December 28, 2021 DRAFT

Modeling Eutrophication Processes in the Delaware Estuary:

Three-Dimensional Hydrodynamics Model for the Delaware Estuary

Report No: 202X-XX

Managing, Protecting and Improving the Water Resources of the Delaware River Basin since 1961

60 years 1961–2021

Delaware River Basin Commission

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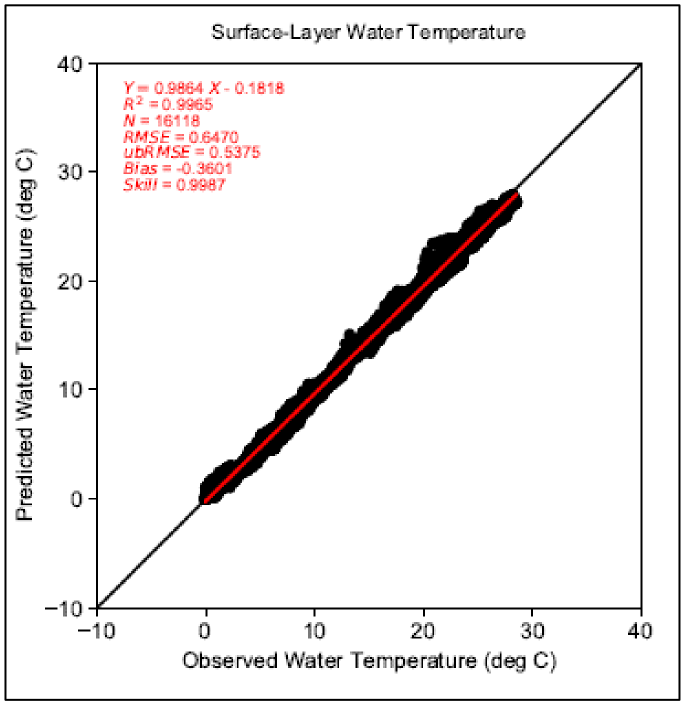
Acknowledgements

This work was funded in part by generous grants from the William Penn Foundation, the United States Environmental Protection Agency, the New Jersey Department of Environmental Protection, and the Pennsylvania Department of Environmental Protection. Critical datasets, without which this work could not have been performed, were obtained from the National Oceanic and Atmospheric Administration's National Climatic Data Center as well as the United States Geological Survey.

The DRBC is grateful for the technical support and direction provided by its Expert Panel, composed of internationally renowned modelers: Dr. Steve Chapra, Dr. Carl Cerco, Dr. Bob Chant, and Tim Wool. In addition to the model expert panel, DRBC acknowledges with appreciation the day-to-day interactions with its modeling consultants, Dr. Victor Bierman and Scott Hinz of LimnoTech.

Finally, DRBC acknowledges the various NPDES permit-holders within the tidal estuary that provided critical discharge data for this work.

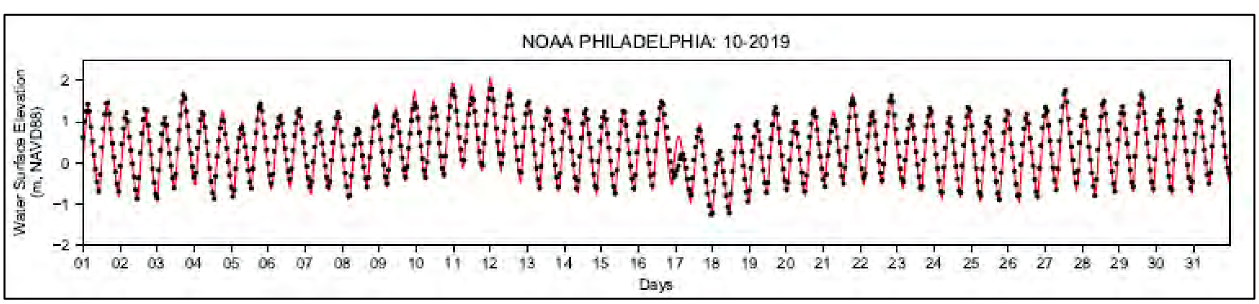
Executive Summary



The hydrodynamics model described herein is one component of a larger eutrophication modeling study of the Delaware Estuary, the goal of which is to develop and calibrate a water quality model of eutrophication processes in the Delaware Estuary and Bay from the head of the tide at Trenton to the ocean. The purpose of the project is to provide the scientific basis for the DRBC to evaluate management options for establishing water quality criteria for dissolved oxygen and nutrients, and for establishing loading targets to achieve these criteria. This report documents the technical approach and fitness of a three-dimensional hydrodynamics model that was deemed by the Expert Panel to be adequately calibrated for its purpose.

The objective of the hydrodynamics model is to simulate transport information (e.g., water depth, current velocity, salinity, water temperature, and mixing coefficient) over a range of hydrologic and loading conditions with the degree of accuracy and confidence necessary to drive the water quality model calibration and application. The hydrodynamic model was developed and calibrated for the periods of 2018-2019 and 2012. A statistical sub-model based on a regional analysis of shared features was developed in order to estimate hydrologic inputs from unmonitored tributaries and watersheds. In addition, an evaluation was performed to determine the extent of vertical resolution needed to adequately simulate gradients and mass transfer in the system. Based on this evaluation, a three-dimensional grid consisting of ten vertical layers in the navigation channel was deemed adequate for the model purposes.

Model performance was evaluated by comparing observations of water surface elevation, current velocity, water temperature and salinity in the estuary with model predictions. The Expert Panel unanimously agreed in May 2020 that the hydrodynamic model is appropriate and sufficiently calibrated to be used as the basis for the eutrophication model.



List of Acronyms/Abbreviations

3D	Three-dimensional
C&D Canal	Chesapeake and Delaware Canal
CMIST	NOAA’s Currents Measurements Interface for the Study of Tides
DRBC	Delaware River Basin Commission
DRB	Delaware River Basin
EFDC	The Environmental Fluid Dynamics Code
EPA	U.S. Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FFMP	Flexible Flow Management Program 2.2
FNC	Federal Navigation Channel
GVC	Generalized Vertical Coordinate (Grid)
NCDC	NOAA's National Climatic Data Center
NGO	Non-Government Organization
NJCAA	New Jersey Climate Adaptation Alliance
NOAA	National Oceanic and Atmospheric Administration
QA	quality assurance
QC	quality control
RM	River Mile
SLR	Sea Level Rise
USGS	U.S. Geological Survey
USACE	U.S. Army Corps of Engineers
WOA	NOAA Ocean Climate Lab’s Product World Ocean Atlas Database

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1. INTRODUCTION

The Delaware River Basin Commission (DRBC or Commission) approved a resolution in September 2017 recognizing the significant water quality improvements in the Delaware River Estuary and the vital importance of determining the appropriate designated aquatic life uses and water quality criteria necessary to support these uses. The resolution specifically requires the development and calibration of a eutrophication model for the Delaware River Estuary and Bay, as well as the formation of an Expert Panel to provide input and advice to the DRBC.

This hydrodynamics model is one component of the larger eutrophication modeling study of the Delaware Estuary, the goal of which is to develop and calibrate a water quality model of eutrophication processes in the Delaware Estuary and Bay from the head of the tide at Trenton, NJ to the ocean. The eutrophication model being developed by the DRBC will enhance our understanding of the impact of nutrient loads on dissolved oxygen conditions in the tidal Delaware River and Bay. This effort includes: 1) the convening of an expert panel to guide the development of the eutrophication model; 2) the completion of a two-year monitoring program in partnership with wastewater authorities in order to obtain data on nutrient loadings from point sources; 3) field studies on primary productivity in the lower Delaware Estuary; and 4) development of a linked hydrodynamic model and eutrophication model. The project will provide the scientific basis for the DRBC to evaluate management options in establishing water quality criteria for dissolved oxygen and nutrients, and for establishing loading targets for point and non-point sources into the Delaware Estuary and Bay to achieve these criteria.

1.1 Objectives of Modeling Study

The three-dimensional (3D) hydrodynamics model described herein provides the foundation for the linked eutrophication model of the Delaware Estuary. Specifically, the spatial resolution of the linked model is generally dictated by the needs of the hydrodynamics model, while information from the 3D hydrodynamic model, including water volume, current velocity, flow, mixing characteristics, salinity, and water temperature, is transferred to the water quality model for use in simulating water column transport of constituents. The objective of the hydrodynamics model, therefore, is to simulate transport information over a range of hydrologic and loading conditions with the degree of accuracy and confidence necessary to drive the water quality model calibration and application.

1.2 Study Area

The study area encompasses the entire Delaware River drainage basin, while the Delaware Estuary (the tidal Delaware River and Bay) defines the hydrodynamic model extent. The Chesapeake and Delaware (C&D) Canal is a unique boundary to the hydrodynamic model and warrants a brief description as well.

1.2.1 Delaware River Basin

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 1.2-1). 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. Approximately 13.3 million people (almost 5% of the nation's population) rely on the waters of the Delaware River Basin for drinking, agricultural, and industrial use. In addition to the more than 8.3 million people in the Delaware River Basin itself, the Catskill Mountain Region of New York State supplies approximately half of New York City's drinking water from three basin reservoirs (Cannonsville, Pepacton, and Neversink).

Situated in the Mid-Atlantic temperate zone, the Delaware River Basin is influenced by two major North American weather systems: 1) low pressure systems originating in the south that move along the coast bringing substantial rainfalls, and 2) Canadian high pressure systems that bring heavy snowfall and cold temperatures to the upper northwest portions of the basin. Coastal influences are more significant in the south and east portions of the basin. Average annual precipitation ranges from 40 inches in southern New Jersey to about 50 inches in the Catskill Mountains of southern New York; annual snowfall ranges from 13 inches in southern New Jersey to about 80 inches in the Catskill Mountains (Dolgopolova, 2014). Generally, precipitation is evenly distributed throughout the year; however, the highest monthly rainfall generally occurs in July or August, comprising 10 percent of the annual total. The mean air temperature at the Philadelphia gage is –4.0°C in winter and +23°C from June to September. The mean annual precipitation amount is 41.6 inches: July averages 4.3 inches while January and February average 2.7 inches.

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 model domain extends from the head of tide at Trenton to the mouth of the bay into the Atlantic Ocean.

The average annual water discharge at Trenton is about 20,290 cfs based on data from 1913 to 2019. The monthly statistics of river discharge show a clear flow seasonality, with the two highest monthly mean flows in March and April (20,400 and 21,900 cfs, respectively) and the two lowest in July and August (6,420 and 6,680 cfs, respectively). The average annual water discharge in the Schuylkill River over the period 1932–2018 is approximately 2,850 cfs.

According to a U.S. Geological Survey (USGS) study prepared for the Federal Emergency Management Agency (FEMA) in 2008, the flood frequencies at Delaware River at Trenton, N.J. are estimated as follows: 94,900 (2-year), 138,000 (5-year), 169,000 (10-year), 211,000 (25-year), 245,000 (50-year), and 280,000 (100-year) in units of cfs (Schopp and Firda, 2008).

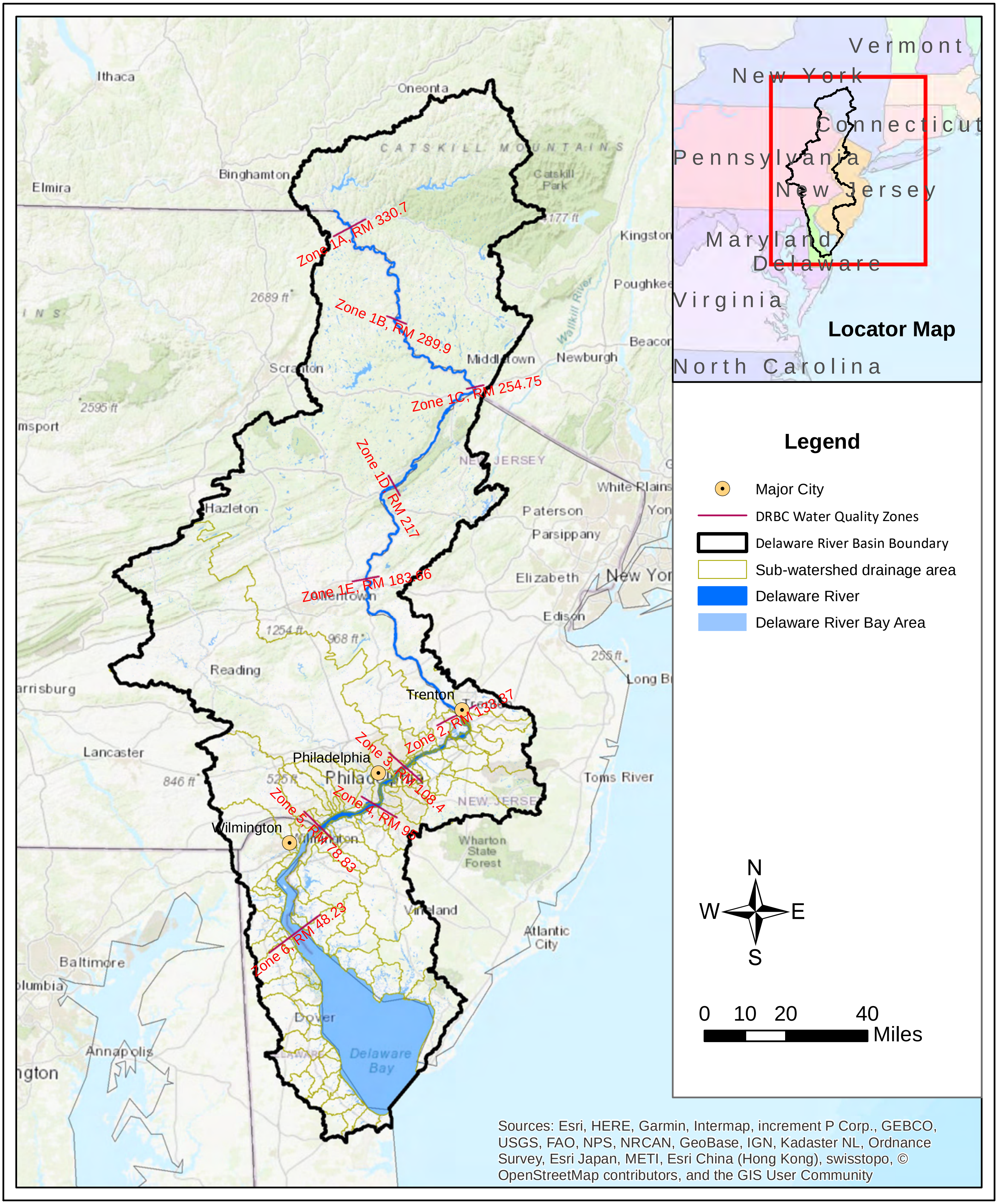

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Figure 1.1-1
Delaware River Basin and Bay

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1.2.2 Delaware Estuary

The tidal portion of Delaware River Basin is a typical coastal plain estuary with a relatively homogeneous shallow depth of about 26 to 33 feet. Eighty percent of the estuary has a depth of less than 30 feet, except for the Federal Navigation Channel (FNC), which was deepened most recently in 2016 to a depth of 45 feet below Mean Lower Low Water (MLLW) level. The width of the Bay at its mouth is 11 miles, and the widest part of the bay is about 27 miles. The width decreases precipitously 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). Affected by its geometry and the rate of estuary narrowing along the river, the amplitude and shape of the tidal wave changes as it propagates along the estuary. According to NOAA, the observed M2 (Principal lunar semidiurnal constituent, and the dominant tidal harmonic constituent) tide amplitude increases from 2.02 feet at Lewes, DE to 2.75 feet at Philadelphia and 3.51 feet at Newbold PA, which is 1.7 times larger than at the mouth of the bay. The range of the tidal surface elevation between MHHW and MLLW is 4.65 feet at the bay mouth, 6.69 feet at Philadelphia, and 8.39 feet at Newbold.

The seasonal and interannual variability in wind and tides near the mouth of Delaware Bay exerts significant influence on salinity and transport of any chemical in the estuary. A consistent seasonality named as Average Seasonal Cycle (ASC) in the observed tides is reported at Lewes, Cape May and Atlantic City NOAA tide gage stations (NOAA). The mean sea level tends to be lower during winter periods (from December to March) and relatively higher during summer periods (from July to October). According to NOAA, ASC is caused by regular fluctuations in coastal temperatures, salinities, winds, atmospheric pressures, and ocean currents. This pattern seems consistent with the observations that wind-induced downwelling occurs more often in the winter and upwelling may be the dominating phenomenon for the summer period. Near the mouth of the Delaware Bay, relatively stable winter northern winds may cause downwelling (i.e., ocean water sinks on the continental shelf), while southern and southwestern winds that primarily blow over the summer and fall may cause upwelling (i.e., rise of ocean water with higher salinity). Persistent downwelling will contribute to a weaker salinity intrusion and relatively stronger vertical stratification. Conversely, upwelling will strengthen the salinity intrusion into the estuary. Change in seawater temperature also makes difference in the water surface elevation due to the change in water density. Near the mouth of the bay, a difference of 10 degrees C in water temperature may cause 20 cm difference in water surface elevation based on personal discussion with Dr. Robert Chant (Rutgers University) during an expert panel meeting in December 2019 at DRBC.

Regarding water column stratification or salinity vertical structure, the temperate Delaware bay is categorized as a weakly stratified or partially mixed estuary resulting from moderate tidal forcing and weak to moderate river discharge (A. Valle-Levinson 2009). The tidally averaged mean salinity profile has either a weak or no stratification from surface to bottom, which indicates vigorous vertical mixing between riverine and oceanic waters. The salinity structure results from competition between river flow forcing, which repels the saltwater moving seaward, and tidal forcing, which drives the saltwater moving into the Delaware Bay and estuary. Salinity (S) is the long-term averaged and depth-averaged salinity with units in parts per thousand (ppt).

Using long-term averaged information, the region can be into four large zones: 1) A 53-mile river reach from the waterfall north of Trenton at RM 132 to the Marcus Hook gage at RM 79, where salinity is less than 0.25 ppt; 2) the upper Delaware Bay estuary, a 54-mile reach where salinity ranges from 0.25 to 25 ppt, from the Marcus Hook gage to the transect between Port Mahon and

Gandys Beach at RM 25; 3) the lower Delaware Bay estuary, a 25-mile reach where salinity exceeds 25 ppt, from RM 25 to the mouth of the bay; and 4) the coastal zone of the ocean (Dolgopolova 2014).

