Philadelphia Water Department Watershed Protection Program

Delaware Estuary Salinity Model Validation

May 2020

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Acronyms

Acronym	Description
ADCP	Acoustic Doppler Current Profiler
C&D Canal	Chesapeake and Delaware Canal
CFS	Cubic Feet Per Second
CSO	Combined Sewage Overflow
CTD	Conductivity, Temperature, Depth sensor
DRBC	Delaware River Basin Commission
EFDC	Environmental Fluid Dynamics Code
EMC	Event Mean Concentrations
EPA	US Environmental Protection Agency
LBC	Lower Boundary Condition
MGD	Million Gallons per Day
NPDES	National Pollutant Discharge Elimination System
PWD	Philadelphia Water Department
RMSE	Root Mean Square Error
SIPS	Strain-induced Periodic Stratification
TDS	Total Dissolved Solids
USGS	United States Geological Survey
NOAA	National Oceanic and Atmospheric Administration
PSU	Practical Salinity Unit

1.0 Introduction

The Philadelphia Water Department (PWD) Water Quality Compliance Modeling (WQCM) group within the Watershed Protection Program performs modeling and analysis of water quality in the tidal Delaware River, which is the source for 60% of the drinking water to the City of Philadelphia. To support infrastructure planning for the PWD Baxter Water Treatment Plant, the PWD estuarine salinity model was developed to enhance the understanding of how salinity intrusion and sea level rise may influence drinking source water quality. The tidal Delaware River is a high quality source of drinking water to the City of Philadelphia, and also a source for process and cooling water to many industries and manufacturers. During severe droughts the tidal Delaware River adjacent to Philadelphia experiences salinity intrusion, during which ocean salt is transported further upstream then during normal conditions.

The current conditions that lead to salinity intrusion as well as the conditions that can manage salinity intrusion will be explored with the PWD salinity model. This report details the components of the PWD salinity model, calibration steps and model validation.

This report does not include the additional model setup necessary to simulate sea level rise. Further work is required to approximate the influence that sea level rise may have on model setup and assumptions related to bathymetry and morphology changes, salinity and boundary conditions. Following the completion of salt line analyses of current conditions with this validated model, PWD will work to amend the model inputs and assumptions to perform sea level rise analyses. PWD will issue an Appendix to this validation report at that time documenting all model changes and assumptions related to sea level rise analysis.

2.0 Numerical Model

2.1 Model Objectives

The objective of the model development is to create a salinity model that can simulate salinity conditions in the tidal upper Delaware Estuary, specifically in the region adjacent the City of Philadelphia and the PWD Samuel S. Baxter Water Treatment Plant (Baxter). Model predictions are compared to observed conditions at stations in the Delaware River to calibrate and validate the model. For this report, salinity conditions for the years 2014 (main validation) and 2016 (drought conditions in fall) are simulated, with special concentration on analyzing axial salt distributions during low flow periods in late summer and early fall. Sensitivity analyses are performed with respect to salt transport and hydrodynamic conditions to better understand and replicate important physical processes.

2.2 Modeling Approach

Various sources that contribute salt to the tidal Delaware River considered here include:

- Marine salt transported from the Delaware Bay
- Land-based sources delivered by tributary rivers and creeks
- Land-based sources delivered by stormwater runoff
- Process-water sources discharged directly to tidal waters

The complexity of salt transport in tidal waters suggested the need for a 3-dimensional hydrodynamic and transport modeling approach and the US Environmental Protection Agency (EPA) Environmental Fluid Dynamics Code (EFDC) was selected for this application. Table 2-1 summarizes input sources and model parameters for the modeling approach used to develop the PWD salinity model, the major elements of which are described below and throughout this report.

Table 2-1: Summary Salinity Modeling Approach Sources

System Inputs	Sources	Parameters
Loads	Tributaries and Direct Runoff • USGS gaging stations and CTD sensors Philadelphia Combined Sewer Overflows (CSOs) • Direct Combined Sewer System Stormwater Management Model (SWMM) • CSOs discharging into Non-tidal Cobbs and Tookany Tacony-Frankford Creeks above U.S. Geologic Survey (USGS) gaging stations were represented by USGS gaging stations and CTD sensors Camden County Municipal Authority, Delaware County, Delaware County Regional Authority, and Wilmington CSOs • Estimates based on available information Permitted Dischargers • Discharge Monitoring Reports (DMRs)	National Pollution Discharge Elimination System (NPDES) Permitted Dischargers, Tributaries, and Direct Runoff • Flow Rate • Temperature • Salinity from specific conductance/total dissolved solids
Downstream Open Boundary (Lower Model Extent)	• National Oceanic and Atmospheric Administration (NOAA) tide and temperature gage at Delaware City, DE • PWD conductivity, temperature and depth (CTD) sensor	• Water Level • Temperature • Salinity from specific conductance
Climate	• NOAA National Climatic Data Center (NCDC) Station at the Philadelphia International Airport • Algorithms for Clear-Sky Solar Radiation	• Wind Speed and Direction • Air Temperature • Dew Point Temperature • Atmospheric Pressure • Cloud Cover and Solar Radiation
Hydrodynamic Model		• Friction Height • Turbulence closure • Salt transport • Temperature

2.3 Study Area

The principal sources of freshwater discharge to the Delaware Estuary is the Delaware River at the head of tide at Trenton, New Jersey, supplying about 52% of the total mean freshwater inflow (Ketchum, 1953; Garvine, McCarthy and Wong, 1992). Between the head of tide, and Delaware City, DE, the Schuylkill River and 41 other tributaries contribute additional freshwater to the upper estuarine system. The domain of this study includes the tidal freshwater region, including tidal reaches from 3 miles above the confluence with the Chesapeake and Delaware Canal to the head of tide at Trenton, stretching from River Mile 61.8 to 134.4 (Note that the DRBC River Mile system is used throughout this report; see: https://www.nj.gov/drbc/basin/river/).

The Delaware Bay is a weakly stratified coastal plain estuary (Janzen and Wong, 2002). The principal interface between the predominantly freshwater portions and the saltier waters of the lower Bay generally is located between River Miles 31 and 75. Salt transport in this part of the Delaware Estuary is predominantly driven by gravitational circulation with strong contributions from secondary lateral flow (Aristizábal and Chant, 2015). Philadelphia County is situated between River Mile 91 and River Mile 111, upstream of the average landward extent of marine salt intrusion (Figure 2-1).

