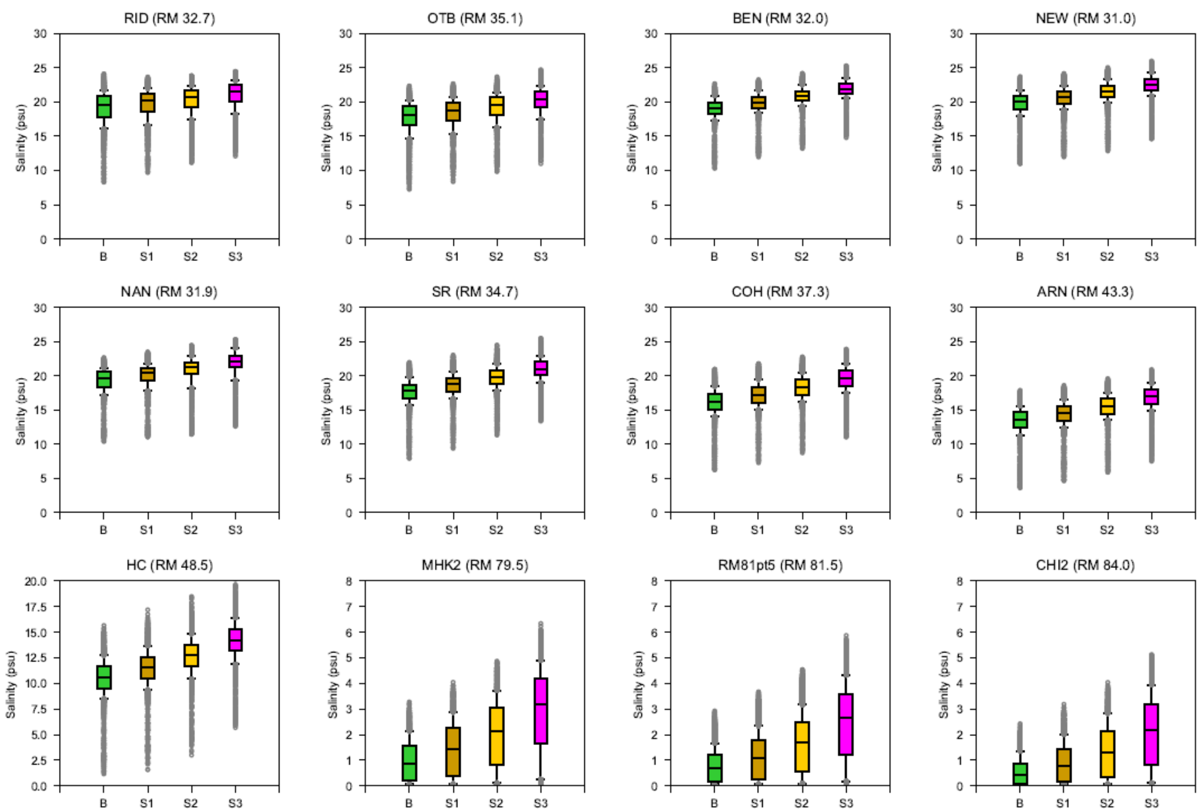


Table A.3-1 Summary of Observed and Predicted Daily-averaged Near Bed Salinity at Nine Oyster Bed Monitoring Sites during June through December 2018 Period

STATION	STATION ID	NOBS	Data Mean	Model Mean	Data Median	Model Median	DATA STDEV	Model STDEV	Bias
Ridge	RID	171	12.7	16.0	12.5	16.2	2.7	2.8	3.3
Over the Bar	OTB	119	11.3	14.3	11.5	14.4	2.7	3.0	3.0
Bennies	BEN	144	13.3	16.2	13.5	16.0	1.9	2.1	2.9
New Bed	NEW	130	13.3	17.1	13.6	17.2	1.8	2.5	3.8
Nantuxent	NAN	170	12.4	15.6	12.7	15.6	2.2	3.2	3.2
Shell Rock	SR	170	11.1	14.2	11.3	14.1	2.1	2.6	3.1
Cohansey	COH	115	9.4	11.6	9.0	11.6	2.4	2.5	2.2
Arnolds	ARN	161	7.2	8.6	7.3	8.8	2.4	2.6	1.4
Hope Creek	HC	141	4.6	5.1	4.4	5.4	2.2	2.5	0.6