1.2.3 Chesapeake & Delaware Canal

The Chesapeake & Delaware Canal (C&D Canal) is a ship channel 18 miles in length that connects the Delaware River with the Chesapeake Bay through the states of Delaware and Maryland. In 1954, the United States Congress authorized further expansion of the channel to 450 wide (bottom width) and 35 feet deep. These improvements began in the 1960s and were completed in the mid-1970s. Today's canal is a modern electronically controlled commercial waterway, carrying 40 percent of all ship traffic in and out of the Port of Baltimore (Ward et al. 2009).

The flow magnitude, flow direction, and the net flow in the canal are controlled by the amplitude and phase of tides and water density at the eastern and western ends of the canal. According to information from the NOAA, the MLLW level at Chesapeake City near the western boundary (the Chesapeake Bay end) is over 16 inches higher than at Reedy Point near the eastern boundary (the Delaware Estuary end). In addition, about 10 hours tidal phase difference is observed between the Delaware and Chesapeake ends of the C&D Canal. The salinity at the eastern end of the canal is higher than the western end by 2 to 3 ppt. USACE conducted a hydraulic study for C&D Canal in 2009 using data collected from 1992 to 1993, which concluded that the average net flow in the C&D Canal is normally from Chesapeake Bay to Delaware Estuary. During the time period of their study, the mean net flow ranged from 3,000 to 4,000 cfs moving from west to east; however, reversed direction flow during winter period of November and December 1992 was also observed.

In a hydrodynamic and water quality modeling work conducted for Chesapeake Bay (Wang and Johnson, 2002), the C&D Canal was treated as a river boundary with a constant outflow of 750 cfs specified at the eastern end of the C&D Canal. This information was also used by DRBC staff for developing its 1-D hydrodynamic model DYNHYD5 (DRBC, 2003). In reality, flows are dynamic and can occur in excess of 100,000 cfs through the canal. Normally, the flow reverses direction every 6 hours or so as the tide changes. However, during episodic events, large flows can continue in the same direction for 2-3 days. Thus, the treatment of the C&D Canal as a river with a constant outflow in the 3D Chesapeake Bay hydrodynamic model is a simplification, and their estimated long-term average net flow differs from USACE's study significantly. A more thorough study may be needed over a longer time span, considering the large net flow from the Chesapeake Bay to the Delaware Estuary through the C&D Canal. In this model, the C&D Canal is treated as an open boundary to allow flows in and out of the Delaware Estuary system.

1.3 Salinity Intrusion

Salinity gradients are complex in the Delaware Estuary, and the model's ability to capture them provides an important demonstration of fitness for the hydrodynamic model. Understanding the salinity structure, salinity transport and seasonal to inter-annual variability, and the underlying principle driving forces is critical to advance our understanding of the hydrodynamics in Delaware estuary. In addition, the simulation of salinity is directly relevant to water quality modeling processes including light extinction and phytoplankton toxicity.

With nearly zero salinity from upland freshwater inflows at Trenton and close to constant salinity of about 32 to 35 ppt in ocean water 40 to 50 miles from the bay mouth on the continental shelf, a temporally variable longitudinal salinity profile is formed and is the unique characteristic that differentiates tidal rivers and estuaries from any other types of surface waters. The salinity structure is maintained mainly by two competing forces: a) river flow, which tends to drive saltwater seaward; and b) tidal forcing and the gravitational circulation, which tends to drive saltwater landward. Other influential factors that affect the salinity structure include turbulent shear and meteorological forcings such as precipitation, evaporation, and wind. Although most of the upper portion of the tidal river upstream of RM 70 is typically well-mixed, a clear vertical stratification exists in the lower portion of the estuary, especially near the entrance of the bay. During low-flow and spring tide periods, stratification weakens due to the relatively stronger tidal forcing against the smaller river inflows, while high-flow and neap tide periods cause a stronger vertical stratification. Following a strong high-flow event, the salt front location usually retreats quickly in the seaward direction.

Salinity in the estuary is monitored by tracking the location of the salt front. The salt front represents the interface of salt water and fresh water in the estuary as well as the extent of salinity intrusion into the estuary. It is defined as the 7-day average of the 250 mg/l chloride concentration (isochlor). The value of 250 mg/l is a secondary drinking water standard, used as a guideline to assist public water systems in managing their drinking water for aesthetic considerations, such as taste, color, and odor.

The seven-day average 250 mg/l chloride concentration was selected as a criterion for salinity monitoring and reservoir operations. It is a more stable indicator of the trend in the movement of the salt front, given the variability of day-to-day measurements. DRBC calculates the salt front location daily and reports it on a weekly basis on its website using the map of the estuary presented in Figure 1.3-1. The normal range of the salt front is between River Mile 67 and 76 (landmarks: RM 67 is near Pennsville, NJ; RM 68.7 is the Delaware Memorial Bridge; RM 76 is near Marcus Hook, PA).

Since specific conductance is tightly correlation with chloride concentration, salinity can be derived from chloride concentration or chlorinity. The “textbook” empirical relationship between salinity (in ppt) and chlorinity (chlorides) is given as:

Salinity = 0.03 + 1.805 × Chlorinity (g/kg sea water); or

Salinity = 0.0018066 × Chlorinity (mg/l).

For example, 250 ppm Chlorinity is equivalent to 0.45 ppt salinity.

Based on site specific boat-run data collected by DRBC between 2000 to 2018, the relationship between specific conductance and Chloride concentration was re-evaluated and is shown in Figure 1.3-2. The relationship exhibits a bi-linearity between specific conductance and Chlorinity with a cutoff value at 320 (µS/cm at 25 °C). These relationships were used when making model-to-data comparison of Chloride concentrations.

Salt Line

The Salt Line: What is it and Where is it?

The below graphic shows the current location of the salt line (aka salt front) in relation to several other sites along the river. Estimates of the salt line are based on provisional data and subject to change if better data becomes available.

Salt Line Location: December 9, 2019

12/9/2019 Location: RM 71

Normal December Location: RM 69

Median Monthly Salt Front Locations

January	69
February	71
March	70
April	67
May	68
June	69
July	70
August	74
September	76
October	72
November	70
December	69

(RM= river mile)

One important metric for understanding salinity concentrations in the Delaware Estuary (the tidal Delaware River & Bay) is the seven-day average location of the salt line, the 250 mg/L chloride concentration based on drinking water quality standards. Chloride concentrations indicate the degree to which ocean derived saltwater has moved into the upper portion of the estuary; freshwater flowing downstream from the non-tidal Delaware River helps repel, or flush back, the salt-laced water. While you cannot see the "salt line," its location fluctuates in response to changing freshwater inflows, which either dilute or concentrate chlorides in the river.

DRBC website for salt line information

https://www.state.nj.us/drbc/hydrological/river/salt-line.html

Figure 1.3-1

Estuary Map and Location of the Salt Front

Report Name

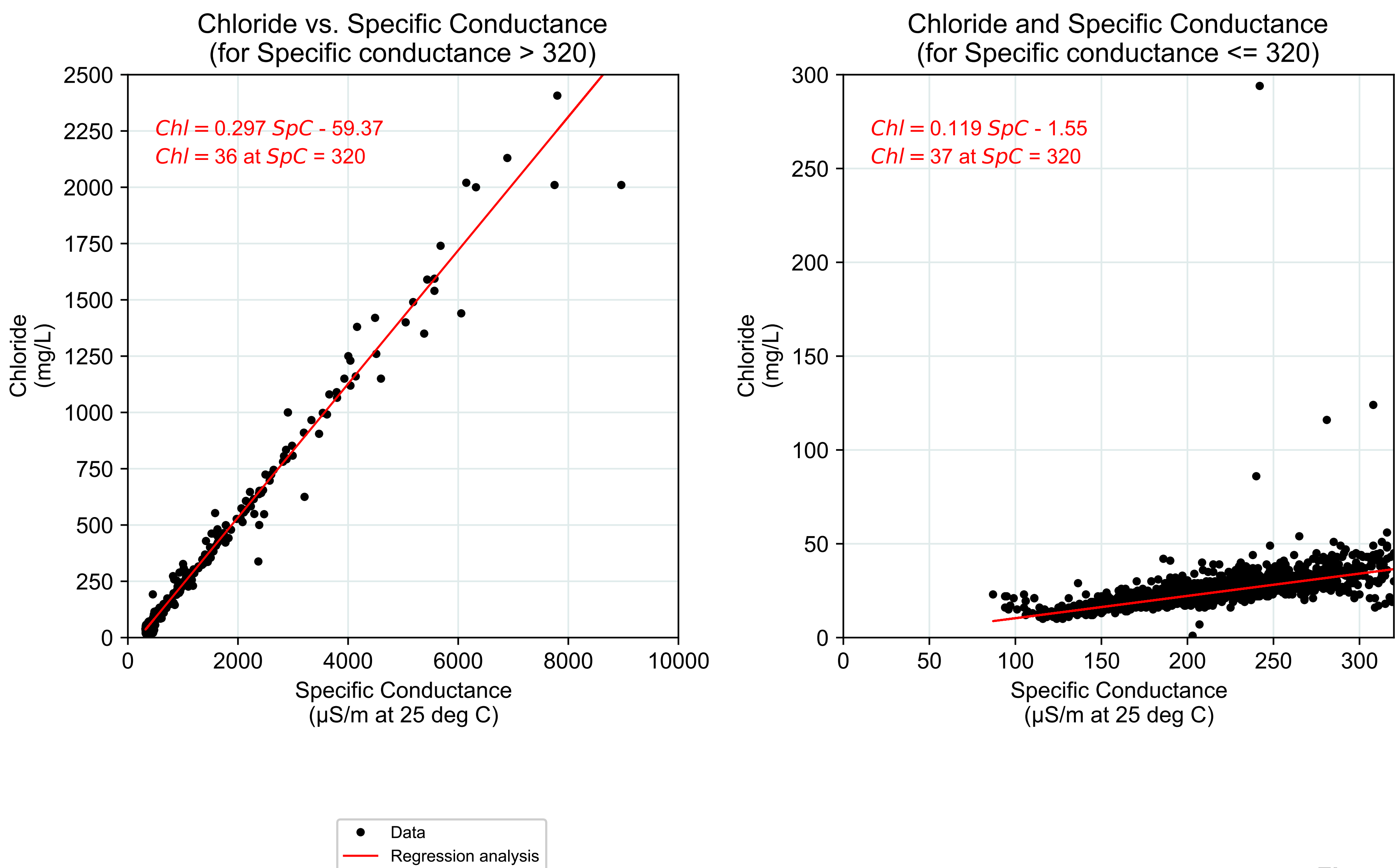

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Figure 1.3-2

Relationship between Chloride Concentration and Specific Conductance

DRBC boat-run data collected upstream of River Mile 70 and from 2000 to 2018 were used in this analysis.
Segmented linear regression with two segments separated by a breakpoint of 320 µS/m at 25 deg C) was used to develop the relationship.

1.4 OVERVIEW OF TECHNICAL APPROACH

The hydrodynamics and salinity transport in Delaware estuary have been studied in the past through simplified analytical methods. For example, the relative importance due to tidal advective diffusion to the residual salt transport was investigated by coupling the width-averaged, shallow-water equation and the salinity equation with well-mixing assumption and excluding lateral transport processes (Wei 2014). This type of model excludes the influence of local bed friction variations on water motion and salt dynamics among other important factors. Full 3D numerical simulation takes more physical processes into consideration, including buoyancy forcing due to river discharges, tidal forcing, climatological/meteorological forcing, surface heat exchange, wind forcing (local and remote), wind-wave induced current, etc. and have been used to study the vertical stratification and its variability during flood-tide and ebb-tide and cross-channel momentum balance (Aristizábal and Chant 2012), the salt fluxes (Aristizábal and Chant 2013), thermal circulations (Salehi 2017), the effect of wind waves on momentum budget and subtidal exchange (Fernando Pareja-Roman, et al., 2019), wave energy and interactions between bathymetry and wave processes (Jia-Lin Chen et al., 2018), and the processes responsible for coastal changes including sediment transport (John Warner 2010). Despite the detailed theoretical and modeling studies thus far, many questions about salinity dynamics in Delaware Bay remain unanswered due partly to the fact that most of the studies have been focused primarily on short time scales. Recently, the forcing mechanisms that drive the salinity transport were investigated for longer time scales (seasonal to interannual time frames) for the Chesapeake Bay: 15-year simulation by Jiangtao Wu et al. (2011) and 7-year simulation by Sung-Chan Kim (2013). However, the impacts due to long-term variability in river flows, tidal surface elevation at the ocean boundary as well as climatological/meteorological forcing on the salinity structure and salinity intrusion have not been thoroughly studied for the Delaware Estuary. These impacts strongly influence the hydrodynamics within the estuary.

A 3Dhydrodynamics model of the Delaware estuary was developed based on the Environmental Fluid Dynamics Code (EFDC), which is supported by USEPA. The model was calibrated and validated for the years 2018-2019 and 2012 in order to demonstrate fitness over a wide range of hydrologic conditions. The primary focus of hydrodynamic model calibration was for the period of 2018 and 2019 when continuous conductivity and other water quality data were collected through DRBC's intensive eutrophication modeling study sampling program; however, the 2012 year was added to incorporate a year with drier hydrologic conditions than occurred in 2018-2019.

This study used available data and information to the fullest extent possible, while acknowledging that data gaps exist in the present state of knowledge about the Delaware Estuary study area, as well as potential limitations in the model structure. Multiple lines of evidence were used to evaluate the reliability of the model during the calibration and validation process, especially for salinity intrusion. This approach was applied because limitations exist in the model inputs as well as the various datasets used for calibration and validation of the hydrodynamic model. Model fitness is impacted not just by the quality of calibration, but also by boundary data and field data, neither of which are perfect. These realities must temper expectations, and dictate a multiple lines of evidence approach to optimize model fitness. Model performance was evaluated for major parameters such as tidal harmonic constituents, water surface elevation, water temperature, and salinity, through model to data comparisons.

Before the hydrodynamic model was finalized and successfully calibrated, a sensitivity analysis was conducted to evaluate the effects of various vertical resolutions of the numerical grid on model predictions. The finding of the vertical resolution analysis is included in this report.

2. HYDRODYNAMICS MODEL DEVELOPMENT

2.1 Model Description

The hydrodynamic model code applied for this study is the Environmental Fluid Dynamics Code (EFDC), which was originally developed by Dr. John Hamrick (Hamrick 1992) and is supported by the U.S. Environmental Protection Agency (USEPA). EFDC is a general purpose hydrodynamic model code capable of simulating time-variable flow in rivers, lakes, reservoirs, estuaries, and coastal areas. It solves the conservation of mass and momentum equations, as well as transport equations for temperature and salinity, which are the fundamental equations governing the movement of water in an estuary. The state equation links the water density to salinity and water temperature. EFDC model has being applied to a wide range of environmental studies. A complete description of EFDC is given in Hamrick (1992) and Tetra Tech (2002).

The version of EFDC used in this study was provided by USEPA Region 4, which is equivalent to the public release version of EFDC 2007 via the USEPA website. A high-order advection scheme, Conservative Operator Splitting for Multidimensions with Inherent Constancy (COSMIC) (Leonard et al., 1996), was adopted to simulate density stratification and salinity intrusion more accurately. DRBC staff and its consultant have made improvements to this version of EFDC in two major aspects: 1) enhancement of mass balance when choosing COSMIC scheme with generalized vertical coordinate (see section 2.3); and 2) enhancement of hydrodynamic linkage file to the water quality model.

Although the Delaware Estuary is commonly considered as weakly stratified, vertical mixing and along-channel salinity structure vary in time depending on river discharge, tidal forcing, and meteorological forcing (Aristizabal and Chant, 2013 and 2015). Furthermore, reaeration at the water surface and sediment oxygen demand at the bed may cause dissolved oxygen stratification in the water column. These conditions make it reasonable to use a 3D mode in EFDC to simulate the transport in the Delaware River estuary. EFDC implements the Mellor-Yamada level 2.5 turbulence closure scheme (Mellor and Yamada, 1982) as modified by Galperin et al (1988) to parameterize vertical mixing.

The continuity and momentum equations used in EFDC are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad \text{(Eqn 2.1-1)}$$

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial z} - fv + g\frac{\partial \eta}{\partial x} = \frac{\partial}{\partial z}\left(K_M \frac{\partial u}{\partial z}\right) - \frac{g}{\rho_0}\frac{\partial}{\partial x}\int_z^\eta \rho dz + F_x \qquad \text{(Eqn 2.1-2)}$$

$$\frac{\partial v}{\partial t} + \frac{\partial uv}{\partial x} + \frac{\partial v^2}{\partial y} + \frac{\partial vw}{\partial z} + fu + g\frac{\partial \eta}{\partial y} = \frac{\partial}{\partial z}\left(K_M \frac{\partial v}{\partial z}\right) - \frac{g}{\rho_0}\frac{\partial}{\partial y}\int_z^\eta \rho dz + F_y \qquad \text{(Eqn 2.1-3)}$$

$$\frac{\partial T}{\partial t} + \frac{\partial uT}{\partial x} + \frac{\partial vT}{\partial y} + \frac{\partial wT}{\partial z} = \frac{\partial}{\partial z}\left(K_H \frac{\partial T}{\partial z}\right) + \frac{1}{\rho_0 C_p}\frac{\partial I}{\partial z} + F_T \qquad \text{(Eqn 2.1-4)}$$

$$\frac{\partial S}{\partial t} + \frac{\partial uS}{\partial x} + \frac{\partial vS}{\partial y} + \frac{\partial wS}{\partial z} = \frac{\partial}{\partial z}\left(K_H \frac{\partial S}{\partial z}\right) + F_S \qquad \text{(Eqn 2.1-5)}$$

where:

η = water surface elevation;

u, v, and w = velocity components along the x, y, and z direction, respectively;

ρ_0 and ρ = reference density and in situ density of water;

g = gravitational acceleration;

f = Coriolis parameter;

K_M = vertical viscosity for momentum mixing;

F_x and F_y = horizontal momentum diffusion in x and y direction, respectively;

T = water temperature;

S = salinity;

K_H = vertical diffusivity for turbulent mixing of temperature and salinity;

F_T and F_S = horizontal diffusion terms for temperature and salinity, respectively;

$\partial I/\partial z$ = solar radiation forcing term; and

C_p = specific heat.

Certain physical processes, such as groundwater-surface water interaction, wave-induced current, and wave-current interaction, are not included in this hydrodynamics modeling study because their impacts on the long-term salinity and water quality transport in the Delaware Estuary are considered to be insignificant.

2.2 Model Domain and Numerical Grid

The model domain extends from the head of tide on the Delaware River at Trenton (River Mile [RM] 135) to the mouth of the Delaware Bay (RM 0). The C&D Canal westward to the NOAA tide gage station at Chesapeake City is included in the domain. Thirty-three major tributaries and 124 sub-basin drainage areas are incorporated for freshwater inflows, as described in Section 2.4 below.