Hydrodynamics and transport in the upper estuary are driven primarily by the interactions of nonlinearities among tidal flows, freshwater inputs, gravitational circulation, and meteorological influences (Garvine, McCarthy and Wong, 1992). Secondary driving mechanisms may include the effects of axial curvature and Ekman forcing (Chant, 2009), and the action of vertical shear flow dispersion (Linden and Simpson, 1986; Garvine, McCarthy and Wong, 1992). Analysis of current data at River Mile 75 suggests the existence of vertical shear flow dispersion through strain-induced periodic stratification (SIPS) (Simpson et.al., 1990) during low flow/high salinity intrusion events, usually in late summer/fall. As well, analysis of cross channel currents at this location suggest that differential advection may contribute to estuarine circulation (Lercak & Geyer, 2004; Macready & Geyer, 2010). Together these mechanisms may contribute to enhanced upstream transport of marine salt in the lower domain of the model during periods of low freshwater inflow.

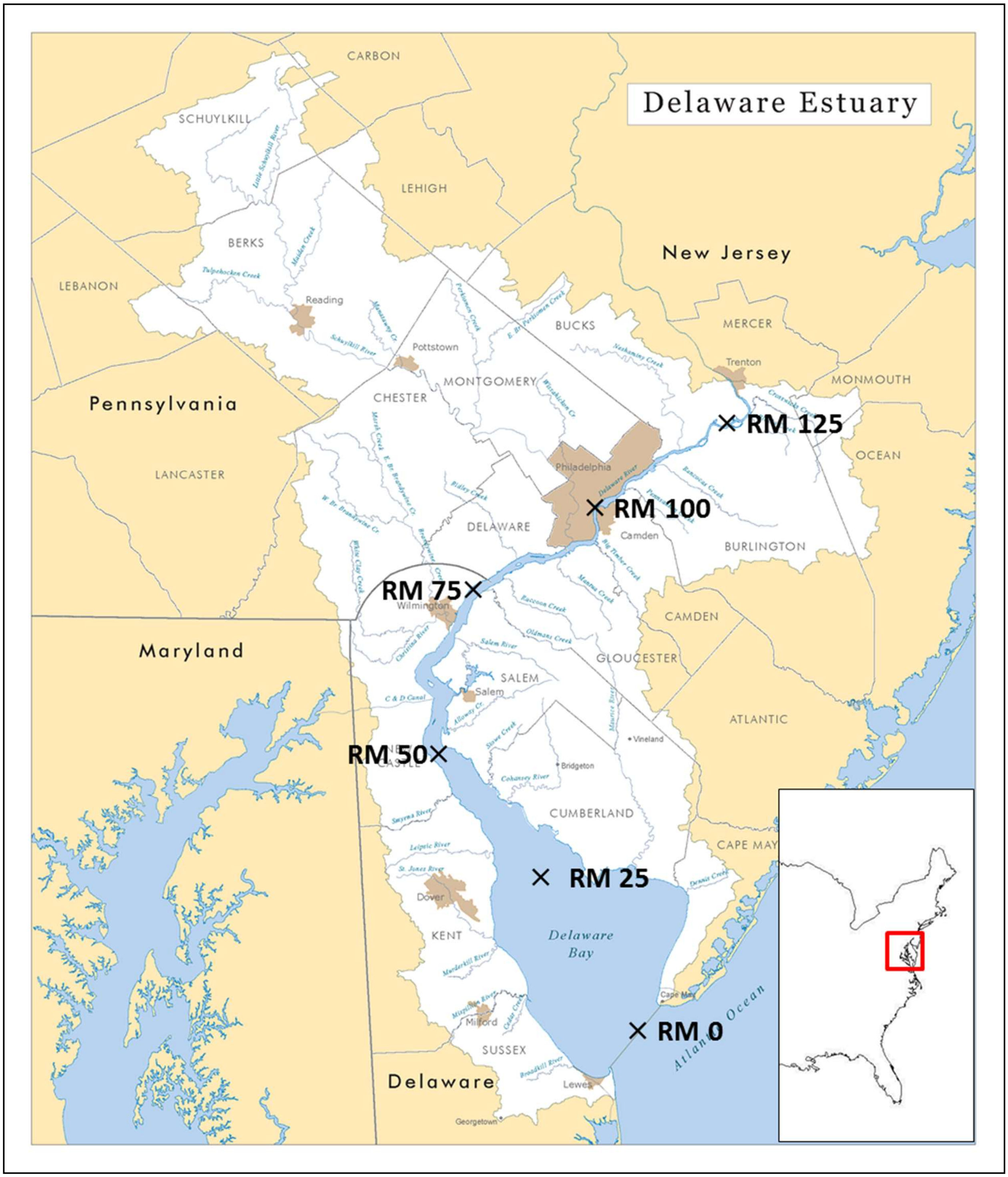


Figure 2-1: Map of Delaware Estuary with along-channel river mile reference locations

2.4 Salinity Conversion Methods

The EFDC model needs salt related boundary and initial conditions as salinity in Practical Salinity Unit (PSU). The data used for the model inputs comes from a variety of sources, in different formats and units, thus conversion methods are required. Most continuous data sources, such as tributary sondes, allow estimates of salt content from observations of specific conductance [µS/cm] and associated water temperatures (degrees C). Tributary grab samples and industrial or municipal discharges report salt also in measures of chloride and Total Dissolved Solids (TDS) in mg per liter. Specific Conductivity and temperature may be used to estimate salinity. Standard Methods 2520 B and D provide background, references, and calculations for estimating salinity through conductance and temperature observed in natural waters. When salinity is determined through conductivity measurements it is based on the Practical Salinity Scale.

For chloride, a relationship to salinity is developed based on available paired data from combined PWD and DRBC Boat Run data. Observed specific conductance and temperature values from this dataset are converted to salinity using the above method and analyzed with paired chloride values using a combination of MATLAB's POLYFIT, POLYCONF, and CORRCOEF functions to create a linear regression equation with the 95% confidence interval and the Pearson's R-squared coefficient. The resulting equations are below.

$$S = CL*1.8e\text{-}03 + 0.046 \qquad \text{(Eq. 2-1)}$$

$$S = TDS*8.5e\text{-}04+0.052 \qquad \text{(Eq. 2-2)}$$

2.5 Boundary Conditions

Boundary conditions for the 2014 and 2o16 salinity models include discharge, salinity and temperature for tributaries and anthropogenic point sources, such as stormwater Combined Sewer Overflows (CSOs), municipal and industrial dischargers, salinity, water temperature and water level at the open boundary, and atmospheric and wind information.

2.5.1 Tributaries

2.5.1.1 Streamflow

Streamflow is monitored by United States Geological Survey (USGS) at stations on many of the rivers and creeks within the Delaware River watershed. Records of continuous streamflow time series are available from USGS for most of the major tributary rivers and creeks of the tidal Delaware River within the model domain from Trenton to Delaware City (Figure 2-2). Streamflow estimates for ungaged tributaries are prepared using a watershed area ratio method with flow data from nearby or similar gaged tributaries. The USGS stations on the gaged tributaries are located on the streams above the influence of the tide. For many of the tributaries, especially on the New Jersey side of the Delaware River where the watershed is relatively flat, a significant portion of the watersheds lie downstream of the gage.