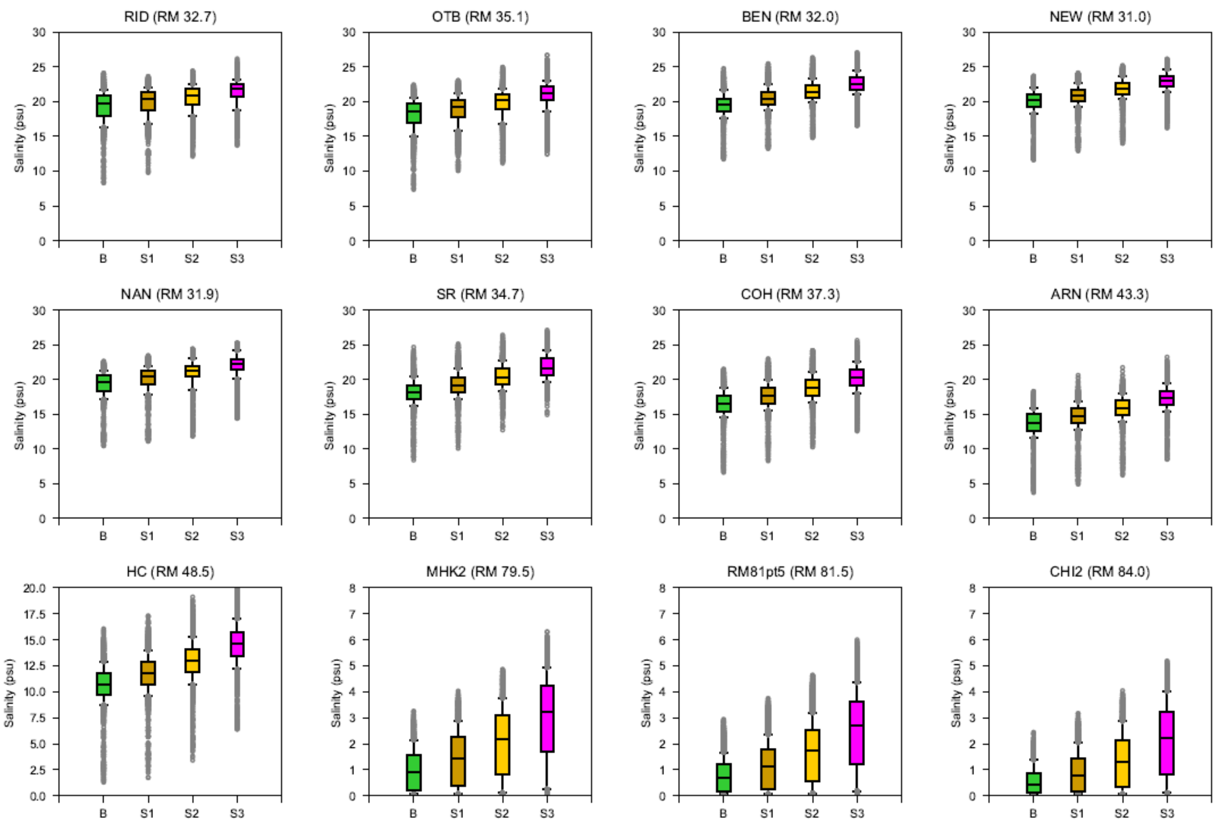
Appendix B Simulation Results for Salinity with Sea Level Rise and 2002 Drought Conditions

Figure B.1-1 Simulated Depth-averaged Salinity Distribution in Key habitat Areas for the Atlantic Sturgeon and Oysters under Sea Level Riser and 2002 Drought Conditions.