Curvilinear and orthogonal numerical grids were created to represent the geometry of the study area (Figure 2.3-1 and Appendix A). The model domain contains a total of 1890 grid cells, with the upper portion (Zones 2, 3 and 4) of the tidal river being discretized by 946 grid cells in the horizontal plane, and lower portion (Zones 5 and 6) by 944 grid cells. The river channel was generally delineated by 4 to 6 grid cells in the cross-channel direction, and the navigational channel was represented by one cell in the horizontal plane. Grid resolution is higher in the tidal river than in the Bay. For example, the average grid cell sizes in the river channel upstream of RM 70 are 580 m and 190 m in the longitudinal and lateral directions, respectively. Grid cells in

Zone 6 are much coarser, with the average lengths in longitudinal and lateral directions being 2020 m and 1900 m, respectively.

2.3 BATHYMETRY AND GENERALIZED VERTICAL COORDINATE (GVC)

Bathymetry data were based on a Digital Elevation Model (DEM) from the Federal Emergency Management Agency (FEMA, 2011), in which the horizontal datum is NAD83 and vertical datum is NAVD88. The DEM incorporated the latest coastal Lidar and other topographic survey data sets with the most reliable bathymetric datasets of the region. The raster grid resolution in the DEM is 1/3 arc-seconds (~10 meters). Bathymetry in C&D Canal was set to 35 feet below Mean Lower Low Water (MLLW) according to NOAA nautical chart.

US Army Corps of Engineers (USACE) completed a 102.5-mile long channel deepening project in 2016. The existing 40-feet deep federal navigation channel from Philadelphia Harbor, PA and Beckett Street Terminal in Camden, N.J. to the Delaware Bay was deepened to 45 feet deep. This dredging project was reflected in the model setup; the navigation channel was set to 45 feet below MLLW for simulations after 2016 and 40 feet below MLLW for earlier years. The final bathymetry projected on the numerical grid is shown in Figure 2.3-1 and Appendix A.

According to Tetra Tech (2006), EFDC model was originally formulated with a sigma stretched vertical coordinate. In the sigma coordinate formulation, the number of vertical layers is the same at all horizontal locations in the model domain. This formulation is widely accepted, conceptually attractive and adequate for a large range of applications. However, in the Delaware River estuary, bathymetry may vary rapidly in the lateral direction from a deep navigational channel to a much shallower flank, forming V or T-shaped cross-sections. A traditional Z or hybrid coordinate is more desirable. In this study, a generalized vertical coordinate (GVC) was chosen for representing the lateral bathymetry variation more efficiently and accurately. This approach allows the horizontal model domain to be represented by laterally constrained and localized-sigma regions (LCL sigma) (Figure 2.3-2). In the LCL region, the number of active vertical layer is variable, as opposed to a traditional sigma coordinate in which the number of vertical layers is constant. While at a given horizontal location, the number of vertical layers is fixed during simulation, regardless of water level rising and falling. Theoretical and computational aspects of the generalized vertical coordinate are described in Tetra Tech (2006).

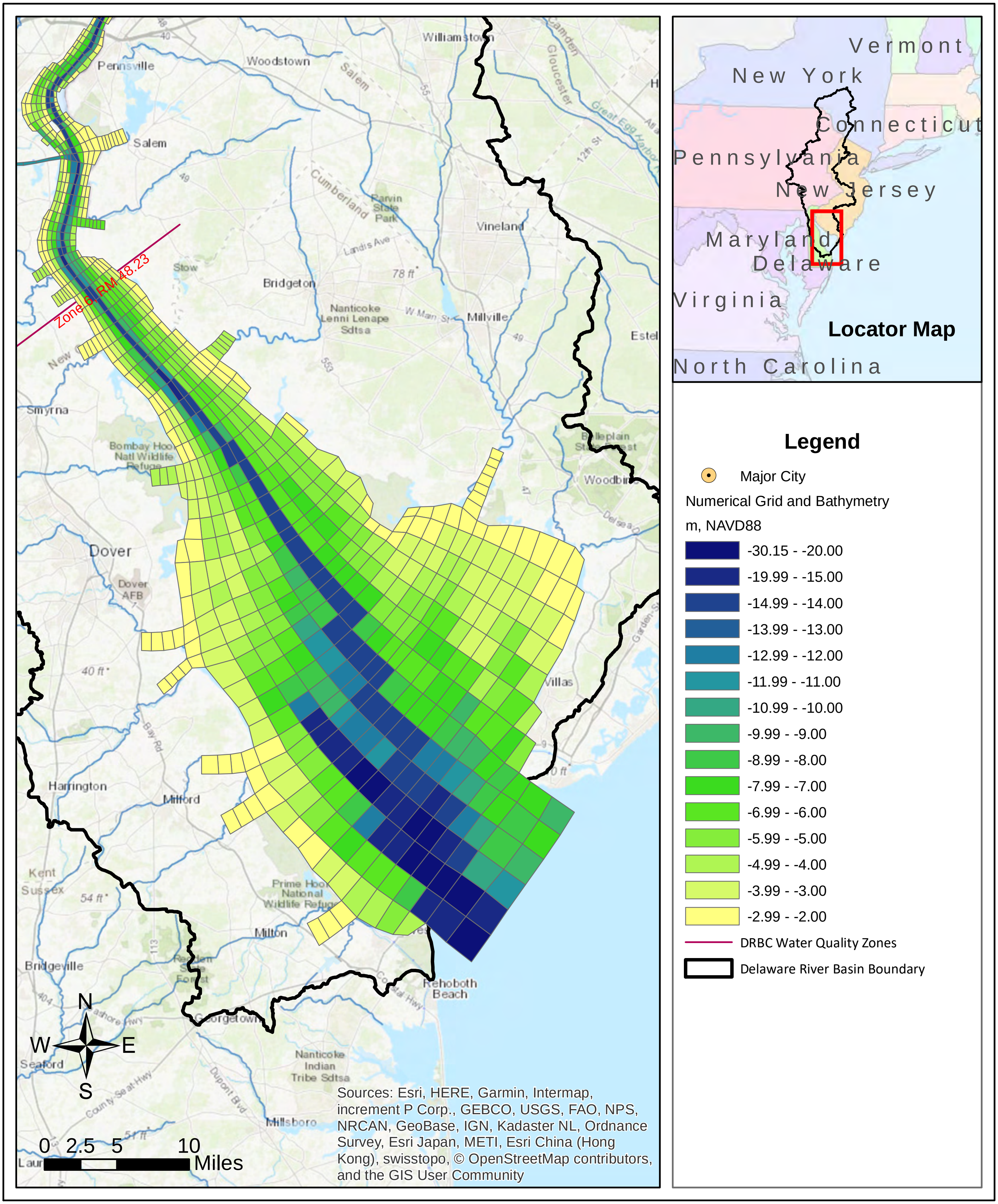

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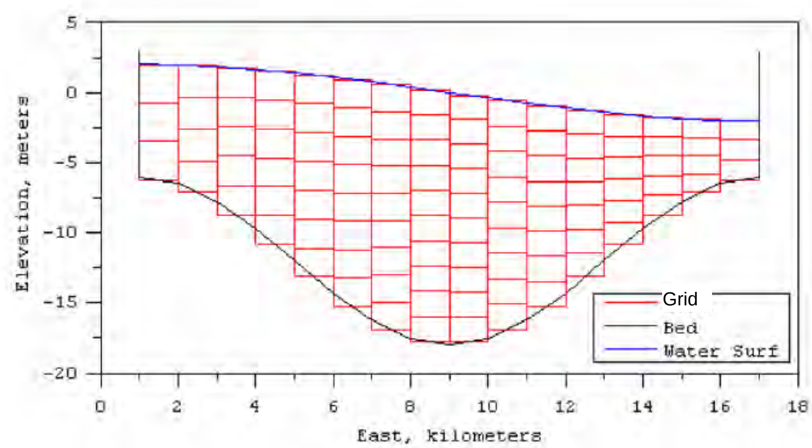
Figure 2.3-1b
Numerical Grid and Projected Bathymetry, Zone 6

Figure 2.3-2 Example of GVC Grid



Example of GVC Grid reproduced from Figure 3 (p.26) of Theoretical and Computational Aspects of the Generalized Vertical Coordinate Option in the EFDC Model, EFDC Technical Memorandum prepared for USEPA Region 4 (Tetra Tech, March 2006)

In this study, a maximum of 12 vertical layers were assigned to a few cells near the ocean boundary. Ten vertical layers was maintained in most of the cells inside the navigational channel. Spatial variation of number of vertical layers is shown in Figure 2.3-3. Sensitivity tests to vertical layer resolution (see Section 3.4 for details) indicated that the number of layers inside the navigational channel should be greater than five but need not be more than ten to perform adequately.

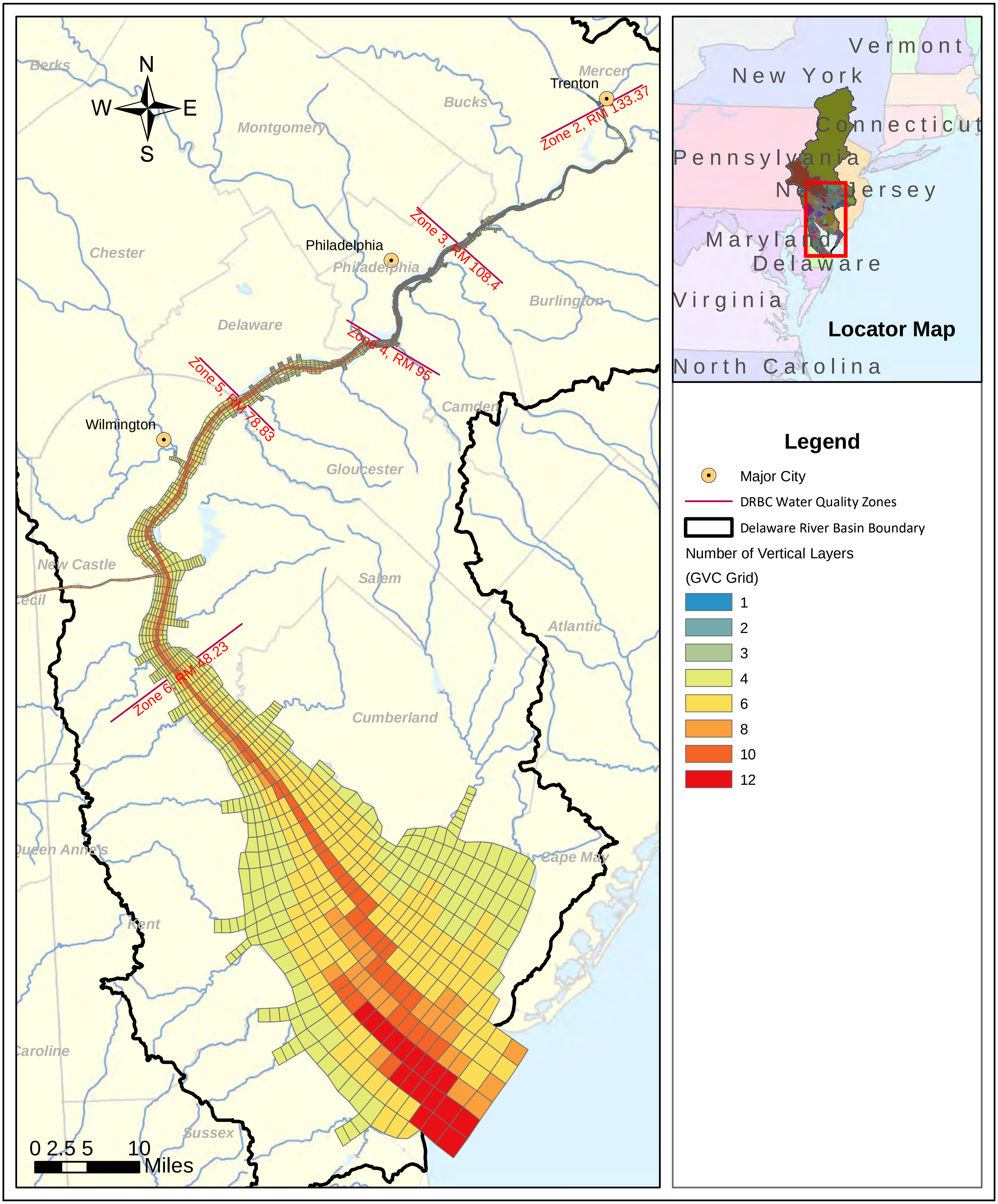


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Figure 2.3-3
Number of Vertical Layers

2.4 Boundary Conditions

The hydrodynamic model requires specification of the following boundary conditions:

- Water surface elevations at the mouth of the Bay and the western end of the C&D Canal;
- Freshwater inflows into the main stem of Delaware Estuary;
- Salinity and water temperature at inflow and open boundaries; and
- Climate/meteorological forcings including air temperature, pressure, dew point, precipitation, wind speed and direction, and solar radiation.

2.4.1 Water Surface Elevations

In this study, verified hourly data of water surface elevations collected at NOAA stations at Lewes, DE (8557380) and Chesapeake City, MD (8573927) were used to specify open boundary conditions at the mouth of the Bay and the west end of C&D Canal, respectively. These data include the signals of astronomical tides and meteorological forcing (i.e., sub-tidal signal), which are the two major components of water surface elevation. The dominant astronomical tidal constituent in the model domain is the principal lunar semi-diurnal (M2). All water surface elevation data were converted to the vertical datum of NAVD88 in meters to be consistent with the bathymetry (Table 2.4-1).

Table 2.4-1 Summary of NOAA Stations and Datum Conversion

No.	Station	Station ID	Vertical Datum	Conversion Factor to NAVD88 m
1	Lewes, DE	8557380	NAVD88	0.000
2	Cape May, NJ	8536110	NAVD88	0.000
3	Brandywine Shoal Light, DE	8555889	MLLW	-0.872
4	Ship John Shoal, NJ	8537121	MLLW	-0.963
5	Reedy Point, DE	8551910	NAVD88	0.000
6	Chesapeake City, MD	8573927	MLLW	-0.474
7	Delaware City, DE	8551762	MLLW	-0.887
8	Marcus Hook, PA	8540433	MLLW	-0.890
9	Philadelphia, PA	8545240	NAVD88	0.000
10	Burlington, Delaware River, NJ	8539094	MLLW	-1.016
11	Newbold, PA	8548989	MLLW	-1.152

Notes: NAVD 88 meter = MLLW meter + Conversion Factor
Conversion factor values are based on NOAA's Vertical Datum Transformation, V.3.6.1

2.4.2 Freshwater Inflows

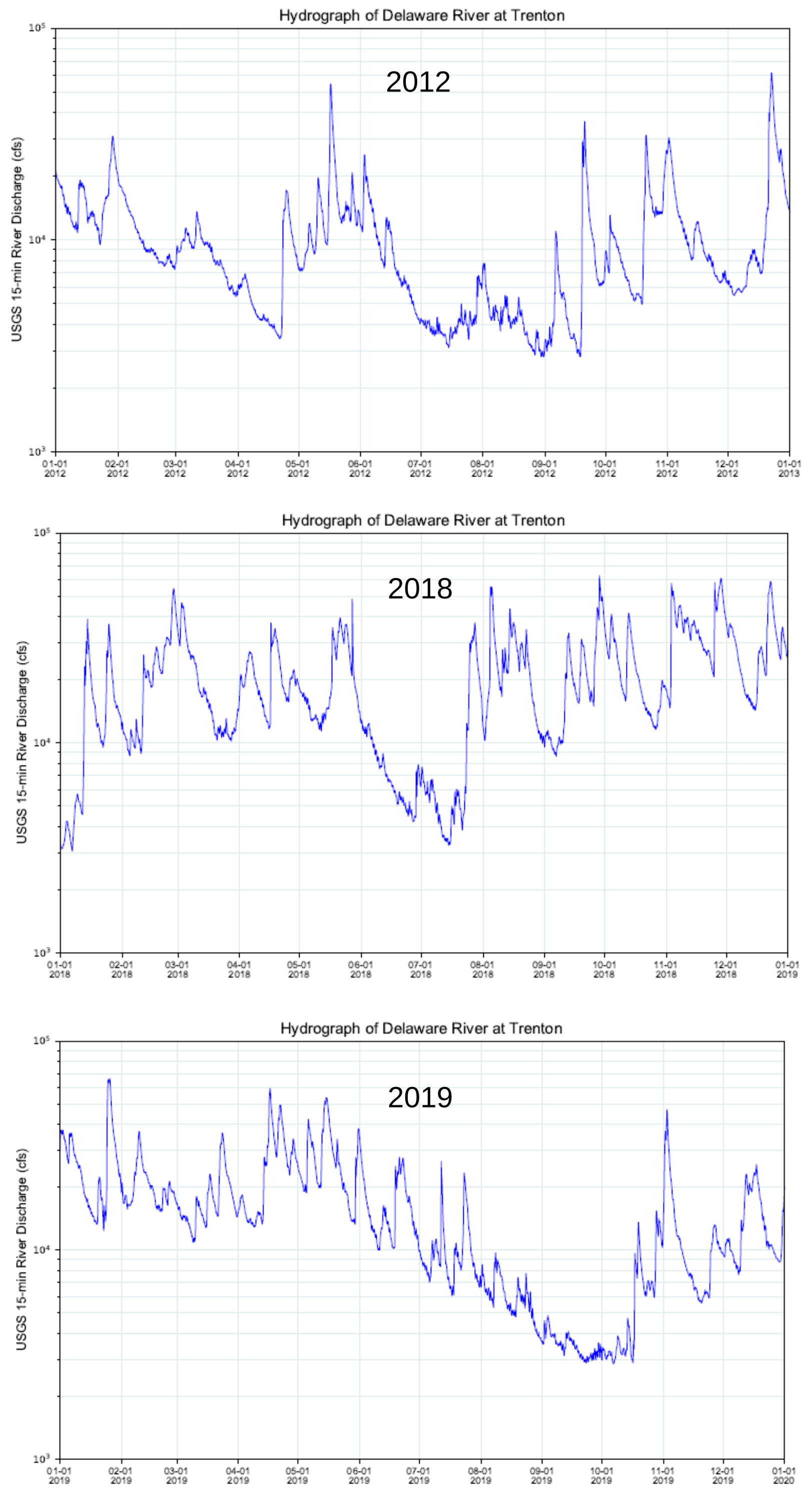
Freshwater inflows into the main stem of Delaware River estuary include the flows from upstream boundary, tributaries (gaged and ungaged), non-point sources and MS4, point source dischargers, CSOs, direct precipitation onto the waterbody, and withdraws. Groundwater and surface water interaction was not explicitly considered in this study.