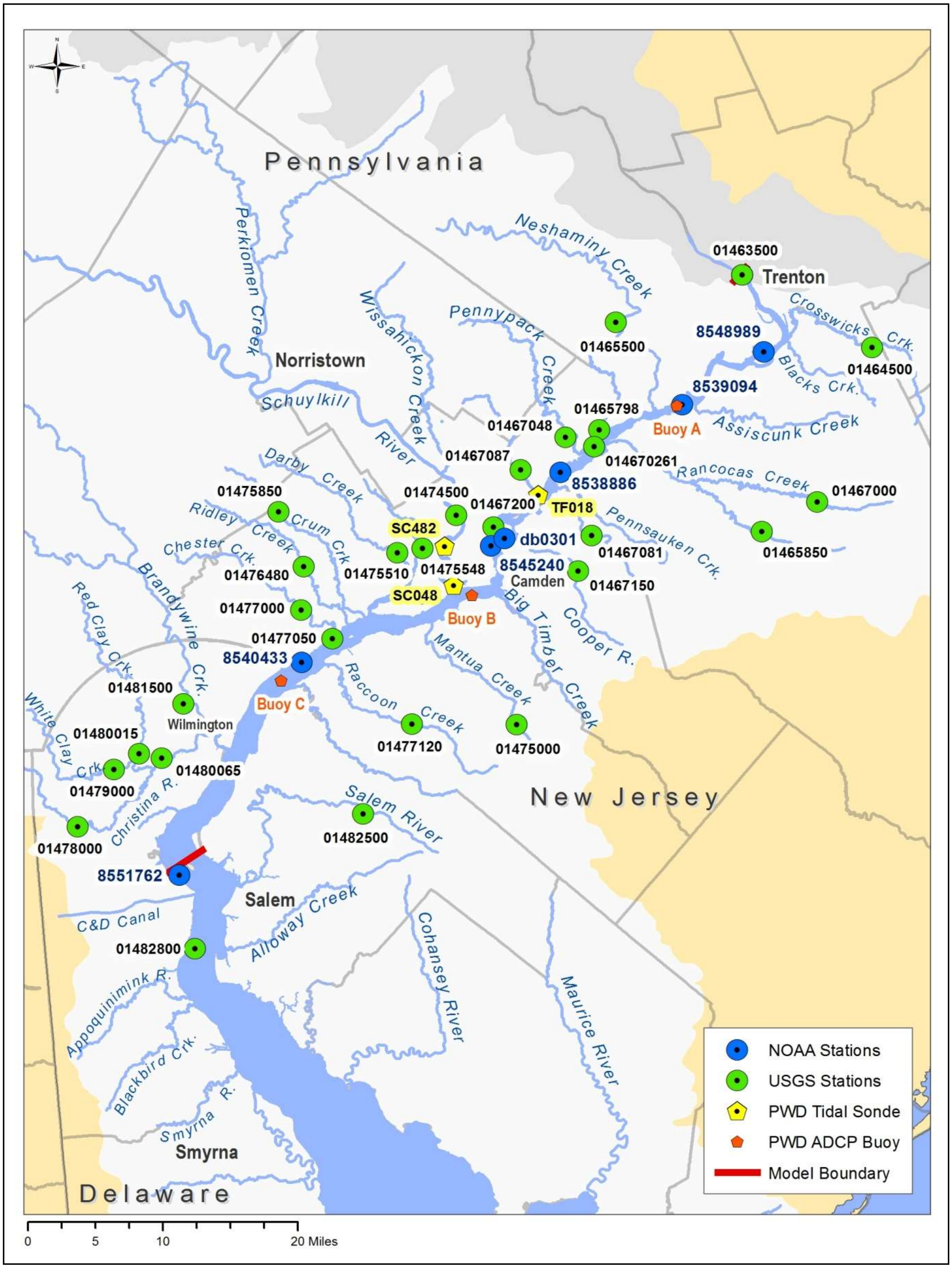


Figure 2-2: Tributary and River Monitoring

The watershed area ratio method is used to estimate streamflow from these lower (ungaged) watershed areas based on the flow recorded at the USGS gage of the tributary. Flow is also estimated using the watershed area ratio method for the areas between tributaries that contribute stormwater runoff directly to the Delaware River. These areas are referred to as "direct runoff areas." During the salinity model validation, it is determined to be necessary to make some adjustments to the flows estimated for the ungaged tributaries and direct runoff areas. This process is discussed in further detail in Section 3.5.

Gaps larger than 6 hours in the gaged tributary streamflow data are filled using the average daily discharge reported by USGS when data points are missing during peak flow events. Gaps in streamflow during essentially constant baseflow conditions are linearly interpolated by the model itself. Table 2-2 provides an overview of the tributaries that are included in the model domain with information on gage availability and gap filling.

Table 2-2: Tributaries included in model domain

River/Tributary	USGS Gage	Gap Filling or Ungaged Estimate Methodology	River Mile
Delaware River	01463500	2014: 8 gaps filled w/ daily avg. discharge 2016: 7 gaps filled w/ daily avg. discharge	134.25
Blacks Creek	None	Crosswicks Creek	128.0
Crosswicks Creek	01464500	Only 2014: 4 gaps filled w/ daily avg. discharge	128.0
Stream @ Crystal Lake	None	Crosswicks Creek	126.0
Crafts Creek	None	Crosswicks Creek	124.0
Bustleton Creek	None	Crosswicks Creek	119.75
Assiscunk Creek	None	Rancocas Creek	118.0
Stream @ Burlington	None	Rancocas Creek	117.75
Neshaminy Creek	01465500	2014: 4 gaps filled w/ daily avg. discharge 2016: 6 gaps filled w/ daily avg. discharge	115.0
Poquessing Creek	01465798	Only 2016: 3 gaps filled w/ daily avg. discharge	111.25
Swede Run	None	Cooper River	110.75
Rancocas Creek north	01467000	NA	110.5
Rancocas Creek south	01465850	Only 2014: 5 gaps filled w/ daily avg. discharge	110.5
Pennypack Creek	01467048	Only 2016: 3 gaps filled w/ daily avg. discharge	109.0
Pompeston Creek	None	Cooper River	108.5
Pennsauken Creek	01467081	Only 2016: 1 gap filled w/ daily avg. discharge	104.75
Frankford Creek	01467087	Only 2014: 3 gaps filled w/ daily avg. discharge	104.0
Cooper River	01467150	Only 2014: 1 gap filled w/ daily avg. discharge	100.5
Newton Creek	None	Cooper River	96.75