Note: from left to right: B, S1, S2, S3 are the Baseline, and 0.5, 1.0, 1.6 meter SLR, respectively. middle orange line = median; Edge = 25, 75 percentiles; Whiskers = the 10 and 90 percentiles

Figure B.1-2 Simulated Near Bed Salinity Distribution in Key habitat Areas for the Atlantic Sturgeon and Oysters under Sea Level Riser and 2002 Drought Conditions.



Note: from left to right: B, S1, S2, S3 are the Baseline, and 0.5, 1.0, 1.6 meter SLR, respectively. middle orange line = median; Edge = 25, 75 percentiles; Whiskers = the 10 and 90 percentiles

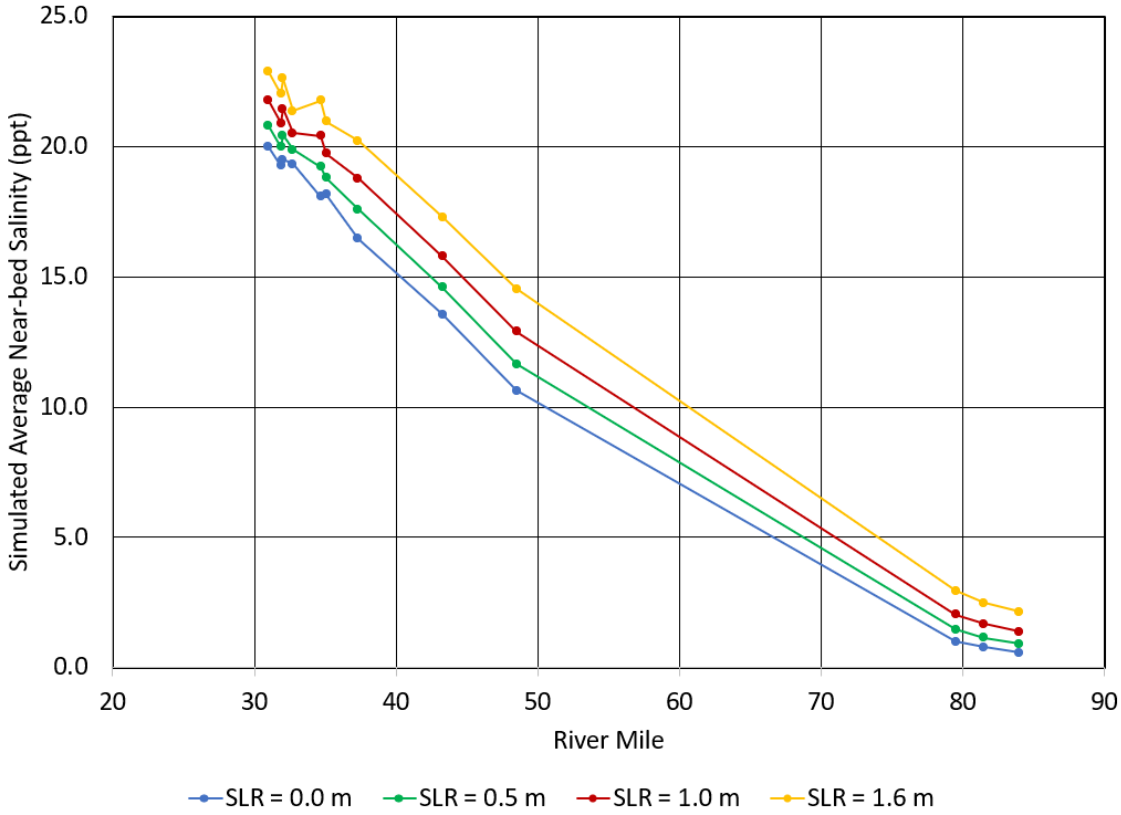
Table B.1-1 Summary of Simulated Near Bed Salinity in Key habitat Areas for the Atlantic Sturgeon and Oysters under Sea Level Riser and 2002 Drought Conditions