The flow rate at the upstream boundary was specified based on data collected at USGS gaging station 01463500 (Delaware River at Trenton NJ). Flow at Trenton during 2012, 2018 and 2019 period are presented in Figure 2.4-1. Inflows from other 32 major tributaries were specified using available USGS gaging station data. Hourly flow data were utilized for the Delaware River at Trenton and Schuylkill River because of their significant contributions to the total freshwater input, while daily flows were utilized for the rest of tributary inflows. Missing streamflow values were imputed by fitting a structural time series model to the data followed with a smoothing function. Average flow rates of the tributaries during the 2018-2019 model calibration period are provided in Table 2.4-2 below.

Table 2.4-2 Summary of Tributary Flow Boundaries

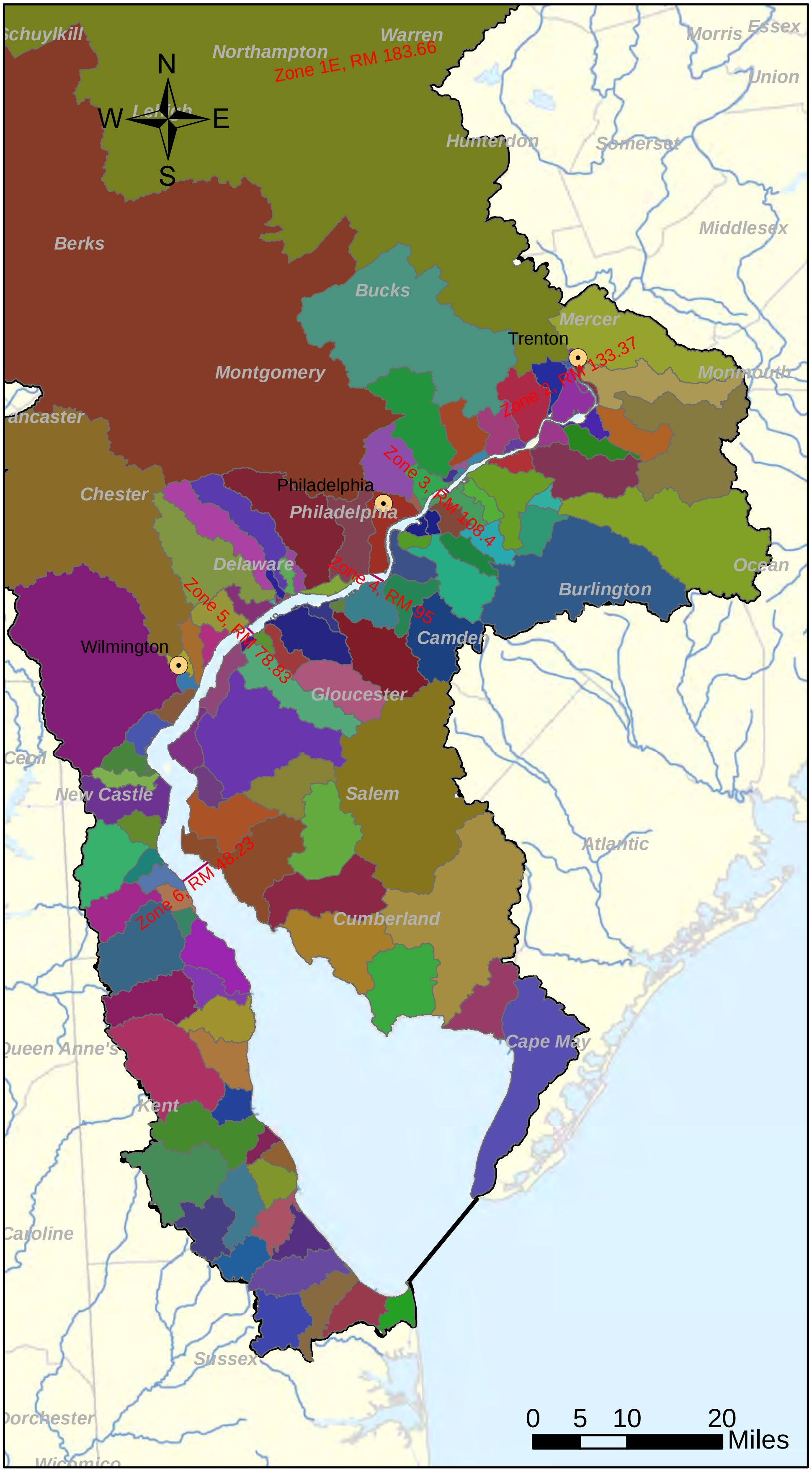
Count	Tributaries	Mean flow during 2018-2019 (cfs)	RM	USGS Gauge
1	Delaware River at Trenton (mainstem)	17,877	134.3	USGS01463500
2	Assunpink Creek	220	133.8	USGS01464000
3	Crosswicks Creek	217	128.41	USGS01464500
4	Neshaminy Creek	526	115.63	USGS01465500
5	Rancocas Creek North Branch	295	111.06	USGS01467000
6	Rancocas Creek South Branch	260	111.06	USGS01465850
7	Poquessing Creek	44	111.66	USGS01465798
8	Pennypack Creek	135	109.75	USGS01467048
9	Pennsauken Creek South Branch	34	105.4	USGS01467081
10	Pennsauken Creek North Branch	37	105.4	N/A
11	Frankford Creek	30	104.6	USGS01467087
12	Cooper River	67	101.58	USGS01467150
13	Big Timber Creek	83	95.46	N/A
14	Schuylkill River	5,176	92.47	USGS01474500
15	Mantua Creek	86	89.66	N/A
16	Darby Creek	154	85.28	N/A
17	Crum Creek	73	84.9	USGS01475850
18	Ridley Creek	78	84.2	USGS01476480
19	Chester Creek	151	82.93	USGS01477000
20	Raccoon Creek	66	80.66	USGS01477120
21	Oldman Creek	69	77	N/A
22	Christina River	570	70.73	USGS01478000
23	Brandywine Creek	757	70.73	USGS01481500
24	Salem River	145	58.37	USGS01482500
25	Alloway Creek	54	54.45	N/A
26	Appoquinimink River	58	51.2	N/A
27	Blackbird Creek	38	49.25	N/A
28	Smyrna River	116	45	N/A
29	Cohansey River	73	37.8	USGS01412800
30	Leipsic River	78	35	USGS01483500
31	St. Jones River	145	23.7	USGS01483700
32	Murderkill River	84	23.14	USGS01484000
33	Maurice River	387	21.03	USGS01411500

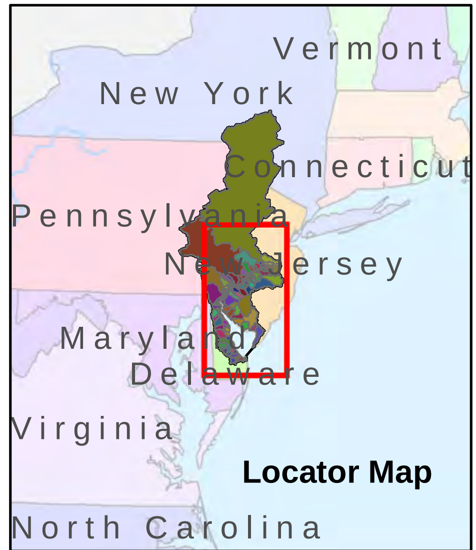
Figure 2.4-1 Hydrograph of Delaware River at Trenton



Discharge gaging stations are often located at or above the head of tide, often leaving substantial portions of the watershed ungaged. For these areas and upland tributaries absent of flow data, flow rates were estimated based on data from a similar watershed. Similarity among gaged and ungaged catchments was determined by environmental classification owing to the availability of high-quality, hydrologically relevant digital datasets; classes are defined based on physical and climatic attributes that are assumed to produce a similar hydrologic response independent of geographic location. Basin characteristics were chosen among broad categories such as morphology (channel length and slope, basin shape, drainage density, etc.), soil properties, land use/land cover, geology, and climate and constitute a subset of those typically used in the regionalization of streamflow statistics. A hierarchical agglomerative clustering technique (HACA) was used to objectively determine the optimal number of clusters with similar descriptive attributes and to assign membership of 124 subwatersheds (gaged and ungaged, Figure 2.4-2) to seven general landscape types. Reference gages were assigned to ungaged watersheds within their respective clusters. The daily hydrograph at each reference gage was partitioned into baseflow and runoff components using standard hydrograph separation techniques prior to transfer of flow information using the drainage-area-ratio approach. Low-gradient, tidally influenced basins directly adjacent to the river and bay were assigned runoff only, all others were assigned the full hydrograph. The inflow boundary of a tributary was set at the DRBC monitoring stations, whereas inflow boundaries for all others were set at the outlet point of the subwatershed. This approach results in 103 aggregated non-point sources and MS4 freshwater inputs, in additional to 33 major tributaries.

A point discharge monitoring program was conducted to estimate loadings of nutrient from individual facilities during the model calibration period of 2018-2019. A total of 71 major point source discharges were selected (Table 2.4-3). These dischargers were categorized into Tiers 1, 2, and 3 according to their nutrient loadings. Tier 1 and 2 dischargers collected samples weekly and monthly, respectively. No additional monitoring was required for Tier 3 dischargers. Measured flow rates during this monitoring program were used to specify freshwater inflows from Tier 1 and 2 dischargers. Tier 3 flow rates were based on monthly NPDES reports. Point discharger flows during model confirmation period of 2012 were based on the Round 1 of Point-Discharge Monitoring started in 2011-2015.





Legend

- Major City
- DRBC Water Quality Zones
- Delaware River Basin Boundary

Notes:
Color coded polygons represent sub-basin drainage areas.
Total 124 sub-basin dranage areas were used to prepared the flows for MS4 and NPS.

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Figure 2.4-2
Dileanation of Watershed Drainnage Areas

Table 2.4-3 Summary of Point Source Discharges

Count	NPDES ID	Facility Names	Tiers
1	PA0026701-201	Morrisville Borough Municipal Authority	1
2	NJ0020923-001A	Trenton Sewer Utility	1
3	NJ0026301-001A	Hamilton TWP WPCF	1
4	PA0026468-001	Lower Bucks County JMA	1
5	NJ0023361-001A	Willingboro Water Pollution Control Plt	1
6	PA0026689-001	PWD Northeast	1
7	NJ0026182-001A	Delaware 1 WPCF (Camden)	1
8	PA0026662-001	PWD Southeast	1
9	PA0026671-001	PWD Southwest	1
10	NJ0024686-001A	GCUA	1
11	PA0027103-001	Delcora	1
12	DE0020320-001	City of Wilmington	1
13	NJ0024678-001A	Bordentown SA Black's Creek STP	2
14	PA0043818-001	GROWS Landfill, Waste Management	2
15	NJ0023701-001A	Florence Township STP	2
16	NJ0021709-002A	Central Ave. WTP, Burlington TWP	2
17	PA0027294-001	Bristol Borough Water & Sewer Authority	2
18	NJ0024660-002A	Burlington City STP	2
19	NJ0025178-001A	Hartford RD WPCF	2
20	NJ0024015-001A	Mount Holly WPCF	2
21	NJ0022519-001A	Riverside Sewerage Authority	2
22	NJ0023507-001A	Delran TWP Sewer Utility Department	2
23	NJ0024007-001A	Cinnaminson Sewerage Authority T2	2
24	NJ0024996-001	Moorestown TWP WWTP	2
25	NJ0005029-001	Paulsboro Refining Company	2
26	NJ0005045-001A	Polymer Additives Inc. (VSC)	2
27	NJ0005100-662A	Chambers Works, Tier-2	2
28	NJ0021598-001A	Pennsville Sewerage Authority	2
29	DE0000256-601	Delaware City Refining	2
30	NJ0024651-001A	Cumberland County Utilities Authority	2
31	DE0020338-001	Kent County Levy Court	2
32	NJ0029467-001A	Millville WTP	2
33	NJ0004995-441A	Mercer Generating Station	3
34	PA0013463-203	US Steel, Fairless-203	3
35	PA0013463-103	US Steel, Fairless-103	3
36	PA0012769-009	Rohm & Haas Chemicals, Bristol	3
37	NJ0005002-WTPA	PSEG Fossi,Burlington Generating Sta	3
38	NJ0027481-001	Beverly Sewerage Authority	3
39	NJ0004375-001A	Hoeganaes Coorporation	3
40	NJ0021610-001A	Riverton STP	3
41	NJ0024449-001A	Palmyra STP	3
42	NJ0031216-001B	Menu Food Inc	3
43	NJ0004090-001A	MAFCO Worldwide Corp	3
44	NJ0005584-003A	ORMER BP PAULSBORO TERMINAL NO 4555	3
45	NJ0004219-001	Chemours Company Repauno	3
46	PA0028380-001A	Tinicum TWP	3
47	PA0013323-001	Boeing	3
48	PA0013714-107	Exelon Generating Company, Eddystone	3
49	PA0051713-001	Evonik Degussa	3
50	NJ0005240-001A	Bridgeport Disposal LLC	3
51	NJ0027545-001A	Logan Township MUA	3
52	PA0012637-201	Monroe Energy	3
53	DE0000655-001	General Chemical	3
54	PA0244449-001	FPL Energy Marcus Hookl	3
55	DE0050911-001	Occidental	3
56	NJ0004286-001	Mexichem Specialty Resins	3
57	DE0000051-001	DuPont Edgemoor	3
58	DE0000558-016	Calpine Mid-Atlantic Generation	3
59	NJ0024023-001A	Penns Grove Sewerage Authority	3
60	NJ0021601-001A	Carneys Point STP	3
61	DE0000612-001	Formosa Plastics	3
62	DE0021555-001	Delaware City STP	3
63	NJ0024856-001A	Salem City Wastewater Treatment Facility	3
64	DE0021539-001	Port Penn STP	3
65	DE0050547-001	Middletown-Odessa-Townsend	3
66	NJ0005622-048C	PSEG Nuclear Salem Generating Station	3
67	NJ0025411-461A	Hope Creek Generating Station	3
68	NJ0062201-001A	Canton Village STP	3
69	NJ0004766-001A	SURFSIDE PRODUCTS LLC	3
70	DE0021491-001	Milton STP	3
71	DE0021512-001	City of Lewes	3

Freshwater inflows from CSOs during the model calibration and confirmation periods were provided to various degrees of resolution by four municipalities: Philadelphia Water Department (PWD), Camden County Municipal Utilities Authority (CCMUA), Delaware County Regional Water Quality Control Authority (DELCORA), and City of Wilmington (CoW). For simplification all CSO outfalls were aggregated to 14 locations: five for PWD CSOs; three for CCMUA CSOs; three for DELOCRA CSOs; and three for CoW CSOs.

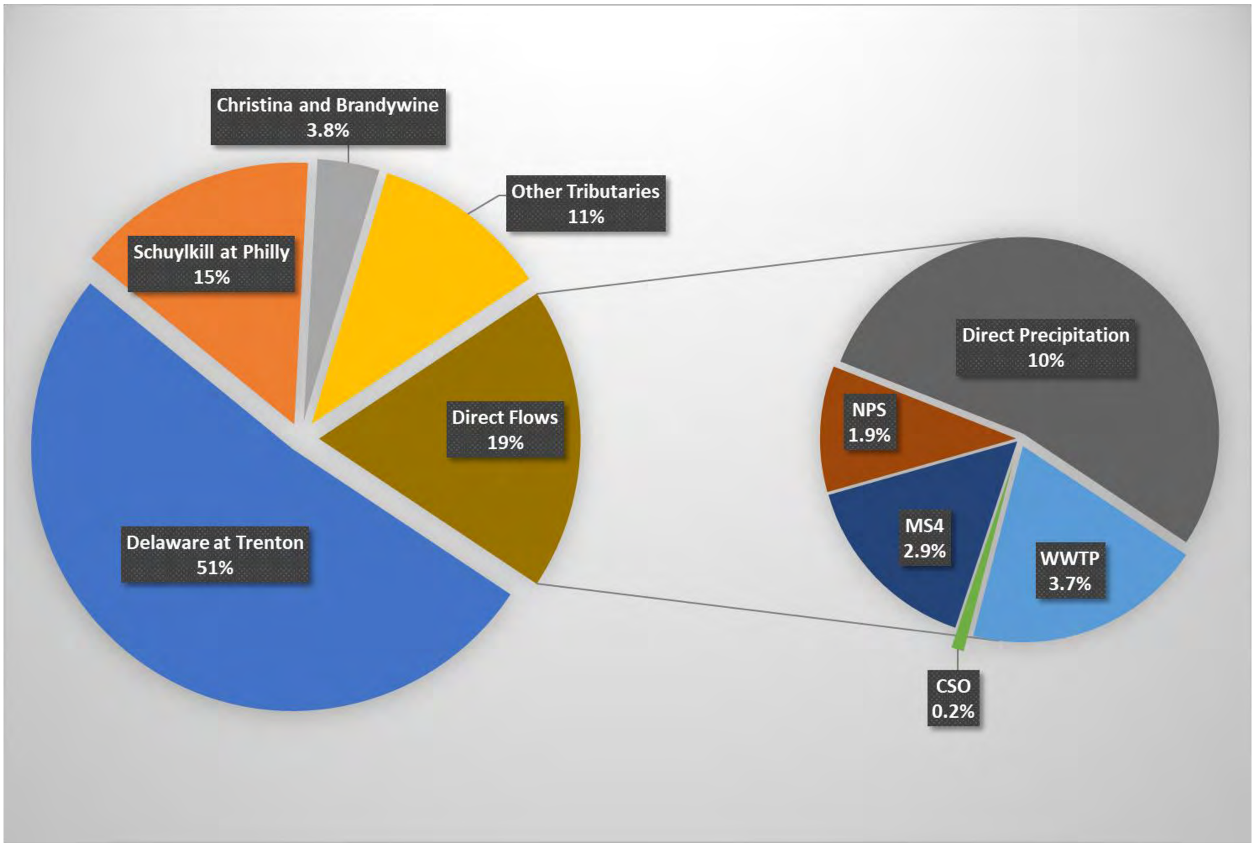
Eight major withdrawal facilities were included in the model and are listed in Table 2.4-4. The monthly withdraw rates were based on DRBC Water Use database for the model confirmation period of 2012 and assumed insignificant change for the model calibration period of 2018-2019, since the data for 2018-2019 are not available yet.