River/Tributary	USGS Gage	Gap Filling or Ungaged Estimate Methodology	River Mile
Big Timber Creek	None	Cooper River	95.5
Schuylkill River	01474500	Only 2014: 1 gap filled w/ daily avg. discharge	92.25
Woodbury Creek	None	Cooper River	91.5
Little Mantua Creek	None	Mantua Creek	90.5
Mantua Creek	01475000	Raccoon Creek, Salem River	89.75
Clonmell Creek	None	Mantua Creek	87.0
Cobbs Creek	01475548	2014: 5 gaps filled w/ daily avg. discharge 2016: 2 gaps filled w/ daily avg. discharge	85.0
Darby Creek	None	Crum Creek	85.0
Crum Creek	01475850	2014: 7 gaps filled w/ daily avg. discharge 2016: 2 gaps filled w/ daily avg. discharge	84.8
Ridley Creek	01476480	2014: 7 gaps filled w/ daily avg. discharge 2016: 5 gaps filled w/ daily avg. discharge	84.0
Chester Creek	01477000	2014: 5 gaps filled w/ daily avg. discharge 2016: 4 gaps filled w/ daily avg. discharge	82.5
Little Timber Creek	None	Raccoon Creek	82.5
Still Run	None	Raccoon Creek	82.0
Raccoon Creek	01477120	2014: 8 gaps filled w/ daily avg. discharge 2016: 3 gaps filled w/ daily avg. discharge	80.0
Stoney Creek	None	Chester Creek	80.0
Marcus Hook Creek	None	Chester Creek	79.5
Namaan Creek	None	Chester Creek	77.75
Oldmans Creek	None	Raccoon Creek	76.0
Brandywine River	01481500	2014: 4 gaps filled w/ daily avg. discharge 2016: 2 gaps filled w/ daily avg. discharge	70.5
Christina River	01478000	Only 2016: 34 gaps filled w/ daily avg. discharge	70.5
Red Clay Creek	01480015	2014: 6 gaps filled w/ daily avg. discharge 2016: 5 gaps filled w/ daily avg. discharge	70.5
White Clay Creek	01479000	2014: 6 gaps filled w/ daily avg. discharge 2016: 5 gaps filled w/ daily avg. discharge	70.5
Salem River	01482500	2014: 2 gaps filled w/ daily avg. discharge 2016: Raccoon Creek	68.75
Army Creek	None	Christina River	64.0

2.5.1.2 Salinity for Gaged Tributaries

Temperature, used together with salinity for calculating density in the hydrodynamic model, is available for several tributaries and can also be used as substitutes for ungaged tributaries because of temperature's low spatial variability. However, continuous specific conductance time series are only available for very few tributaries. An approach was needed to generate continuous specific conductance time series for all tributaries based on available data. In addition to the few time series that were available, grab samples are used to determine median values for ungaged tributaries.

Continuous specific conductance data from USGS gages is available at the Delaware River at Trenton (USGS01463500), Schuylkill River at Philadelphia (USGS01474500), and Brandywine Creek (USGS01481500). Data for Christina River is ignored because it is influenced by salinity from downstream due to tides. USGS data from PWD maintained stations is available at Poquessing Creek, Pennypack Creek, Frankford Creek, and Cobbs Creek.

Potential specific conductance data for gap filling from upstream USGS gages is available at Schuylkill River at Norristown, Pennypack Creek at Pine Road, Tacony Creek at Adams Ave, Schuylkill at Philadelphia, and Cobbs Creek at Highway 1.

Reference specific conductance data in the Delaware River main stem for calibration/validation is available at Delaware River at Chester, PA (USGS01477050), Delaware River at Ben Franklin Bridge (USGS01467200), Delaware River at Pennypack Woods (USGS014670261), PWD Buoy B at Eagle Point and Buoy C at Marcus Hook.

An overview of available specific conductance data periods, gaps, and data used for gap filling can be found in Table 2-3 below and their respective locations in Figure 2-2.

In a first check, missing data entries marked as NaN (Not a Number) are removed from each time series. The remaining time series is checked for gap longer than one day. Only gaps from stations with data that exhibited large amplitudes or that missed salinity events in winter are gap filled. Gaps during dry weather or with small amplitude data, such as in the main stem salinity stations, can be considered constant conditions and are left untreated to be linearly interpolated directly by the model. Occasional outliers are adjusted manually to better-match ambient conditions as seen in the measurements directly before and after the outlier.

Most tributary-specific conductance stations do not operate in winter due to potential ice damage. The only continuous tributary time series that covered the full year is available for Brandywine Creek. Time periods in early and late winter that showed data for both Brandywine and those tributaries without winter data are used to determine a multiplication adjustment factor and vertical shift for Brandywine data, to match the receiving waters time series.

Table 2-3: Observed tributary specific conductance data availability and gap filling methodology for 2014 & 2016

River/Tributary	USGS Gage	Gap Filling Methodology	Delaware River Mile
Delaware	01481500	2014: No missing data 2016: No missing data	134.25
Delaware River @ Ben Franklin Bridge	01467200	2014: Winter gap filled w/ shifted Baxter 2016: No missing data	100.00
Schuylkill @ Fairmount Dam	01474500	2014: Winter gap filled w/ Queen Lane 2016: Winter gap filled w/ shifted Belmont	Schuylkill
Delaware River @ Chester	01477000	2014: No missing data 2016: Winter gap filled w/ shifted Baxter	82.50
Brandywine	01481500	2014: No missing data 2016: No missing data	70.50
Poquessing (PWD)	01465798	2014: Winter gap filled w/ shifted Wissahickon 2016: Winter gap filled w/ shifted Wissahickon	111.25
Baxter (PWD)	014670261	2014: 2 gaps about a day long; 1 gap is 4 days long 2016: 1st gap filled w/ shifted Brandywine	110.50
Pennypack (PWD)	01467048	2014: Winter gap filled w/ shifted Wissahickon 2016: Winter gap filled w/ Poquessing	109.00
Frankford (PWD)	01467087	2014: Winter gap filled w/ shifted Pennypack 2016: Winter gap filled w/ shifted Pennypack	104.00
Wissahickon (PWD)	01474000	2014: Winter gap filled w/ shifted Brandywine 2016: Winter gap filled w/ shifted Brandywine	Schuylkill
Cobbs (PWD)	01475548	2014: Winter gap filled w/ shifted Wissahickon 2016: Winter gap filled w/ shifted Wissahickon	85.00

The urban tributaries typically exhibit distinctly different temporal patterns than Brandywine Creek. Overall, they are higher in salinity and show larger dilution excursions during wet weather events. Figure 2-3 shows the salinity time series at Brandywine (light grey), Wissahickon (dark grey), and Cobbs (black), which is similar to Frankford and Pennypack Creeks.