			SLR = 0 m	SLR = 0.5 m	SLR = 1.0 m	SLR = 1.6 m
Paramete	STATION	RM	Near-bed	Near-bed	Near-bed	Near-bed
maximum	NEW	31	23.7	24.2	25.2	26.2
mean	NEW	31	20.0	20.8	21.8	22.9
median	NEW	31	20.2	20.9	21.8	22.9
maximum	NAN	31.9	22.6	23.4	24.4	25.3
mean	NAN	31.9	19.3	20.0	20.9	22.0
median	NAN	31.9	19.7	20.4	21.3	22.2
maximum	BEN	32	24.8	25.5	26.4	27.1
mean	BEN	32	19.5	20.4	21.4	22.6
median	BEN	32	19.5	20.4	21.4	22.6
maximum	RID	32.7	24.1	23.7	24.4	26.2
mean	RID	32.7	19.3	19.9	20.5	21.4
median	RID	32.7	19.8	20.4	20.9	21.8
maximum	SR	34.7	24.7	25.1	26.4	27.1
mean	SR	34.7	18.1	19.2	20.4	21.8
median	SR	34.7	18.1	19.2	20.3	21.6
maximum	OTB	35.1	22.4	23.1	25.0	26.7
mean	OTB	35.1	18.2	18.8	19.7	21.0
median	OTB	35.1	18.6	19.2	20.2	21.3
maximum	COH	37.3	21.5	23.0	24.2	25.6
mean	COH	37.3	16.5	17.6	18.8	20.2
median	COH	37.3	16.6	17.6	18.8	20.2
maximum	ARN	43.3	18.3	20.6	21.7	23.2
mean	ARN	43.3	13.6	14.6	15.8	17.3
median	ARN	43.3	13.7	14.7	15.9	17.4
maximum	HC	48.5	16.1	17.3	19.1	20.9
mean	HC	48.5	10.6	11.7	12.9	14.5
median	HC	48.5	10.7	11.7	13.0	14.6
maximum	MHK2	79.5	3.3	4.0	4.9	6.3
mean	MHK2	79.5	1.0	1.5	2.0	3.0
median	MHK2	79.5	0.9	1.4	2.2	3.2
maximum	RM81pt5	81.5	2.9	3.7	4.6	6.0
mean	RM81pt5	81.5	0.8	1.2	1.7	2.5
median	RM81pt5	81.5	0.7	1.1	1.7	2.7
maximum	CHI2	84	2.4	3.2	4.0	5.2
mean	CHI2	84	0.6	0.9	1.4	2.1
median	CHI2	84	0.4	0.8	1.3	2.2

Table B.1-2 Summary of Change in Simulated Near Bed Salinity in Key habitat Areas for the Atlantic Sturgeon and Oysters under Sea Level Riser and 2002 Drought Conditions