Table 2.4-4 Summary of Major Withdrawals

Count	Facility Names
1	USX-US Steel Division
2	Lower Bucks County Joint Municipal Authority
3	Aqua Pennsylvania, Inc.
4	BURLINGTON CITY WATER DEPT
5	Philadelphia City
6	Kimberly-Clark Corporation
7	Chemours Company, FC, LLC., - Edge Moor
8	Chambers_Dupont_Chemours_Combined

Based on boundary conditions developed for 2018 – 2019, the contribution of freshwater to the total water inflow budget from the mainstem at Trenton, Schuylkill River, the combined Christina and Brandywine Rivers, and remaining tributaries is 51%, 15%, 3.8%, and 11%, respectively. Point source discharges contribute 3.7%, and direct watershed contributions from non-point source (NPS) discharge, including Municipal Separated Storm Sewer System (MS4) and Combined Sewer Overflows (CSOs), contribute 3.8%. Direct precipitation onto the Delaware Estuary waters contributes another 10% of the total water load (Figure 2.4-3).

Figure 2.4-3 Freshwater Budget 2018-2019



2.4.3 Water Temperature and Salinity

Salinity can be calculated based on specific conductance or from conductivity. The conversion from USGS specific conductance or from NOAA conductivity measurements to salinity is summarized in the book "Standard Methods for the Examination of Water and Wastewater" 19th Ed. 1995 (American Public Health Association. 1995). 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. Temporal variations in water temperature, specific conductance and salinity at USGS station (1463500) at Trenton NJ during 2019, for example, are shown in Figure 2.4-4.

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 specific conductance data available, salinity was 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. A data gap for the Schuylkill River specific conductance dataset from January 1 to March 5 of 2018 was filled with 2019 data for the same period. The salinity from point source discharges was set to zero all the time.

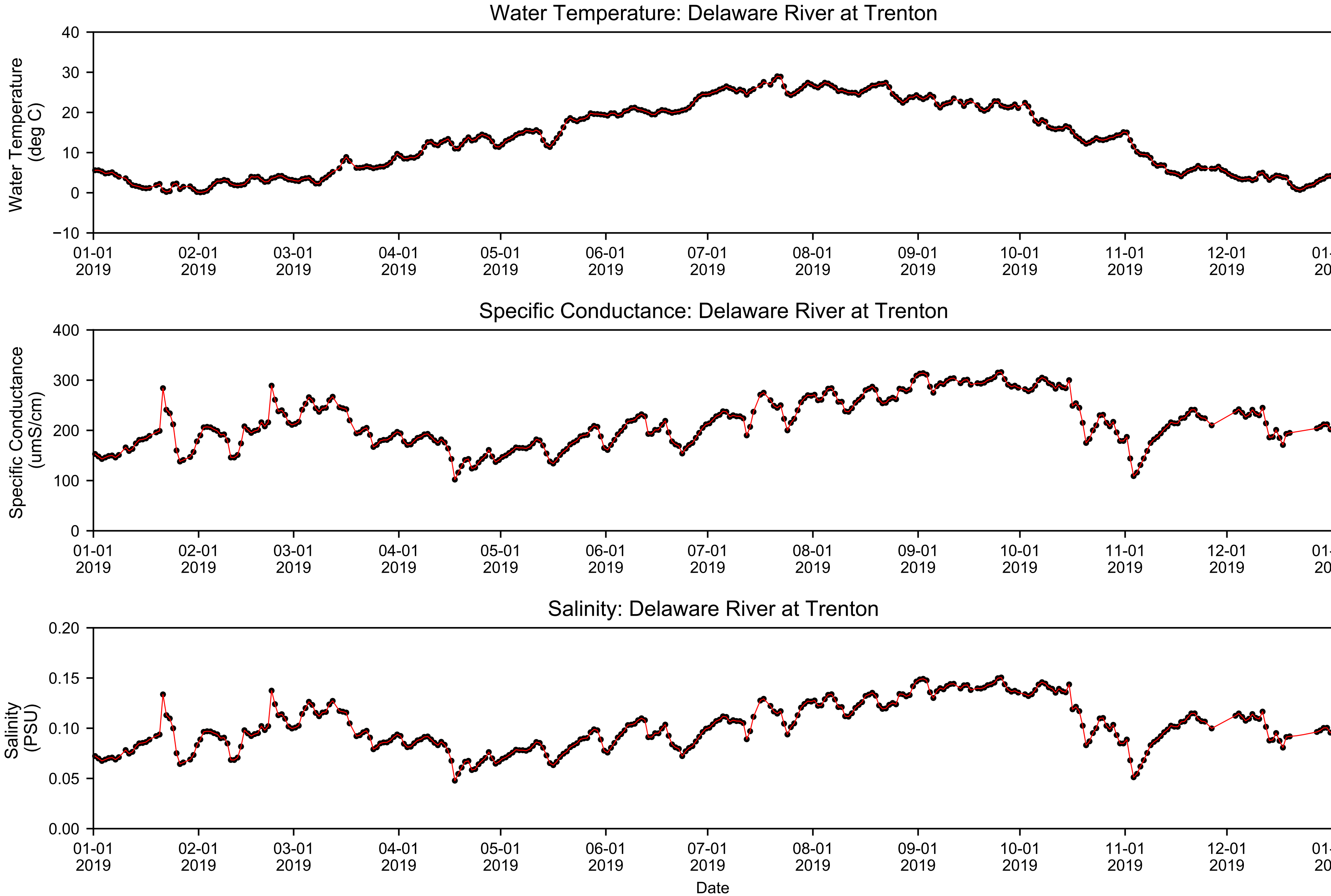


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Figure 2.4-4c
Water Temperature and Specific Conductance Data at USGS Station 01436500 Delaware River at Trenton During 2019
Historical USGS data were used and interpolated to hourly time interval.

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Tributary temperatures boundaries are very important to model performance and will be even more so when applied to a eutrophication model, since dissolved oxygen solubility varies with temperature and all biological and chemical processes are impacted by temperature. Tributary temperatures were assigned based on continuous temperature measurements available as shown in Table 2.4-5. Tributaries with grab temperature measurements were assigned temperatures from tributaries with continuous temperature based on a correlation matrix developed for this purpose. R-squared values all exceeded 0.95. Tributaries without continuous or grab temperature data were assigned based on geographic proximity. Daily or weekly effluent data from Tiers 1 and 2 point source discharges were used to assign effluent temperatures, while Tier 3 discharges were assigned the temperatures recorded at the Delaware River at Trenton or the Schuylkill River based on their location upstream or downstream of Schuylkill River.

Table 2.4-5 Availability of Tributary Temperature Data for Simulation Periods

USGS	Location	Temperature Data	CY2019	CY2018	CY2012
01464290	Crosswicks Ck at Hockamik Rd near Cookstown NJ	10/31/2019 through present			
01464500	Crosswicks Creek at Extonville NJ	01/31/2020 through present			
01465500	Neshaminy Creek near Langhorne, PA	12/19/2018 through present	X		
01465850	South Branch Rancocas Creek at Vincentown NJ	11/14/2019 through present			
01466500	McDonalds Branch in Byrne State Forest NJ	02/08/2012 through present	X	X	X
01466900	Greenwood Branch at New Lisbon NJ	11/12/2019 through present			
01467000	North Branch Rancocas Creek at Pemberton NJ	01/06/2020 through present			
01467005	NB Rancocas C at Iron Works Park at Mount Holly NJ	01/30/2020 through present			
01467024	Rancocas Creek at Bridgeboro NJ	09/25/2019 through present			
01467081	South Branch Pennsauken Creek at Cherry Hill NJ	11/07/2019 through present			
01467087	Frankford Creek at Castor Ave, Philadelphia, PA	10/01/2018 through present	X		
01467150	Cooper River at Haddonfield NJ	02/25/2020 through present			
01475510	Darby Creek near Darby, PA	11/19/2018 through present	X		
01475530	Cobbs Cr at U.S. Hghwy No. 1 at Philadelphia, PA (winter gaps)	10/01/2018 through present	X		
01477070	Raccoon Creek at Wrights Mill NJ	01/29/2020 through present			
01412000	Menantico Creek near Millville NJ	09/24/2019 through present			
01412080	Manumuskin River at Cumberland NJ	10/01/2019 through present			
01483050	Alloway Creek at Hancocks Bridge NJ	10/12/2018 through present	X		
01484080	Murderkill River at Frederica, DE	06/11/2010 through present	X	X	X
01484272	Broadkill River near Milton, DE	12/21/2016 through present	X	X	
01463500	Delaware River at Trenton NJ	10/01/2007 through present	X	X	X
01474500	Schuylkill River at Philadelphia, PA	10/01/2018 through present	X		
01483177	Appoquinimink River Near Odessa, DE	10/26/2011 through present	X	X	X
01481500	Brandywine Creek at Wilmington, DE	10/01/2007 through present	X	X	X
01480065	Christina River at Newport, DE	10/01/2007 through present	X	X	X

The surface water temperature and salinity at ocean open boundary was established based on water temperature and conductivity data collected at NOAA Station (8557380) at Lewes, DE. For the year 2012 period, the data from Lewes were not available; data collected at NOAA Station (8555889) at Brandywine Shoal Light (which is about 10 miles from the mouth of the bay) was adjusted by adding 3 ppt to reflect the salinity gradient in the estuary and used for specification of the boundary conditions. The boundary salinity was further adjusted based on the surface salinity values plus a small adjustment of +3.5 ppt to reflect the vertical stratification at lower depths. The adjustment was applied from the third layer from the top to the bottom, and linear transition was made for the top three layers.

A similar approach was used for water temperature boundaries. Water temperature varies over the course of the year significantly. It was assumed that the near-surface water temperature at the ocean open boundary is about the same as the observed water temperature recorded at 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, which is shown in Table 2.4-6. The averaged 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.

Table 2.4-6 Monthly Mean Water Temperature near the Mouth of Delaware Bay

Month	Water Temp. (surface)	Water Temp. (Depth = 5 m)	Water Temp. (Depth = 10 m)	Difference (surface - D10m)
1	7.11	7.15	7.19	-0.08
2	5.08	5.12	5.38	-0.3
3	5.63	5.58	5.5	0.13
4	10.42	9.19	8.68	1.74
5	14.76	14.24	12.79	1.97
6	20.45	19.76	17.21	3.24
7	23.93	23.09	19.67	4.26
8	24.35	23.94	21.74	2.61
9	21.9	21.81	21.67	0.23
10	16.29	16.42	16.44	-0.15
11	15.1	15.15	15.25	-0.15
12	10.14	10.39	10.39	-0.25
* This is based on WOA13 database				

The water temperature and salinity boundary conditions at 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), a rating curve was used to specify the salinity boundary conditions. Multiple-linear regression analysis was conducted using data collected at 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. The 30-day moving averaged salinity data were used in the analysis and resulted in a regression correlation coefficient R square of 0.77. The observed and predicted salinity at Chesapeake City during the same period (04-01-2017 to 05-31-2019) is presented in Figure 2.4-5. The salinity (ppt) rating curve is given as:

$$\boldsymbol{S = 0.1832 + 0.40083\, S_r + 0.00885 \times 10^6 \times Q_m^{-1}} \qquad \textit{(Eqn 2.4-1)}$$

where *S* = Daily averaged salinity at Chesapeake City (western end of C&D canal); *Sr* = Salinity at Reedy Island; and *Qm* = flow rate (in cfs) at USGS Station at Susquehanna River at Marietta, PA. Daily averaged salinity at Chesapeake City is about half of that observed at Reedy Point; however, the salinity is quite low when there is a high flow from Susquehanna River, indicating an inverse relationship between the salinity at Chesapeake City and Susquehanna River flow at Marietta, PA.

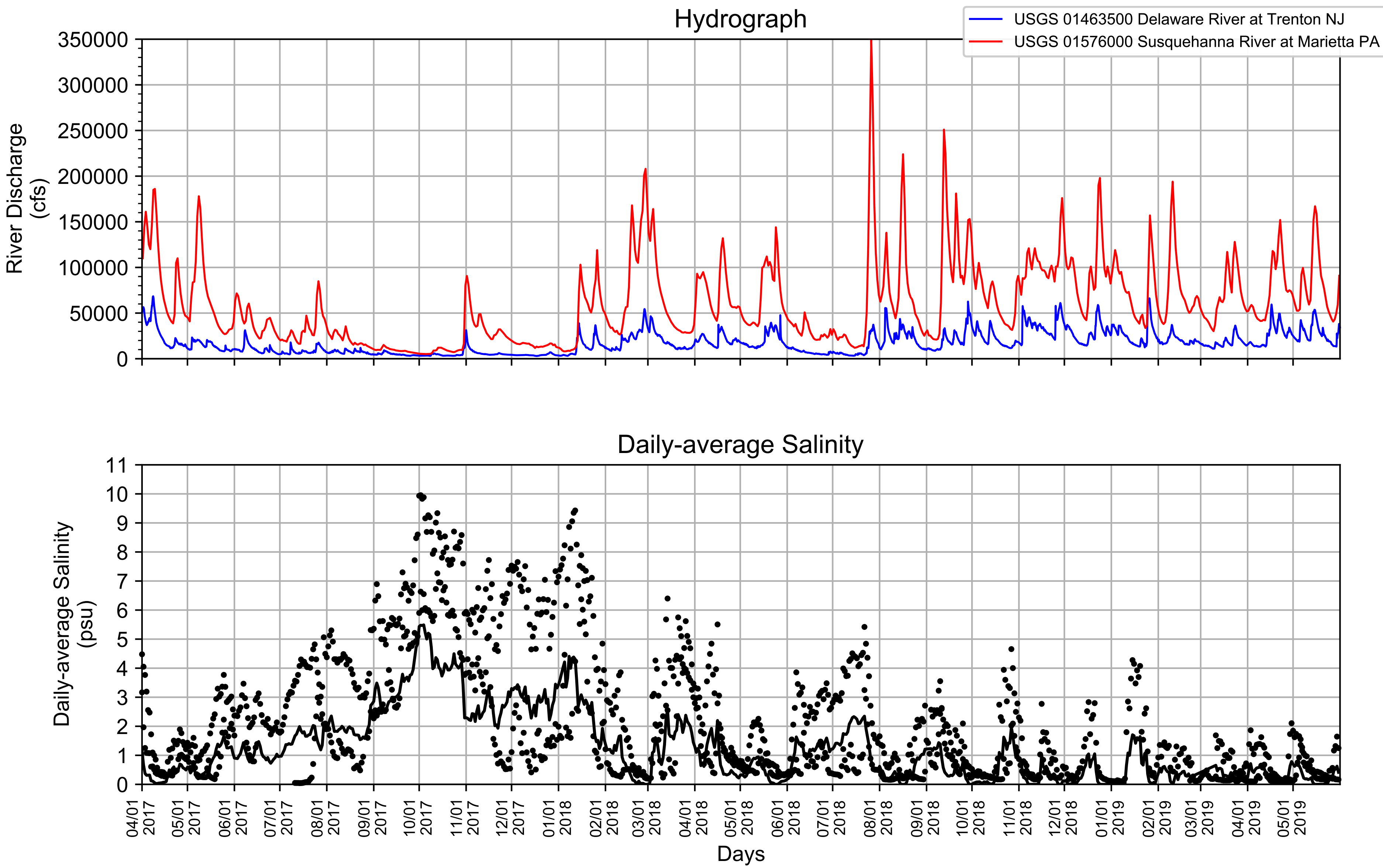

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Figure 2.4-5

Predicted Daily-averaged Salinity at Chesapeakcity using Rating Curve

Predicted salinity at Chesapeakcity was based on salinity at Reedy Island and Susquehanna River flow at Marietta, PA.

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2.4.4 Climate / Meteorological Forcing

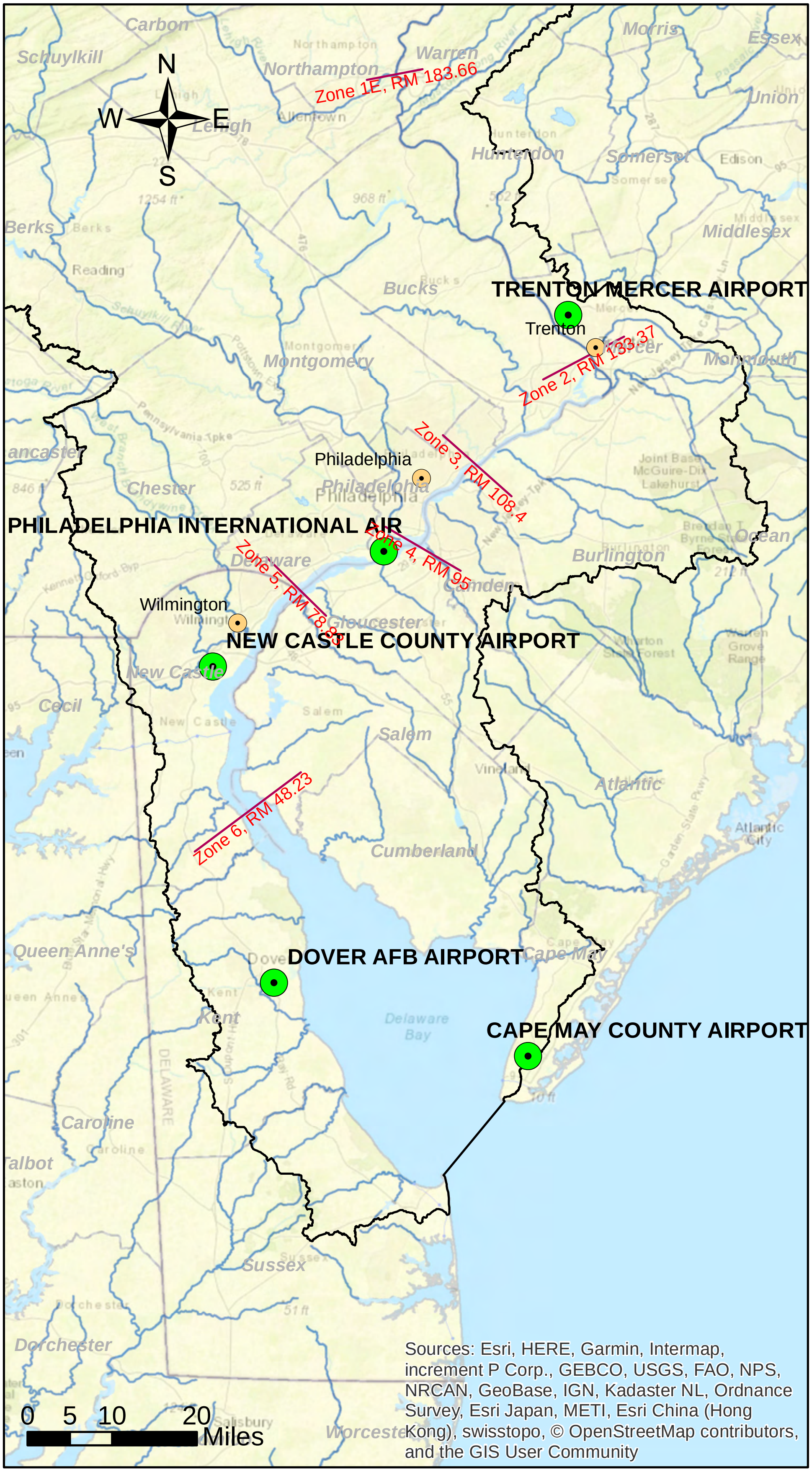
Climate/Meteorological forcing boundary conditions include air temperature and pressure, dew point, cloud conditions, wind speed, wind direction, precipitation, and net shortwave solar radiation. This information was used to calculate the heat flux at the water surface, and it affects the vertical distribution 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. Location of five weather stations that were considered by the model is shown in Figure 2.4-6 and summarized in Table 2.4-7. Temporal variations in meteorological data for 2018 and 2019 are shown in the meteorological data graphs provided in Appendix B. Noted that the shortwave solar radiation, which is required as model input, was calculated based on other parameters rather than from direct measurement from these weather stations. The theoretically calculated net shortwave solar radiation values (not shown in the figures) were used to fill in the data gap in model input files, with assumptions made for dew point, relative humidity and cloud cover.