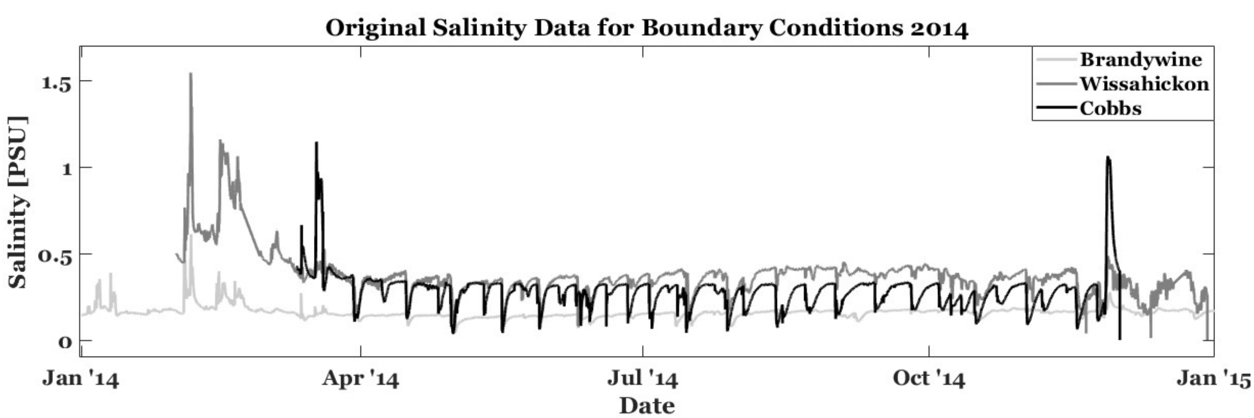


Figure 2-3: Salinity at Brandywine, Wissahickon and Cobbs Creeks

The offset is clearly visible and shows that Wissahickon is the most complete time series with only a one month-long winter gap at the beginning of 2014. This gap was filled with Brandywine data. In 2016 a Wissahickon winter gap at the beginning, and another at the end of the year, were filled with Brandywine data. Gap-filled Wissahickon data is then used to fill the winter gaps of Poquessing, Pennypack and Cobbs Creeks.

Depending on the original time step, all final time series are interpolated onto a regularly spaced time vector to assure that discharge and salinity boundary time series are on the same time-step. This facilitates an easier calculation of model factoids (such as load etc.) for future meta data purposes. Delaware River specific conductance is recorded on an hourly time step, Schuylkill River, Baxter and Poquessing Creek on 30 minutes, and all other stations on 15 minutes.

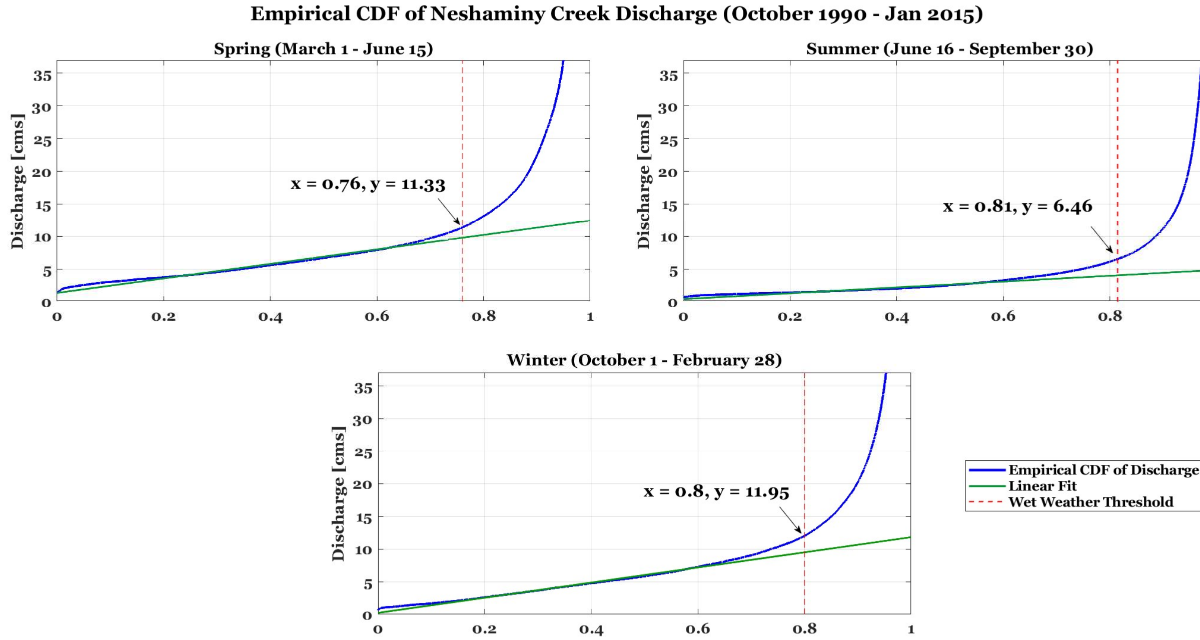
2.5.1.3 Synthesized Salinity Time Series for Ungaged Tributaries

Long term grab sample data for salt content is available for several tributaries in the model domain. Data was analyzed for median values and presented in Table 2-4 below. Depending on data availability and sensitivity to seasons and precipitation, medians are determined for yearly, seasonal or seasonal-wet/dry conditions to support estimates of salinity in ungaged tributaries.

To assemble artificial time series for ungaged tributaries, estimates of their average salinity are needed. All available USGS parameters (salinity [PSU], specific conductance [µS/cm], chloride (CL) [mg/l], and TDS [mg/l]) per tributary are first collected and analyzed. Conversion methods from these parameters to salinity [PSU] are detailed in Section 2.4.

For all gaged rivers, flow thresholds for wet/dry conditions are determined using a cumulative distribution function (CDF) plot. Figure 2-4 shows CDF plots for biological Spring, Summer and Winter, with cumulative probability on the x-axis and discharge in cms on the y-axis. The blue line is the graphed CDF. The method analyzes each flow time series of all available years bound by the dates of each biological season, which are respectively plotted as a cumulative distribution function for each local tributary. The value at which the function deviates from this linear relationship is selected as the wet-weather threshold, with any flow values above this threshold yielding a wet-weather identification. To limit the frequency of false positives, roughly 5% of the max flow is added as a buffer.

Comparison of the threshold to the discharge at grab sample time in the river (or a river nearby, if fully ungaged) helped to determine if the sample was taken during wet or dry weather conditions which has an influence on the salinity. In summer, rain events usually dilute the river water, leading to lower salinity spikes, and in winter snow is often connected to a spike in salinity because of the use of road salts, which eventually wash off streets and into nearby rivers directly or by drainage systems.