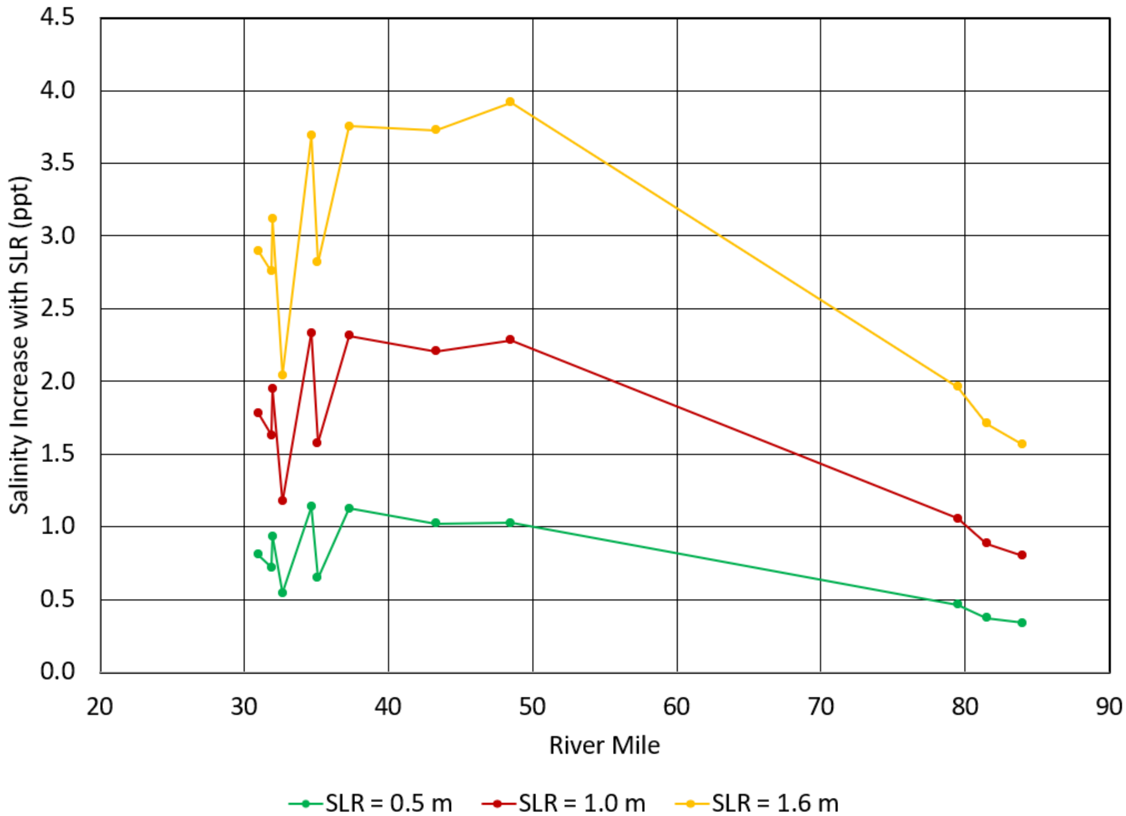
Parameter	Station ID	RM	SLR = 0.5 m	SLR = 1.0 m	SLR = 1.6 m
maximum	NEW	31	0.4	1.5	2.4
mean	NEW	31	0.8	1.8	2.9
median	NEW	31	0.7	1.7	2.8
maximum	NAN	31.9	0.8	1.8	2.6
mean	NAN	31.9	0.7	1.6	2.8
median	NAN	31.9	0.8	1.6	2.5
maximum	BEN	32	0.7	1.6	2.3
mean	BEN	32	0.9	1.9	3.1
median	BEN	32	0.9	1.9	3.1
maximum	RID	32.7	-0.5	0.3	2.1
mean	RID	32.7	0.5	1.2	2.0
median	RID	32.7	0.6	1.2	2.0
maximum	SR	34.7	0.5	1.8	2.5
mean	SR	34.7	1.1	2.3	3.7
median	SR	34.7	1.0	2.1	3.5
maximum	OTB	35.1	0.6	2.5	4.3
mean	OTB	35.1	0.6	1.6	2.8
median	OTB	35.1	0.7	1.6	2.7
maximum	COH	37.3	1.5	2.7	4.1
mean	COH	37.3	1.1	2.3	3.8
median	COH	37.3	1.1	2.2	3.6
maximum	ARN	43.3	2.3	3.4	4.9
mean	ARN	43.3	1.0	2.2	3.7
median	ARN	43.3	1.0	2.2	3.6
maximum	HC	48.5	1.2	3.1	4.8
mean	HC	48.5	1.0	2.3	3.9
median	HC	48.5	1.0	2.3	3.9
maximum	MHK2	79.5	0.8	1.6	3.1
mean	MHK2	79.5	0.5	1.1	2.0
median	MHK2	79.5	0.6	1.3	2.3
maximum	RM81pt5	81.5	0.8	1.7	3.1
mean	RM81pt5	81.5	0.4	0.9	1.7
median	RM81pt5	81.5	0.4	1.0	2.0
maximum	CHI2	84	0.7	1.6	2.7
mean	CHI2	84	0.3	0.8	1.6
median	CHI2	84	0.4	0.9	1.8

Figure B.1-3 Spatial Variation of Simulated Average Near Bed Salinity along the Delaware River in Key habitat Areas for the Atlantic Sturgeon and Oysters under Sea Level Riser and 2002 Drought Conditions.