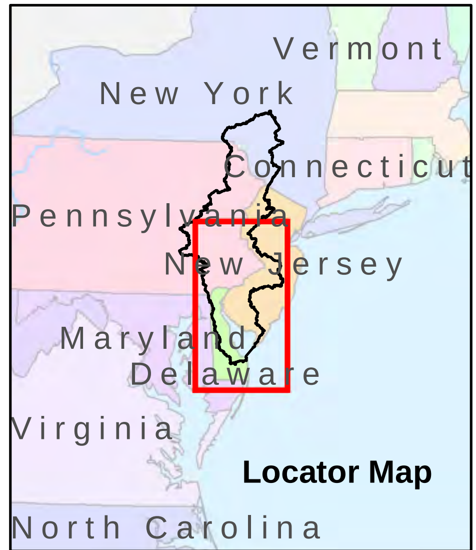
Table 2.4-7 NOAA-NCDC Weather Stations

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

The wind roses for year 2018 and 2019 shown in Appendix B depict temporal frequencies of wind speed and directions at NOAA-NCDC stations at Trenton, Philadelphia, New Castle, Dover and Cape May, respectively. Overall, over the bay area wind usually comes from the north or northwest direction during the most part of the wintertime, while most of the winds blowing from the south, southeast or southwest directions during summer period.

Heat flux into and out of the sediment bed was not incorporated into the hydrodynamic model because limited data are available to specify or calculate this heat flux. Typically, heat flux at the sediment bed is not included in estuarine hydrodynamic model simulations.





Legend

- NOAA NCDC Stations
- Major City
- DRBC Water Quality Zones
- Delaware River Basin Boundary

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Figure 2.4-6
Location of Five Weather Stations

2.4.5 Initial Conditions

Model simulations were set to start at the January 1st of the start year. A model spin-up period of 31 days was conducted before the start of each hydrodynamic model calibration simulation, with water temperature and salinity boundary conditions held the same as the ones for January of the start year. Flow rate at Trenten as well as inflows from all other flow boundaries were held as constant throughout the spin-up period. The flow rate at Trenton was set to be the same as that of January 1st of the simulated year. The initial conditions for water surface elevation, water temperature and salinity for the spin-up period were set as interpolated values between upstream boundary at Trenton and the ocean open boundary at the beginning of the spin-up simulation. The 31-day spin-up period was sufficient to ensure that any transient effects on model predictions due to initial conditions were eliminated prior to the start of a model calibration simulation. The simulation of consecutive years was set upped as “hot-start”, which the hydrodynamics parameters at the end of the previous year were taken as the initial conditions.

3. HYDRODYNAMICS MODEL CALIBRATION

3.1 Calibration Approach, Model Accuracy, and Reliability

Calibration of the hydrodynamic model was accomplished by comparing model predictions to observed water surface elevation (WSE), current velocity, temperature, and salinity data collected at various locations within Delaware River and Bay study area during the 2018 through 2019 period, as well as the drier 2012 period an additional model calibration year.

Hydrodynamic calibration focused on reproducing observed WSE, depth-averaged current velocity, and the longitudinal and vertical distribution of salinity and water temperature. Detailed summaries of model calibration periods and the data from NOAA and USGS used to calibrate the hydrodynamic model are provided in Appendix C, which formed part of the model calibration metrics. Other datasets used for model calibration include DRBC boat run dataset. Locations of NOAA tide and velocity stations are shown in Figure 3.1-1 and Figure 3.1-3. USGS stations are shown in Figure 3.1-2, while DRBC Boat Run sampling locations are presented in Figure 3.1-4. The calibration metrics are listed below:

- Predicted water surface elevation (astronomic tidal and sub-tidal fluctuations) at NOAA stations;
- Predicted current velocity at NOAA stations;
- Predicted salinity at NOAA stations;
- Predicted salinity (Chlorinity) at USGS gaging stations;
- Predicted salinity (Chlorinity) at DRBC boat-run sampling stations;
- Predicted water temperature at various NOAA and USGS stations; and
- Predicted salt front locations.

In this study, the hydrodynamic model performance was evaluated through both visual comparisons and quantitative measures to differentiate among calibration runs. Visualization of a time history of simulated result against observed data tells whether the model is able to capture the general trend and overall magnitude of the observed condition. To quantify the quality of fit between the observations and model predictions of water surface elevation, current velocity, salinity and water temperature, a series of statistical measures were used similar to those used in MacWilliams (2015). These statistical measures that characterize the model accuracy and reliability include 1) Model Skill, 2) Correlation Coefficient (r), 3) Bias and normalized bias of model estimates by the standard deviation of the observed data, 4) Root Mean Square Error (RMSE), and 5) unbiased Root Mean Square Difference (ubRMSD) and normalized ubRMSD by the standard deviation of the observed data.

Model skill is calculated as:

$$\boldsymbol{Skill} = \mathbf{1} - \left[\sum_{n=1}^{N} |X_{Mi} - X_{Oi}|^2\right] / \left[\sum_{n=1}^{N} (|X_{Mi} - \overline{X}_O| + |X_{Oi} - \overline{X}_O|)^2\right] \qquad \text{(Eqn 3.1-1)}$$

The bias of model estimates is calculated as

$$\boldsymbol{bias} = \frac{1}{N}\sum_{n=1}^{N} X_{Mi} - \frac{1}{N}\sum_{n=1}^{N} X_{Oi} \qquad \text{(Eqn 3.1-2)}$$

Negative bias indicates that the model underpredicts relative to data; positive bias indicates that the model overpredicts relative to data.

The ubRMSD is calculated as

$$\boldsymbol{ubRMSD} = \left[\frac{1}{N}\sum_{n=1}^{N}\left[(X_{Mi} - \overline{X}_M) - (X_{Oi} - \overline{X}_O)\right]^2\right]^{0.5} \qquad \text{(Eqn 3.1-3)}$$

The ubRMSD metric quantifies the model-data differences with the bias removed. It is similar to a root-mean-square error analysis, but the effects of bias are removed from the calculation. As ubRMSD increases, the difference between oscillations in the predicted and observed variable becomes larger. Formulations of the commonly used parameters Correlation Coefficient (or coefficient of determination, R^2) and RMSE are not given in this section.

Guidelines of model acceptance have been recommended by many researchers (e.g., Willmott 1981 and Bever et al. 2013). To provide a succinct method to evaluate and report the accuracy of a large number of comparisons, MacWilliams M.L. et al (2015) established a standardized set of cutoff values for both the skill scores and target statistics. In this study, statistical measures such as bias, RMSE, ubRMSE, and Correlation Coefficient (r) or R-squared are used to quantitatively evaluate the model performance. In accordance with the established Quality Assurance Project Plan (DRBC, 2019) for this project, a “weight of evidence” approach was used in close coordination with the Expert Panel in order to judge the acceptability of the model for its intended purpose.

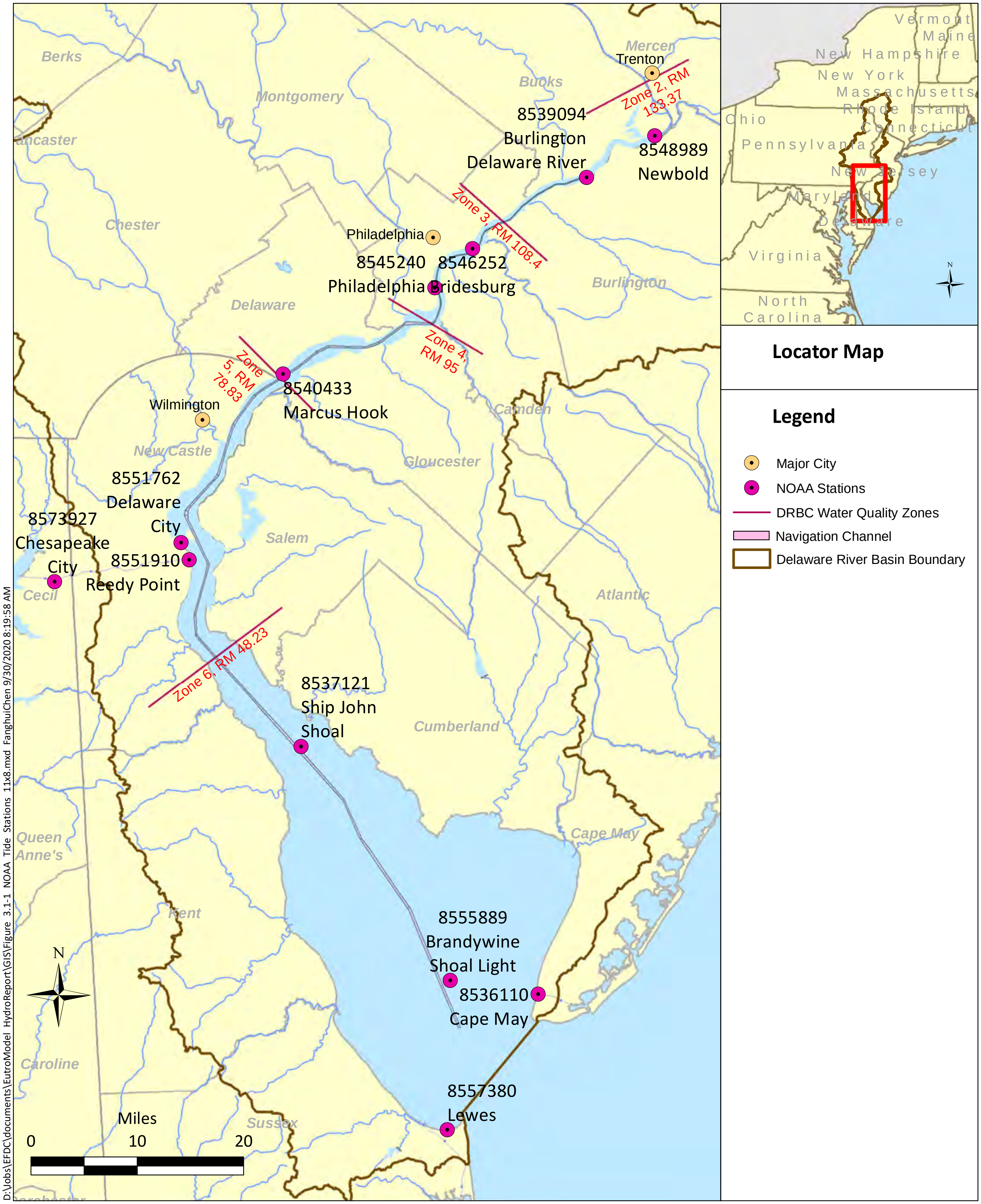

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Figure 3.1-1
Location of NOAA Tide Stations

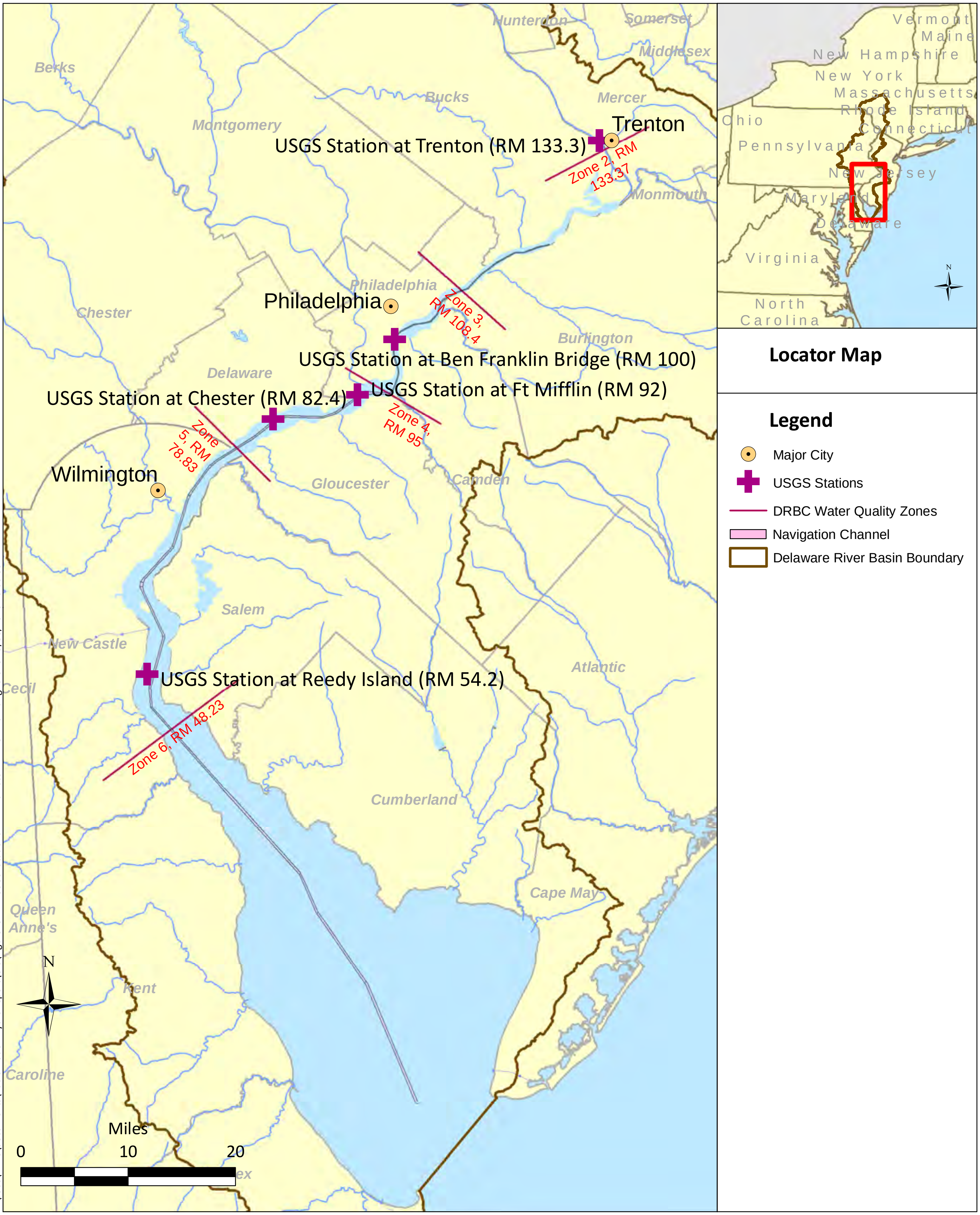

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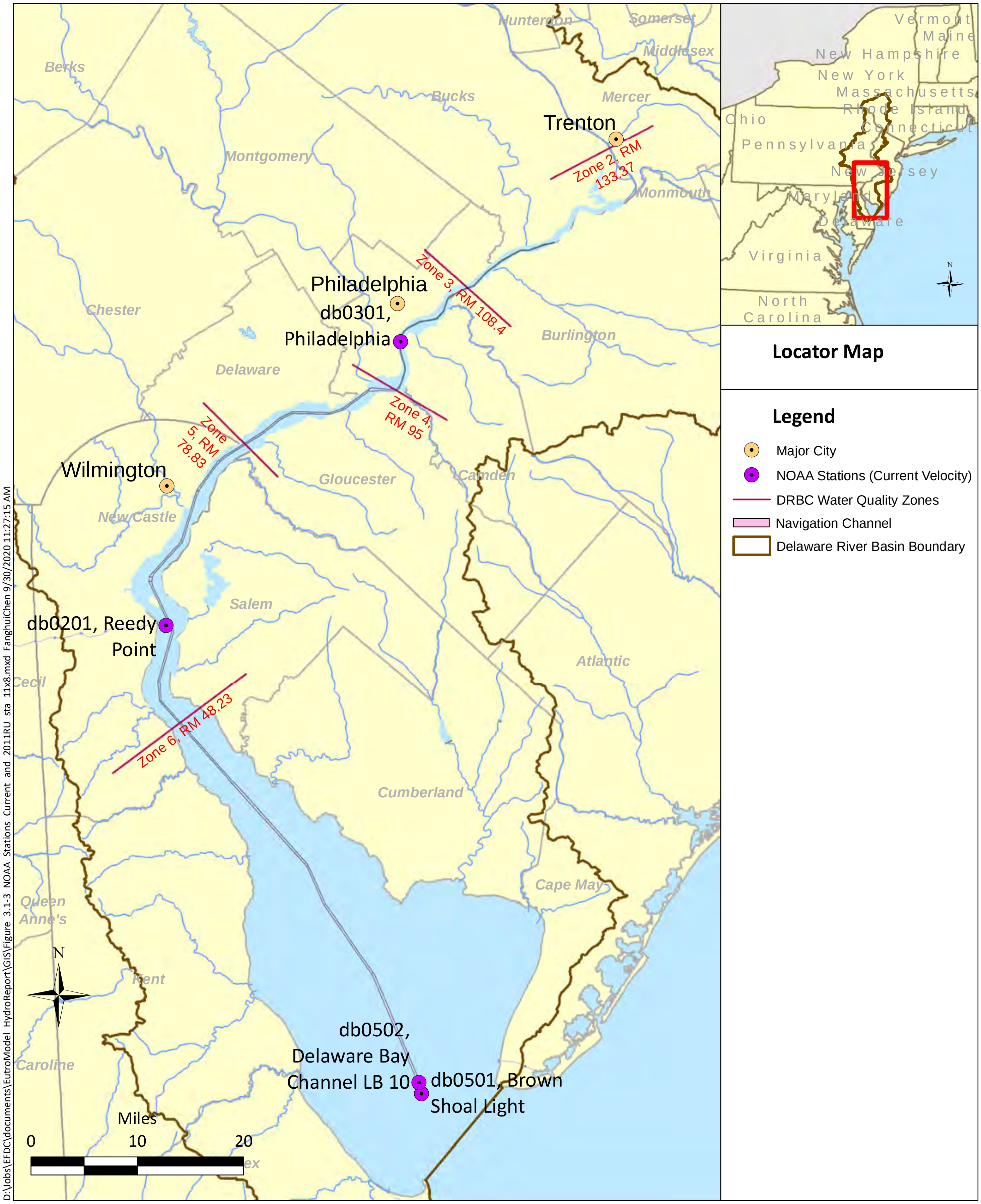
Figure 3.1-2
Location of USGS Stations on Delaware River Mainstem