Spring (3/1 - 6/15), Summer (6/16 - 9/30), Winter (10/1 - 2/28)

Figure 2-4: Seasonal identification of wet weather threshold, Neshaminy Creek example

Additionally, the season in which the sample was taken is determined. Using this information, plots by tributary for seasons, flow (wet/dry), and wet/dry seasons for all salinity related parameters are generated and respective median values determined (Table 2-4).

While some tributaries showed a sensitivity to wet/dry events, most can be described by a constant salinity value, either by season or yearly. The final seasonal and overall ungaged tributary salinity is presented in Table 2-4 below. Biological seasons are defined as Spr: Spring (3/1 - 6/15), Sum: Summer (6/16 - 9/30), Win: Winter (10/1 - 2/28)

Table 2-4: Median grab sample salinity [PSU] for ungaged tributaries. Spr: Spring (3/1 - 6/15), Sum: Summer (6/16 - 9/30), Win: Winter (10/1 - 2/28), D: Dry, W: Wet

Tributary	Approach	Spr	Sum	Win	SpD	SpW	SuD	SuW	WiD	WiW	Overall
Assiscunk	overall										0.11
Assunpink	seasons	0.13	0.15	0.16							
Army	seasons	0.19	0.12	0.14							
Blacks	overall										0.09
Big Timber	seasons	0.08	0.08	0.09							
Crafts	overall										0.14
Crosswicks	seasons	0.08	0.10	0.09							
Chester	overall										0.20
Crum	overall										0.12
Cooper	seasons	0.14	0.10	0.10							
Doctors	seasons/ weather				0.08	0.08	0.10	0.08	0.10	0.10	
Mantua	Not enough data, use donor trib										
Naaman	seasons/ weather				0.19	0.18	0.17	0.16	0.15	0.19	
Neshaminy	seasons/ weather				0.20	0.22	0.25	0.20	0.26	0.24	
Newton	overall										0.12
Oldmans	seasons	0.09	0.10	0.11							
Pennsauke n	seasons	0.14	0.12	0.14							
RancocasN	overall										0.02
RancocasS	overall										0.09
Raccoon	seasons	0.10	0.10	0.11							
Red Clay	overall										0.19
Ridley	overall										0.15
Shellpot	seasons	0.25	0.21	0.24							
Still Run	overall										0.11
Salem	seasons	0.12	0.12	0.13							
Swede Run	overall										0.15
Woodbury	Not enough data, use donor trib										
White Clay	overall										0.17
Ranocas	flow weighted mean North & South branch										0.06

Tributary discharge time series can be used to determine when a dilution event caused by precipitation happens. It is more difficult to predict when a spike in salinity from snow, ice and road salt is going to happen, because such events are not necessarily reflected in the streamflow record. Therefore, it was decided to generate a yearly time series with two procedures. For this the year was split into winter (01/01-03/15 and 12/01-12/31) and non-winter periods (03/16-11/30), times when it is assumed to snow and freeze, or rain. For the non-winter period, the respective medians are assigned, using a related discharge time series to determine wet events if applicable. For winter, Brandywine or gap filled Pennypack time series are used, with slight adjustments to ensure a smooth transition to the respective non-winter data.

Long-term grab sample data showed that all tributaries, except for Neshaminy Creek, resembled Brandywine Creek. In Figure 2-5 to Figure 2-7, long term continuous Brandywine salinity is plotted against the respective grab samples of the tributaries.

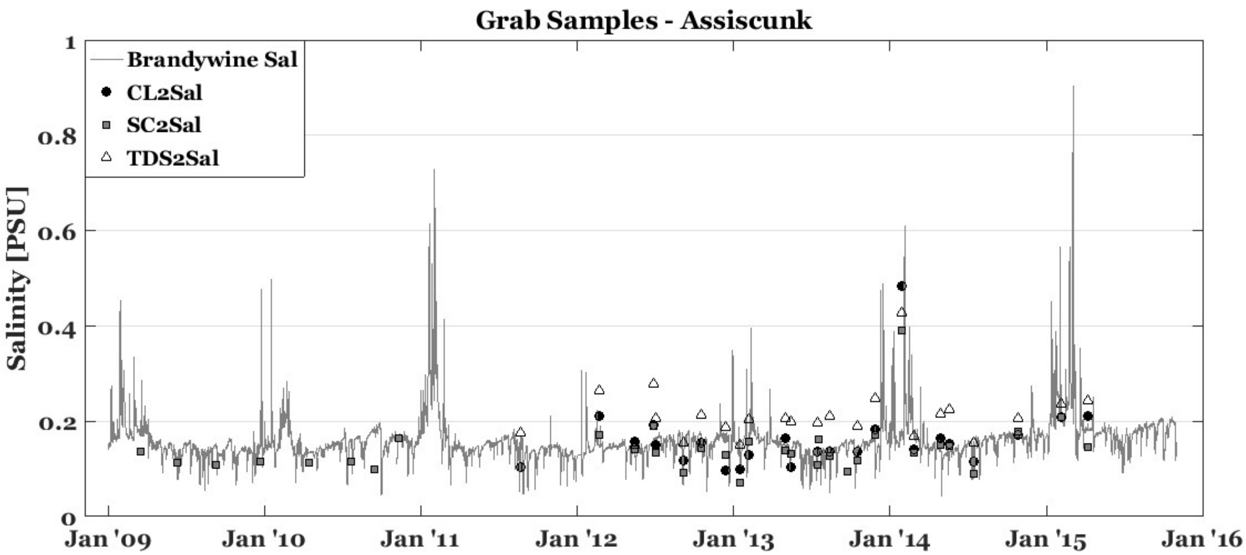


Figure 2-5: Similar range – Assiscunk grab sample vs. Brandywine

Grab sample data measured as chloride (CL), specific conductance (SC), and total dissolved solids (TDS) are converted to salinity (Sal) using the methods described in Section 2.4 (denoted as CL2Sal, SC2Sal, and TDS2Sal in the figures). Many are on the same order as Brandywine Creek salinity (such as Assiscunk Creek Figure 2-5) or a little below (e.g. Crosswicks Creek Figure 2-6).