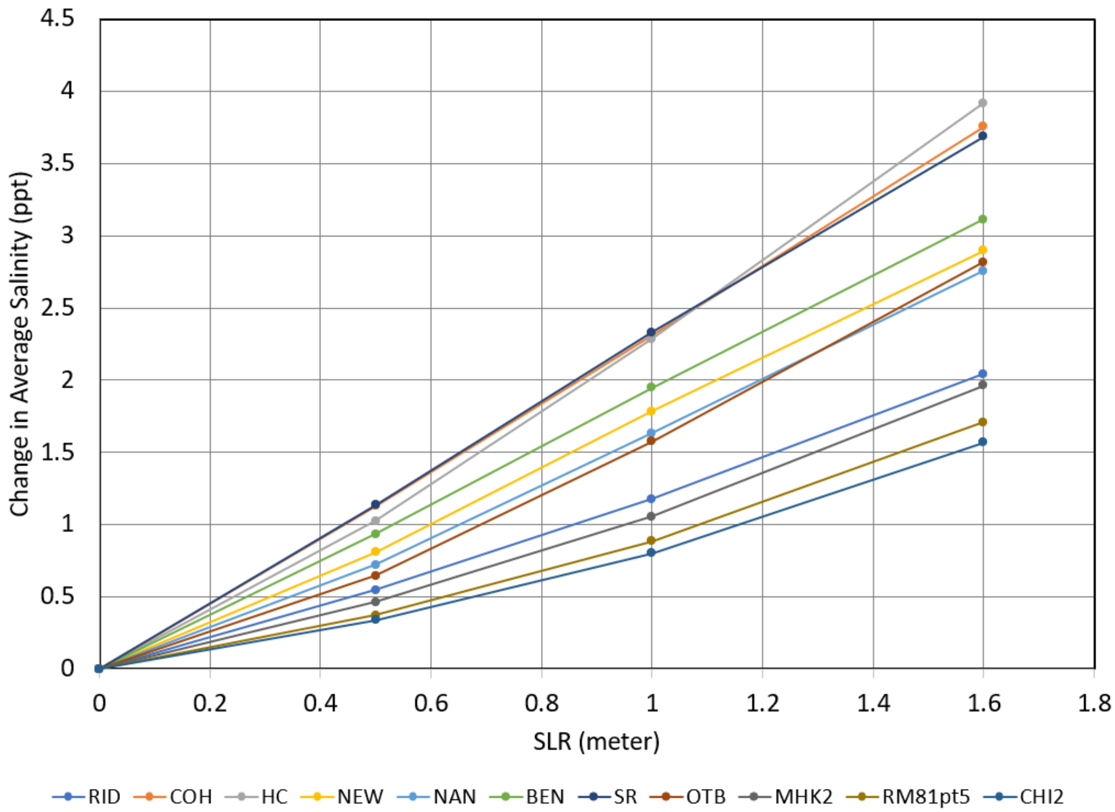
Note: hourly model output for near bed salinity were averaged over four-month drought period from July through October 2012.Values were given in Table B.1-1. Notice that the longitudinal profile between RM 48.5 and RM 79.5 was shown as straight line, which should not be considered as such. River mile associated with symbols indicate the monitoring locations.

Figure B.1-4 Increase in Simulated Average Near Bed Salinity with respect to Basline along the Delaware River in Key habitat Areas for the Atlantic Sturgeon and Oysters under Sea Level Riser and 2002 Drought Conditions.



Note: hourly model output for near bed salinity were averaged over four-month drought period from July through October, 2012. Values were given in Table B.1-2. River mile associated with symbols indicate the monitoring locations.

Figure B.1-5 Increase in Simulated Average Near Bed Salinity with respect to Basline at Given habitat Areas under Sea Level Riser and with the 2002 Drought Conditions.



Note: hourly model output for near bed salinity were averaged over four-month drought period from July through October 2012. Values were given in Table B.1-2. River mile associated with symbols indicate the monitoring locations