D:\Jobs\EFDC\documents\EutroModel HydroReport\GIS\Figure 3.1-3 NOAA Stations Current and 2011RU sta 11x8.mxd FanghuiChen 9/30/2020 11:27:15 AM

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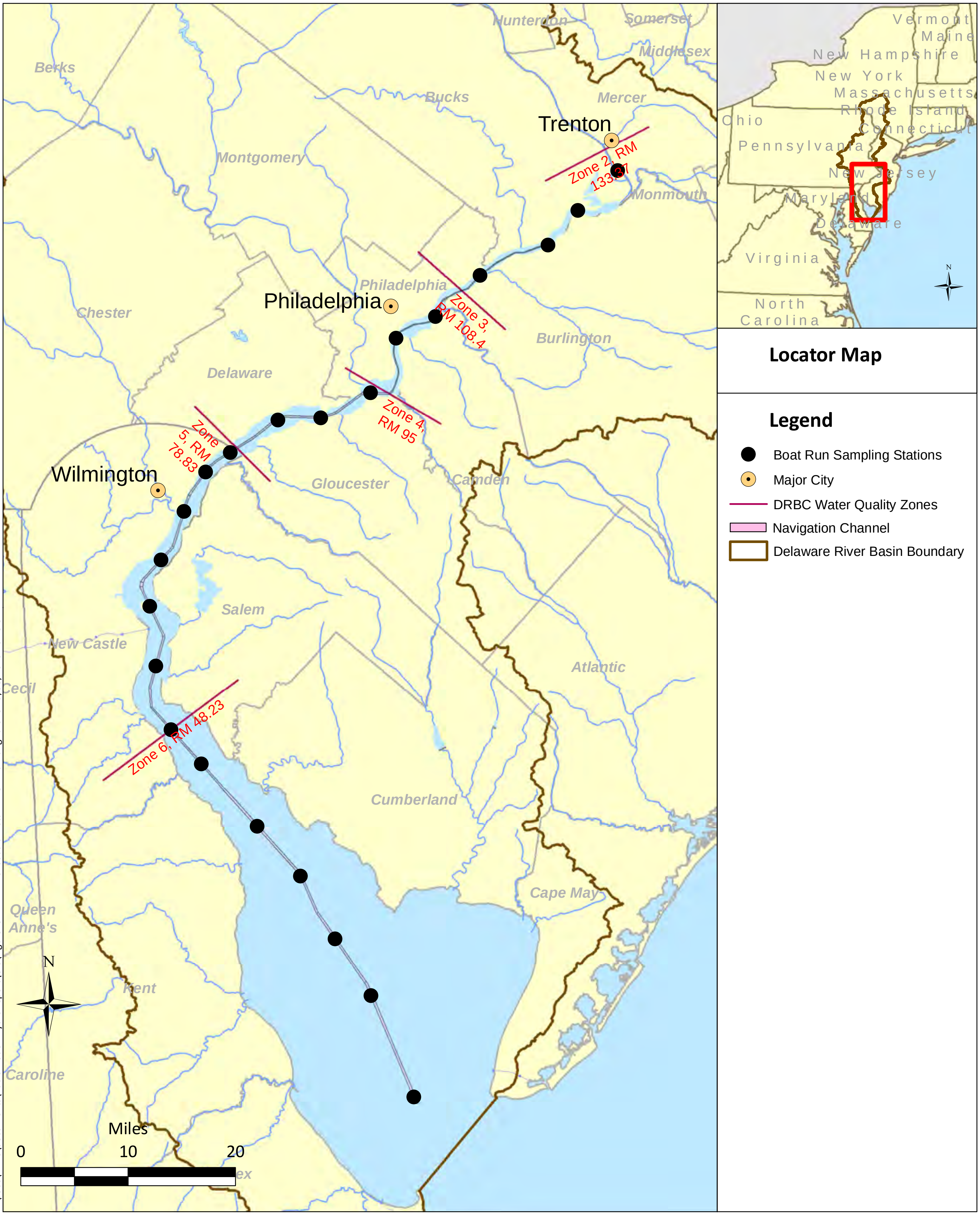
Figure 3.1-3

Location of NOAA Stations for Current Velocity Data



D:\Jobs\EFDC\documents\EutroModel HydroReport\GIS\Figure 3.1-4 DRBC boatrun sta 11x8.mxd FanghuiChen 9/30/2020 10:15 52 AM

Figure 3.1-4
DRBC Boat-run Sampling Locations

3.2 Calibration Parameters

There are four major parameters adjusted to calibrate the hydrodynamics model, described as follows in the same sequential steps used during the calibration process.

3.2.1 Bottom Roughness Height Z0

The model was first calibrated against tidal water surface elevation using the data collected at total of nine NOAA tide stations along the river by adjusting the effective bed roughness which account for the friction from the bed in the hydrodynamic model. It affects the current circulation in the system as well as the amplitude and phase of the progressive wave that propagates from the mouth of the bay towards upstream.

The composition of bottom sediments in the upper estuary includes fine sands, coarse sediment and gravel with silt accumulated in spots. Muddy and fine sediments is found in the estuarine turbidity maximum zone (ETM) approximately from RM 55 to 75 This spatial variability made it necessary to implement a spatial variable effective bottom roughness throughout the model domain, ranging from 2 to 20 mm. The range of effective bed roughness typically used in estuarine hydrodynamic models is 1 to 100 mm (Blumberg and Mellor 1987). Table 3.2-1 summarizes Z0 values used in the model and presented in Appendix D. Bottom roughness height was set to be small in Zone 5, where the ETM is located, to reflect the clay and silt sediment bed locally. The bottom roughness height was set to be slightly higher in the deeper navigation channel than the shallower area adjacent to it in Zones 4, 5 and 6 to reflect relatively rough sediment bed due to a higher current velocity and near-bed shear stress.

Table 3.2-1 Bottom Roughness Height

Zone	In Channel (mm)	Outside Channel (mm)
2 (upstream RM 132)	12	12
2 (downstream RM132, except Burlington Is. Area)	8	8
2 (Burlington Is. Area, RM 118 to 195)	12	12
3	5	5
4	2	2
5 (upstream RM 68)	1.6	1.5
5 (downstream RM 68)	1.5	1.2
6	2.2	2
C&D Canal	20	
Tributary	10	

Maximum Active Layer, KC = 12
Total Number of Cells = 1890

3.2.2 Turbulent Model Parameter

The EFDC hydrodynamics model utilizes the Mellor and Yamada (1982) turbulence model to calculate the eddy viscosity and eddy diffusivity, which governs the vertical mixing process due to turbulent shear and buoyancy from vertical stratification of water temperature and salinity. The original model of Mellor and Yamada (1982) considered equal contribution of turbulent shear and buoyancy to the length scale equation. Hans Burchard (2001) demonstrated that all empirical parameters in M&Y 1982 model were calibrated except one named E3 (or here in EFDC named as CTE3). CTE3 was set equal to CTE1 as 1.8 as the default value due to lack of information. In this study, CTE3 was calibrated through model-to-data comparison of salinity. A final CTE3 value 12 was selected, which is higher than the range of 1 to 8 given in some literature (Hans Burchard, 2001). Varying CTE3 value had minimal impact on simulated tidal water surface elevation, but significant impact on salinity intrusion. Sensitivity analysis demonstrated that increasing CTE3 enhanced salinity vertical stratification as well as salinity intrusion further upstream.

3.2.3 Adjustment to Tidal Surface Elevation in C&D Canal

As discussed, vertical datums used in the model were all relative to NAVD88 and apply to all model inputs and model outputs. NOAA tide data collected at Station (8573927) Chesapeake City, MD were based on MLLW datum, and tidal water surface elevation was converted from MLLW to NAVD88 in meters as follows: NAVD88 = MLLW – 0.474. The uncertainty for NOAA provided vertical datum that associated with datum conversion is about +/- 10 cm (based on https://vdatum.noaa.gov/docs/est_uncertainties.html).

Given the relatively large uncertainty, the adjustment to tidal water surface elevation at C&D canal western boundary within the uncertainty range was treated as an additional calibration parameter. Preliminary sensitivity analysis showed that the model predicted net flow in the C&D canal may be sensitive to the tidal water surface elevation at both ends of the canal, and the net flow moving from Chesapeake Bay to Delaware estuary (or vice versa) may have significant impact on the salinity intrusion in the Delaware River. The final adjustment of -2 cm was selected for the calibrated model in this study. The average monthly residual flow in C&D canal are 16, 7, and 55 m3/s for year 2018, 2019, and 2012 respectively. These predicted net flows are in good agreement with the data-based estimations in the literature (Ward et al. 2009).

3.2.4 Numerical Stability and Time Step

Preliminary diagnostic simulations were conducted with the hydrodynamic model to ensure that the numerical grid structure and resolution did not produce localized numerical instabilities or unrealistic results. The preliminary simulations were also used to determine the optimum timesteps for numerical stability which was determined to be 10 seconds for the 3D hydrodynamic model. In this study, wetting and drying option was turned off. The flooding and inundation of low-lying marsh areas in Zone 6 is of lesser concern in the water quality study. Excluding the wetting and drying enhances the efficiency of model simulations and minimize the error introduced in the hydro-linkage file between hydrodynamics model and the WASP water quality model.

3.3 Calibration Results

Representative results from the calibration simulations for the hydrodynamic model are presented in this section.

3.3.1 Water Surface Elevation

3.3.1.1 Astronomical Tide

Evaluating model performance with respect to water surface elevation was the first step during model calibration. The tidal 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 is about 4 feet (1.3 m), increasing to a local maximum of almost 6 feet (1.8 m) at the 37-mile point and a local maximum of 6.5 feet (2 m) at Trenton. Tidal harmonic analyses were performed (Appendix E) on the observed data and model predictions for 1-year (2019) 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. The spatial distribution of the amplitude of shallow water constituent M4 and M6 are also presented in Figure 3.3-1 with focus being on the amplification of tidal amplitude of the dominant harmonic constituent M2. The tidal amplitude of M2 increased from 0.6 m at the mouth to about 0.85-0.9 at RM 37, decreased to about 0.8 at RM 79 near Marcus Hook, and then increased again all the way to the head of tide at Trenton. The M2 amplitude at Newbold is about 1.1 m (about 126 mi from the mouth), which is about a factor of 2 increase. The maximum error in predicted M2 tidal amplitude is 9.3 cm at NOAA Station Ship John Shoal. M4 and M6 reflect the influence of river inflows as well as impact from bathymetry. A complete model-to-data comparison of the amplitude and phase of nine major harmonic constituents at nine NOAA tide stations is summarized in Appendix F. These results indicate that the hydrodynamics model adequately reproduced amplitude and phase of the astronomical tide components.

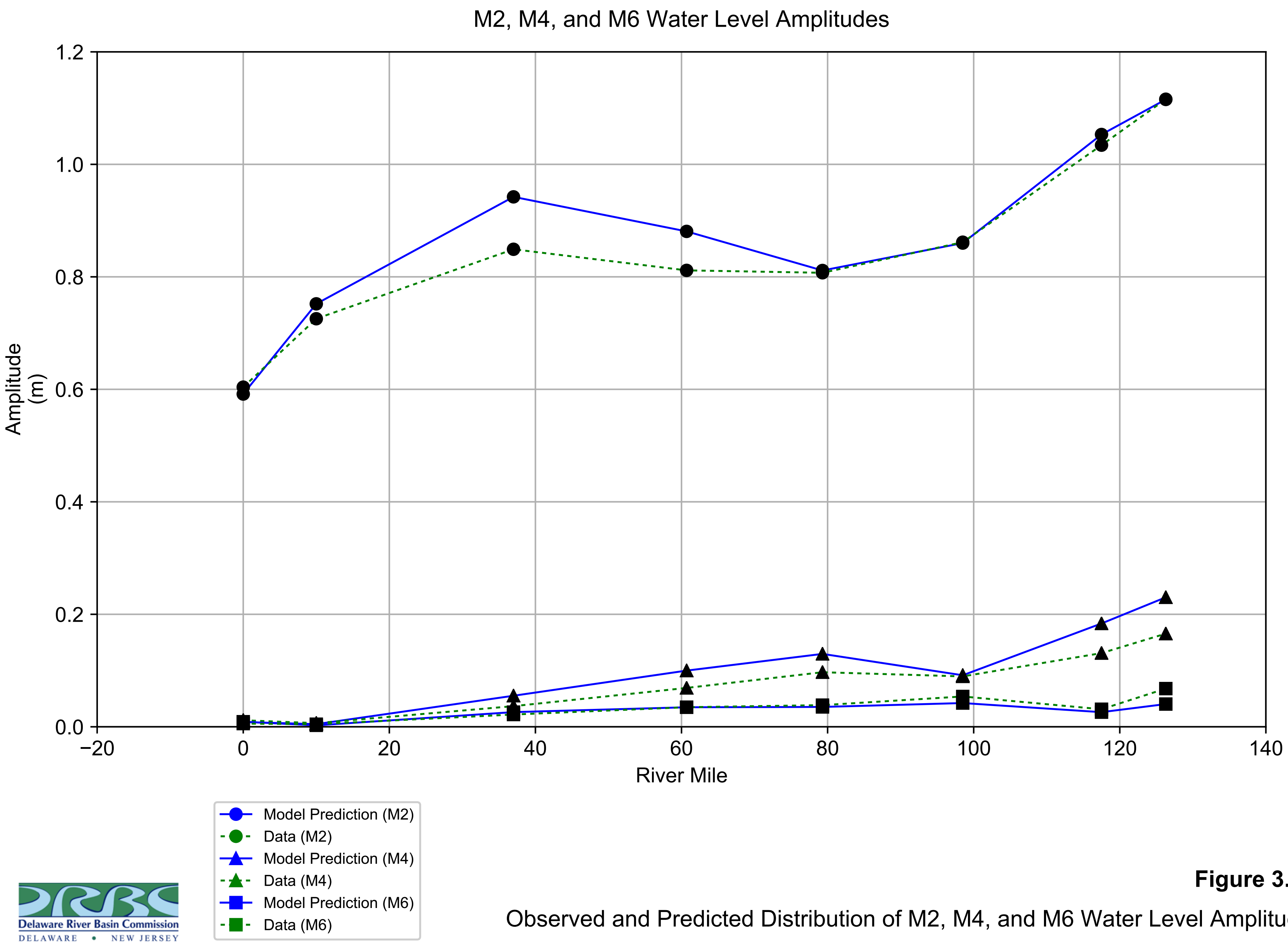


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Figure 3.3-1

Observed and Predicted Distribution of M2, M4, and M6 Water Level Amplitudes

Run ID: EFDC_HYDRO_G72_2020-05-16, Fine grid GVC, Grid 7.2, KC = 12.
Results from 01-01-2018 to 12-31-2019 were used for tidal harmonic analysis using T_Tide program.

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3.3.1.2 Water Surface Elevation

Appendix G shows time history graphs of predicted and observed water surface elevations at nine NOAA tide stations for the period of October through December of 2018 as examples to visualize the model predictions qualitatively. A more though statistical analysis evaluated 1-to-1 comparisons based on two-year simulations of 2018 and 2019 (Appendix H). Statistical measures are summarized in Table 3.3-1 to quantify the model performance.

Table 3.3-1 Model Performance Predicting Tidal Elevation at NOAA Stations (2018-2019)

Station	State	NOAA ID	N	R^2	Bias (m)	RMSE (m)	ubRMSE (m	Skill Score
Lewes*	DE	8557380	17519	0.995	0.009	0.036	0.035	0.999
Cape May*	NJ	8536110	17514	0.978	-0.008	0.089	0.088	0.994
Brandywine	NJ	8555889	17183	0.986	-0.023	0.076	0.072	0.996
Ship John Shoal	NJ	8537121	17514	0.984	-0.052	0.120	0.108	0.992
Reedy Point	DE	8551910	16487	0.979	-0.045	0.117	0.108	0.992
Delaware City	DE	8551762	17514	0.976	-0.039	0.119	0.112	0.992
Marcus Hook	PA	8540433	17514	0.966	-0.054	0.131	0.119	0.989
Philadelphia	PA	8545240	17514	0.960	-0.050	0.144	0.135	0.989
Burlington Delaware River	NJ	8539094	17514	0.971	-0.101	0.173	0.141	0.988
Newbold	PA	8548989	17514	0.968	-0.034	0.161	0.158	0.991

** These stations are too close to ocean bounary.*

The hydrodynamic model simulates water surface elevation with sufficient accuracy to satisfy the objectives of this study. Predicted tide has minimal bias (typically less than 0.1 m) and low ubRMSD (ranging from 0.04 to 0.16 m). For example, the model Bias and ubRMSE error at Philadelphia are -0.05 m and 0.13 m, respectively. Overall model skill score ranged from 0.988 to 0.999. The comparison at Burlington station is slightly worse compared to other stations. This station with the lowest skill of 0.988 is close to the downstream end of Burlington Island; bottom roughness was smoothly transitioned from 2 mm to a relatively high value 5 mm upstream. Overall, the model adequately captured the progressive wave that propagates from bay mouth all the way to Trenton as well as the increase in the amplitude as observed in the data. These statistical measures demonstrate that model accurately predicts tidal water surface elevation throughout the entire system.

3.3.2 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 of predicted current velocity. DRBC are currently working with the USGS to collect addition current velocity data in late 2019 and 2020 at addition locations. Those data will be used to strengthen the model calibration in the near future.

Representative comparisons of observed and predicted depth-averaged velocity along and cross-channel at NOAA station db0502 (Delaware Bay Channel LB 10), which is located about 7 miles from the bay mouth at the starting point of the federal navigation channel, are provided in Appendix I for period of 10/1-7/2018 in addition to 1-to-1 model-to-data comparison of the velocity magnitude for a longer time period from 9/6/2018 to 2/25/2019. The model showed a reasonably good agreement between predicted and observed depth-averaged current velocity at db0501 against the data collected during June 2012 period. Appendix I also shows the comparisons of temporal variation of the depth-averaged current velocity at db0501 for period of 6/25-30/2012, and 1-to-1 comparison based on the entire dataset for the June 2012 period.