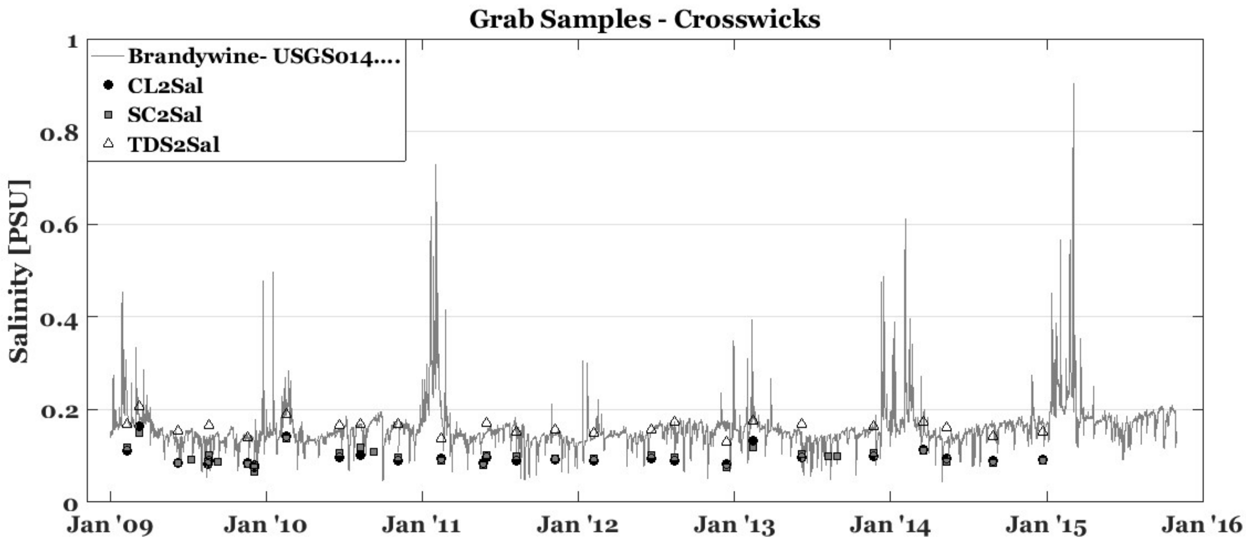


Figure 2-6: Dissimilar range – Crosswicks grab sample vs. Brandywine

Neshaminy Creek resembles the higher salinity regime of Pennypack and other Philadelphia Creeks (Figure 2-7). There is insufficient data to compare higher peak values in winter to grab sample data, which are seldom taken during or right after respective peak salinity events. Therefore, it was decided to only apply a vertical shift to the Brandywine time series that brings base salinity to the same level as suggested in the grab sample data.

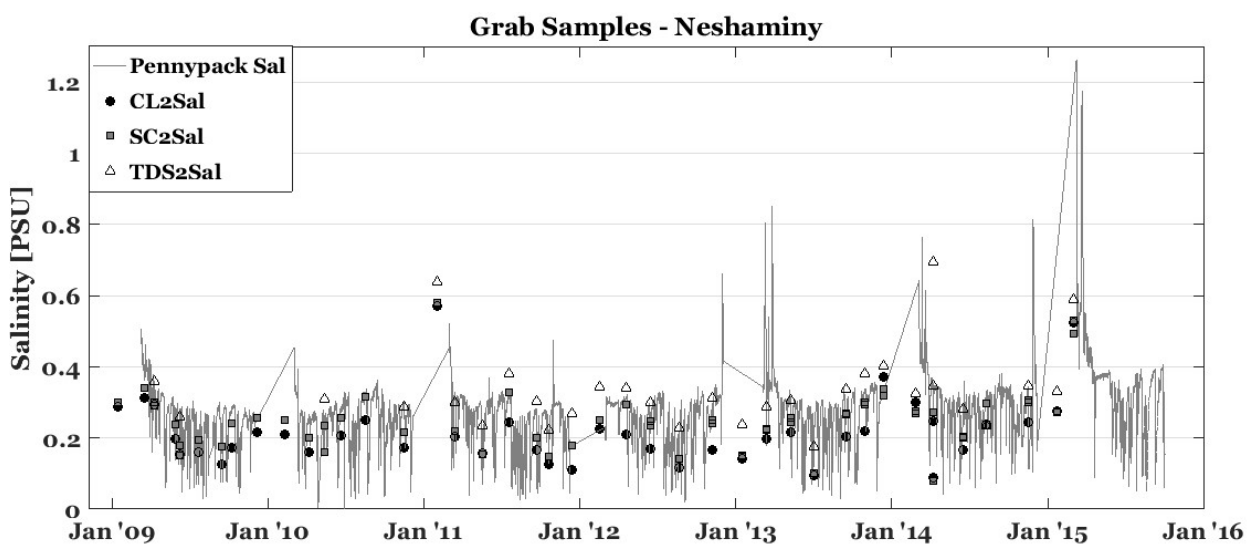


Figure 2-7: Neshaminy vs. Pennypack

A last check of the method is made when connecting the median-based and Brandywine time series together into one (Figure 2-8). If Brandywine connects smoothly to the following median time series, no adjustment is needed. In some cases, slight adjustments are made to the vertical factor to improve the transition (Table 2-5).