Moving further upstream from the mouth of the bay, representative comparisons of observed and predicted depth-averaged along and cross-channel current velocity at Reedy Point, NOAA station db0201, which is located at 58 miles from the bay mouth in the mainstem near the eastern end of the C&D canal, is shown in Appendix I for period of 1/30/2012 to 2/5/2012, and the comparison of the velocity magnitude for a longer time period from 1/1/2012 to 5/5/2012 is also shown in Appendix I. The statistical measures for predicted depth-averaged current velocity at db0201 for this 4-month period are ubRMSE (14.3 cm/s), bias (-2.8 cm/s), and skill score of 0.97. These statistical measures indicate that the model adequately predicted depth-averaged current velocity magnitude at this location.

The statistical measures for predicted along-channel depth-averaged current velocity at three ADCP station locations are summarized in Table 3.3-2. Overall, the model skill score for predicted depth-averaged current velocity ranged from 0.965 to 0.987 and with unbiased error ubRMSE ranged from 14.3 to 20.9 cm/s. These statistical measures indicate that the hydrodynamic model simulates current velocity with sufficient accuracy to satisfy the objectives of this study.

Table 3.3-2 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
Delaware Bay Channel LB 10	NOAA	db0502	09-06-2018 to 06-25-2019	4075	0.913	-2.835	14.620	14.340	0.973
Brown Shoal Light	NOAA	db0501	06-01-2012 to 06-30-2012	718	0.951	-1.040	10.701	10.651	0.987
Reedy Point	NOAA	db0201	01-01-2012 to 05-05-2012	2811	0.906	8.054	22.427	20.931	0.987

3.3.3 Water Temperature

The hydrodynamics model is capable of simulating density-driven flows in the coastal and estuary environment. The water density is calculated as a function of salinity and water temperature. As water temperature changes, so does the water density. Although the impact of water temperature change on the salinity transport is considered a secondary factor, the accurate prediction of water temperature is important for addressing impact on water quality of the river and habitat areas. Comparisons of near surface water temperature at various of NOAA and USGS gaging stations are presented in Appendix J for period 2018-2019. A summary of the statistical measures is presented in Table 3.3-3 based on analysis for 2018-2019 period. Model produced biases at all locations ranging from -0.91 to 0.97 degrees Celsius. The unRMSE ranged from 0.43 to 1.31 degree Celsius. Model skill scores for predicted water temperature ranged from 0.991 to 0.999. Overall, these results show that the model was able to simulate the seasonal variation in temperature at all stations. However, the model overpredicts temperature at locations in the bay during some summer periods. The reason that model over-estimated water temperature may be attributed to the lack of meteorological data for specification of wind and other meteorological forcing parameters in the bay area, where the wind is observed to be much stronger than the wind observed at Dover airport. A stronger wind will cause more heat loss through evaporation, hence lowering water temperature. Further improvement on predicted water temperature in bay area near the mouth may be considered in the future.

Table 3.3-3 Model Performance Predicting Water Temperature

Agency	Station	State	NOAA ID	N	R^2	Bias (C)	RMSE (C)	ubRMSE (C)	Skill Score
NOAA	Lewes	DE	8557380	16131	0.977	-0.133	1.281	1.274	0.994
NOAA	Ship John Shoal	NJ	8537121	11780	0.990	-0.728	1.177	0.925	0.996
NOAA	Reedy Point	DE	8551910	15987	0.996	-0.533	0.799	0.595	0.998
NOAA	Delaware City	DE	8551762	14931	0.981	0.969	1.631	1.311	0.991
NOAA	Marcus Hook	PA	8540433	17280	0.996	-0.905	1.079	0.588	0.996
NOAA	Philadelphia	PA	8545240	16118	0.997	-0.360	0.647	0.538	0.999
NOAA	Burlington Delaware River	NJ	8539094	11245	0.998	-0.156	0.461	0.434	0.999
NOAA	Newbold	PA	8548989	17229	0.997	-0.285	0.568	0.492	0.999
USGS	Reedy Island	DE	USGS 01482800	17006	0.997	-0.666	0.864	0.551	0.998
USGS	Chester	PA	USGS 01477050	14310	0.995	-0.743	0.938	0.573	0.997
USGS	Ben Franklin Bridge	PA	USGS 01467200	15012	0.997	-0.482	0.703	0.511	0.998
*	2017-2018 Period at NOAA and USGS stations								

3.3.4 Salinity

Prediction of salinity intrusion and salinity structure in the estuary is important for the hydrodynamics model because salinity is essentially a natural tracer that allows us to evaluate transport. Salinity in the estuary is monitored by tracking the location of the salt front, as described previously. The observed extent of the salinity intrusion during the calibration periods ranges from below RM 50 to about RM 77 on September 1st of 2012.

The following three types of salinity data were used to evaluate hydrodynamic model performance:

- Continuous salinity (conductivity or specific conductance) measurements at multiple NOAA and USGS locations;
- Discrete sampling of along-channel salinity profiles (DRBC boat run survey data); and
- Data-based estimation of the salt front (monitored and weekly reported by DRBC).

Predicted salinity at NOAA stations at Lewes (at bay mouth), Brandywine, Ship John Shoal (RM 37) and USGS station at Reedy Island for 2018 to 2019 and 2012 period are presented in Appendix K. Data were not available for year before 2017. Predicted salinity at Chesapeake City reflects that salinity boundary conditions at the western end of the C&D canal and should not be considered as model calibration. Model performance is summarized in Table 3.3-4.

Table 3.3-4 Model Performance Predicting 32-hr-LPF Surface Salinity

2018-2019 Period at NOAA and USGS Stations									
Agency	Station	State	NOAA ID	N	R^2	Bias (C)	RMSE (C)	ubRMSE (C)	Skill Score
NOAA	Lewes	DE	8557380	13884	0.434	-0.705	2.591	2.494	0.710
NOAA	Brinedywine	NJ	8555889	N/A	N/A	N/A	N/A	N/A	N/A
NOAA	Ship John Shoal	NJ	8537121	2684	0.744	-0.620	2.091	1.997	0.913
USGS	Reedy Island	DE	USGS 01482800	16863	0.883	0.098	1.033	1.028	0.965
2012 Period at NOAA and USGS Stations									
Agency	Station	State	NOAA ID	N	R^2	Bias (C)	RMSE (C)	ubRMSE (C)	Skill Score
NOAA	Lewes	DE	8557380	N/A	N/A	N/A	N/A	N/A	N/A
NOAA	Brinedywine	NJ	8555889	6636	0.596	0.602	2.187	2.102	0.856
NOAA	Ship John Shoal	NJ	8537121	4026	0.694	-1.121	2.514	2.250	0.837
USGS	Reedy Island	DE	USGS 01482800	8324	0.840	-0.347	1.209	1.158	0.934

Generally speaking, the model agreed with the observed salinity at two critical stations (NOAA station at Ship John Shoal at RM 37 and USGS station at Reedy Island at RM 54). The model skill scores for predicted surface salinity at Ship John Shoal and Reedy Island are 0.913 and 0.965, respectively. Results at Lewes, which is far from our immediate area of concern, are dissatisfactory; these results likely reflect localized model performance in a corner of the grid domain. Overall, the results demonstrate that the model adequately predicts salinity at the Ship John Shoal area inside the Delaware Bay. Note that 2018 to 2019 were relatively wet years in terms of freshwater flows, and 2012 was a normal year in terms of hydrologic condition. The model might be further tested against salinity intrusion data during a drought year if time and resources allow.

From the perspective of water quality and salinity control for the upper portion of the tidal river (upstream of Reedy Island), model predicted salinity was also converted to chloride concentration (chlorinity) and compared with the USGS data at four sites. Data-based chlorinity was calculated using the empirical relationship between specific conductance and chloride concentration developed using on DRBC boat run data, as discussed previously. Temporal variations of predicted and observed daily-averaged Chloride concentration at Reedy Island (RM 54), Chester (RM 83), Fort Miflin (RM 92) and Ben Franklin Bridge (RM 100) are presented in Appendix L. Since the salinity intrusion for the simulated years was limited to below RM 77.2, the model-to-data comparison at three USGS stations located above RM 83 were not considered (salinity was negligible during calibration periods).

DRBC staff developed 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 (Figure 3.1-4). This dataset essentially provides a snapshot of profiles of various of water quality parameters, including salinity or specific conductance. Comparison of 21 predicted and observed longitudinal salinity profiles during 2018 and 2019 period are presented in Appendix M. The predicted tidally averaged salinity longitudinal profile agreed with the boat run data reasonably well over a wide range of flow and tidal conditions.

Salinity in the estuary is monitored by tracking the location of the salt front. The salt front, defined as the 7-day average of the 250 mg/l chloride concentration (isochlor), represents the interface of salt water and fresh water in the estuary as well as the extent of salinity intrusion the estuary. DRBC calculates the salt front location daily and reports it on a weekly basis on its website.

Observational estimates of the salt front are based on the specific conductance data collected from USGS station at Reedy Island (RM 54), Chester (RM 84), Fort Milfflin (RM 93.1), and Ben Franklin Bridge (RM 100.2) using a log-linear interpolation technique. Model-to-data comparison of salt front for period of 2018-2019 are presented in the last page of Appendix M. The model-to-data comparison of the salt front is considered as a supplementary calibration metrics, because the uncertainty in the data-based estimation using log-linear interpolation is sensitive to the measured specific conductance at the three USGS sites; there is no direct observation of the salt front locations. Nonetheless, the predicted salt front agreed reasonably well with the observational (data-based) estimation. The model appears to underestimated salt front locations somewhat during some periods within 2018-2019. This may be attributed to the relatively frequent high-flow events flushing down a significant amount of water from upland that caused sophisticated circulation pattern and salinity structures near the mouth of the bay, which the model may not fully capture with the embedded turbulent model and transport numerical scheme. Note that the data-based estimation becomes also highly unreliable once the location moves downsteam of Reedy Island under high flow events, so any estimations of salt front under RM 54 were out of considerations for model data comparisons.

Overall, model-to-data comparisons of salinity (including the salt front location) indicate that the model tends to underpredict salinity intrusion somewhat during wet weather and high flow events. Discrepancies between predicted and observed salinity during high flow periods are likely due to uncertainty in the model boundary conditions. Other potential factors that may contribute to these discrepancies include model limitations due to the following:

- Numerical grid resolution in the horizontal and vertical planes; and
- Simulation of horizontal and vertical turbulent diffusion.

The results discussed above show that the hydrodynamic model simulates salinity adequately for the model purposes, though with less accuracy for certain periods of time. Further investigation to improve salinity simulation might needed as time and resources allow. Simulations and calibrations with data collected from more “normal” and drought years would help to enhance the model performance.

3.4 SENSITIVITY TO VERTICAL GRID RESOLUTION

Model predicted salinity transport is 3D in nature. Near the mouth of the bay, a typical two-layer current and salinity structure exists (also known as tidal exchange flow structure) as a result of the competing forcings from the upstream inflows and from the ocean tidal forcing. During a high-flow event, fresher and less dense water flushing out seaward on the surface layer, and saltier and denser water moves landward in the bottom layer. As a result, a relatively strong vertical stratification in salinity is often observed in the lower bay area. Moving upstream from the mouth of the bay, the vertical stratification becomes weaker. Upstream of RM 79 near Marcus Hook, the tidal river becomes nearly well-mixed with a uniform vertical salinity profile. Vertical stratification interrupts the mixing process, and affects the salinity transport in the estuary. To capture the vertical structure correctly, vertical grid resolution must be determined before setting up the model boundary conditions and carrying out any model calibration and simulations.

To determine the appropriate vertical grid resolution, three different models were set up with five, ten, and fifteen vertical layers in the navigation channel. Sensitivity simulations were then conducted for the period of August 2012, which was a relatively calm and dry period with average flow from Delaware River at Trenton around 4200 to 4800 cfs. Model results (current velocity, water temperature, and salinity) were analyzed for a spring-tide period (08-19-2012 16:00 to 08-21-2012 16:00) and a neap-tide period (08-10-2012 10:00 to 08-12-2012 10:00). Simulation conditions of flow and tide are shown in Figure 3.4-1 of Appendix N. Model results from the navigational channel as well as from three cross-sections (shown in Figure 3.4-2 of Appendix N) were used in the sensitivity analysis. Diagnostic analyses were conducted at selected locations as listed below:

Three transects (cross-sections) at RM 37, 42, and 69; and

Three Cells in navigation channel at RM 37, 42, and 69.

Diagnostic analysis focused on predicted water surface elevation, current velocity, salinity, and water temperature. Tidally-averaged longitudinal and vertical structures of the current velocity and salinity were investigated by obtaining and comparing the residual signals, which were calculated as the average of the 32-hour low pass filtered results over 48-hour window for neap and spring tides, respectively. Model-to-model comparison was focused on the velocity/salinity structures (i.e., the gradient and shape of the vertical and longitudinal profile rather than the absolute values).

Models with three different vertical resolutions (5-layer model, 10-layer model, and 15-layer model) all produced nearly identical results for the water surface elevation at the three selected cell locations at RM37, 42, and 69 shown in Figures 3.4-3 (1) through 3.4-3 (3) of Appendix N.

Spatial and vertical distribution of predicted tidally-averaged 32-low-pass filtered salinity results are presented as contours on a vertical slide that cut through the federal navigation channel (FNC) in Figures 3.4-4 (1) and (2) during a 48-hour time window during a spring and a neap tide period, respectively. Model-to-model comparisons of the gradient of the predicted 32-low-pass filtered depth-averaged salinity longitudinal profile is shown in Figures 3.4-5 (1) and 3.4-5 (2) of Appendix N for the same spring and neap tide period. The higher vertical resolution grid tends to predict lesser saltwater intrusion in terms of the longitudinal residual salinity profile. The longitudinal residual salinity profile seems to start deviate from each other at RM 25 in the lower bay area. The difference in predicted depth averaged salinity seems to be larger around RM 40 to 60, where the 15-layer model predicted salinity being less than the 5-layer model predicted salinity by about 2 to 3 ppt.

Noted that the degree of salinity intrusion was not the same amongst the 3 scenarios because the three models were not calibrated for these diagnostic simulations. These vertical resolution test models are not therefore directly comparable. To further investigate the sensitivity to the vertical grid resolution, predicted current and salinity structures on given cross-section were compared among the three models. Normalization was therefore applied to the cross-sectional salinity and velocity outputs to make comparable results among scenarios. Each model result was divided by the maximum value of this cross-section to provide the intensity with values ranged from 0 to 1. Similar approach was applied to the current velocity analysis.

The predicted distribution of the ‘raw’ and normalized tidally-averaged 32-hour-lowpass filtered salinity on the cross-section at RM 37, 42, and 69 are presented in Figures 3.4-6 through 3.4-8, respectively, of Appendix N. At RM 69, the river exhibited a typical riverine well-mixed environment with almost uniform vertical profile of the salinity, and the absolute salinity value was very small. Stronger vertical stratification of salinity was observed at both cross-section at RM 37 and RM 42, with saltier water at the bottom. At these 2 locations, the vertical stratification was stronger during neap tide than spring tide. The water near the Delaware side was relatively fresher than the water closer to New Jersey side. The normalized salinity distribution produced by the three models showed very consistent pattern, with the 10-layer model results being closer to the 15-layer model than the 5-layer model.

The predicted distribution of the ‘raw’ and normalized tidally-averaged 32-hour-lowpass filtered along-channel current velocity on the cross-section at RM 37, 42, and 69 are presented in Figures 3.4-9 through 3.4-11, respectively of Appendix N. A clear typical estuary exchange flow structure was observed at RM 37 and 42, with the fresher water moving in the seaward direction on the top and the saltier water moving landward from the ocean. At RM 69, the velocity profile became the typical logarithmic profile and unidirectional flow. During neap tide, the model predicted a net landward movement of water near the New Jersey side and a net seaward movement of water near the Delaware side in the mid and upper bay, while during spring tide the model predicted net seaward moving water on the top from shore to shore. Comparing the normalized current velocity at these locations, 10-layer model and 15-layer model produced very similar results.

Vertical profile of tidally-averaged 32-hour-lowpass filtered current velocity, salinity and water temperature in the FNC from the three cross-sections were also presented in Figures 3.4-12 through 3.4-20 of Appendix N without normalization. Without pre-calibrate the three models, qualitative comparison was done by visualizing the shape and gradient of the vertical profiles. Based on this sensitivity study on the grid vertical resolution, the 10-layer model and 15-layer model produced very close results and 10-layer model was considered more desirable because of its faster run time and efficiency to store and process the model output.

Sensitivity tests to vertical layer resolution indicated that: a) a model of 10-layers in the navigational channel adequately captures the vertical structures of salinity and current; b) a 5-layer model performed well in most respects, but might not adequately capture all gradients; and c) it is likely that a number of layers greater than five but less than ten would also perform adequately.

4. SUMMARY

The primary objective of the 3D hydrodynamics modeling study was to provide a hydrodynamic platform for the eutrophication modeling study of the Delaware Estuary, the goal of which is to develop and calibrate a water quality model of eutrophication processes in the Delaware Estuary and Bay from the head of the tide at Trenton, NJ to the ocean. The 3D hydrodynamics model described herein provides the foundation for the linked eutrophication model of the Delaware Estuary.

The hydrodynamic model was developed and calibrated for the periods of 2018-2019 and 2012. A statistical sub-model based on a regional analysis of shared features was developed in order to estimate hydrologic inputs from unmonitored tributaries and watersheds. Model performance was evaluated for water surface elevation, current velocity, water temperature and salinity in the estuary. The calibrated hydrodynamic model simulated observed data reasonably well, as documented in this report. The Expert Panel unanimously agreed in May 2020 that the calibrated hydrodynamic model is sufficient to be used as the basis of the eutrophication model.

In addition, an evaluation was performed to determine the extent of vertical resolution needed to adequately simulate gradients and mass transfer in the system. Based on this evaluation, a three-dimensional grid with 10 vertical layers in the navigation channel was selected as the hydrodynamic basis for the eutrophication model. It is likely that a coarser degree of vertical resolution, more than five but fewer than ten layers in the navigation channel, would also be adequate for the model purposes; DRBC may pursue a coarser vertical resolution model as needs dictate (i.e., overall simulation time constraints of the water quality model) and resources allow.

Preliminary findings are summarized in this report. The hydrodynamic model showed a very good prediction for tidal water surface elevation and adequate performance for predicted water temperature and salinity. Results of the calibration process and sensitivity analyses indicate that the performance of the 3D hydrodynamics model is adequate to meet the objectives of the modeling study, namely that the model can be used to evaluate large-scale hydrodynamic circulation processes within the Delaware Estuary and Bay system to a degree necessary to drive water quality modeling of eutrophication processes.

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