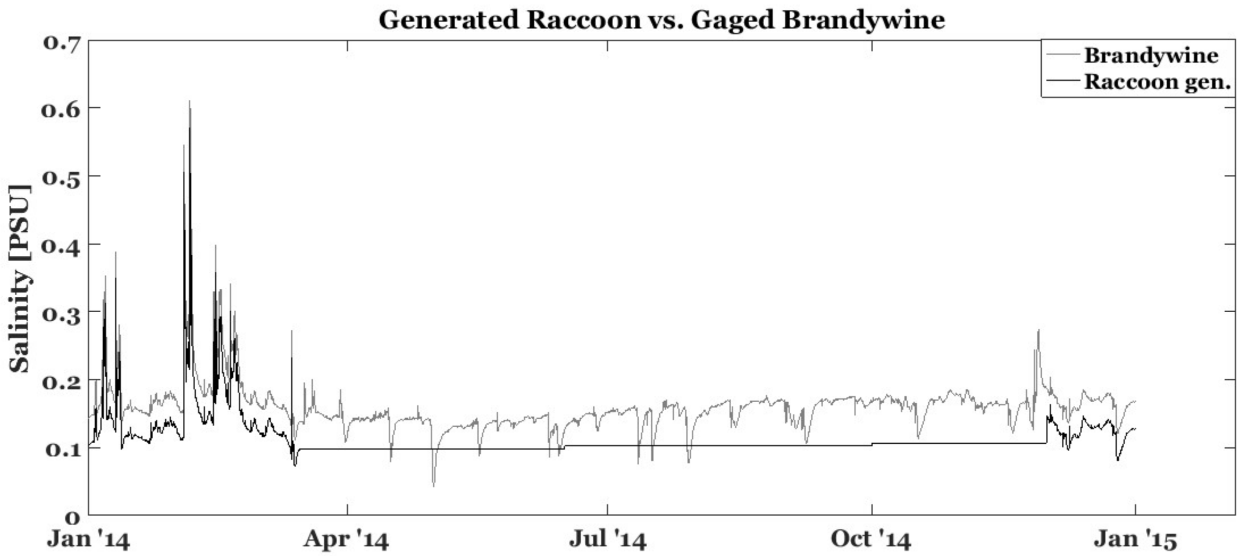


Figure 2-8: Generated Raccoon Creek Salinity vs. Brandywine Creek Salinity

Table 2-5: Vertical adjustment factors for ungaged Tributaries

Tributary	Vertical adjustment factor [PSU]	Tributary for winter gap
Assiscunk Creek	-0.03	Brandywine Creek
Assunpink Creek	0	Brandywine Creek
Army Creek	0	Brandywine Creek
Blacks Creek	-0.05	Brandywine Creek
Big Timber Creek	-0.05	Brandywine Creek
Crafts Creek	0	Brandywine Creek
Crosswicks Creek	-0.05	Brandywine Creek
Chester Creek	0.05	Brandywine Creek
Crum Creek	-0.02	Brandywine Creek
Cooper River	0	Brandywine Creek
Mantua Creek	-0.04	Brandywine Creek
Namaan Creek	0.05	Brandywine Creek
Neshaminy Creek	0	Pennypack Creek
Newton Creek	-0.02	Brandywine Creek
Oldmans Creek	-0.05	Brandywine Creek
Pennsauken Creek	0	Brandywine Creek
Rancocas Creek	-0.09	Brandywine Creek
Raccoon Creek	-0.04	Brandywine Creek
Red Clay Creek	0.03	Brandywine Creek
Ridley Creek	0.02	Brandywine Creek
Shellpot Creek	0	Brandywine Creek
Still Run	-0.03	Brandywine Creek
Salem River	-0.02	Brandywine Creek
Swede Run	0.01	Brandywine Creek
Woodbury Creek	-0.04	Brandywine Creek
White Clay Creek	0.03	Brandywine Creek

Time series are created for all tributaries with grab sample data using this method. For a few remaining tributaries for which no data exists, the salinity time series of a nearby tributary are used (Table 2-6).

Table 2-6: Salinity time series for tributaries without salinity related data

Tributary Without Data	Supplemental Tributary Used
Burlington	Assiscunk Creek
Bustleton Creek	Crafts Creek
Clonmell Creek	Still Run
Crystal Lake	Crafts Creek
Darby Creek	Cobbs Creek
Little Mantua Creek	Big Timber Creek
Little Timber Creek	Big Timber Creek
Mantua Creek	Big Timber Creek
Marcus Hook Creek	Crum Creek
Pompeston Creek	Swede Run
Woodbury Creek	Big Timber Creek

2.5.2 Open Boundary Condition -Salinity

Specific Conductivity data for the near surface waters was collected for PWD by the Woods Hole Group in the vicinity of Pea Patch Island (PPI) during the spring, summer and fall of both 2014 and 2016. The purpose of this data collection effort was to inform the ocean-end member salinity boundary condition for the PWD EFDC modeling efforts. To develop annual series of continuous salinity concentrations for all of 2014 and 2016 without gaps, relationships are developed between the observed data collected at Pea Patch Island, and the data collected by USGS at Reedy Island Jetty (RIJ) in 2014 and 2016. Time series analyses and multivariate statistical modeling are performed to develop the relationships that are used to fill the data gaps.

The observed data from Pea Patch island are transformed to average hourly specific conductivity estimates for use in these analyses, for the periods:

May 8, 2014 – October 26, 2014: 4,128 continuous hours;

April 5, 2016 – October 16, 2016: 4,680 continuous hours.

Data for the Reedy Island Jetty station are retrieved from the USGS National Water Information System web interface (Delaware River at Reedy Island Jetty, DE – 01482800) in an hourly format, and converted to Eastern Standard Time for the period:

September 1, 2007 23:00 hrs. – January 5, 2017 10:00 hrs., 79,382 hours

Minor gaps exist in the 2014 (3 hours) and 2016 (5 hours) Reedy Island Jetty record for periods when the PWD Pea Patch island data acquisition system was not active. These gaps are filled using linear interpretation estimates.

2.5.2.1 Synthesizing a Continuous Estimate of Specific Conductivity at Pea Patch Island

The axial salinity distribution in an estuary results from the relative proportions of sea water and upland runoff from the head of tide, as mixed by tidal and meteorological conditions. The salinity distribution in the Delaware Estuary and its relationships to fresh water inflow have been explored by many investigators (see Rosensweig, 1940; Ketchum, 1951; Cohen and McCarthy, 1962; Sharp, et.al, 1983, Garvine, McCarthy and Wong, 1992; Wong, 1995). Most have concluded that the along-estuary distribution of salinity in the estuary is predominantly the result of tidal mixing, upon which is superimposed on a weak river flow, which essentially is Stommel's original concept that was published in 1951. This concept especially is applicable in the domain of the PWD EFDC model, where essentially there is no vertical salinity stratification (or at most, only ephemeral, weak stratification, mostly limited to the lower portions of the model domain). A recent observational study of the mid-Delaware Bay (Aristizábal & Chant, 2014) found that lateral circulation played a dominant role in enhancing tidally varying stratification.

Initially some effort was expended in this investigation to relate various measures of fresh water inflow to the hourly Specific Conductivity both at Pea Patch Island and at Reedy Island Jetty. Specifically, the subtidal Specific Conductivity signals were compared to numerous lagged accumulations of Delaware River inflow at Trenton and Schuylkill River inflow at Philadelphia. In addition, effects of the implied transport through the Chesapeake and Delaware Canal was included in that analysis. In general, the relationships investigated consistently explained no more than about 50%-60% of the variance in Specific Conductivity, with the most favorable lag of about 3 weeks from the time of the Trenton daily discharge. That result is consistent with expectations that measures of fresh water inflow alone cannot be expected to fully describe salinity conditions along the estuary, especially when employing only multivariate statistical tools in the time domain.

The early work on fresh water discharge - conductivity response reinforced a return to exploring the relationships between the Specific Conductivity signal at Reedy Island Jetty and the signal at Pea Patch Island to yield a reliable predictive capability for the EFDC model boundary condition. The concept is that the net fresh water inflow and large-scale tidal and meteorological influences predominantly are reflected in the Specific Conductivity at subtidal frequencies. The readily available continuous Specific Conductivity data reliably recorded by USGS at Reedy Island Jetty at sub-hourly time steps makes it attractive to use as an exogenous input to predict values at Pea Patch Island.

2.5.2.2 Comparison of the Subtidal Frequencies Signals

A time series of hourly subtidal (low-passed) Specific Conductivity is estimated by applying a modified Lanczos filter with a cutoff period of 34 hours and a filter length with a half-window-width of 1.5 times the cut-off period, yielding an hourly filter length of 109 weights. Inspection of the time series graphs of these low-passed results for Reedy Island Jetty and Pea Patch Island revealed that the subtidal Specific Conductivity at the two stations appear well correlated and in phase with one another for the periods of concurrent observations in both 2014 and 2016.

2.5.2.3 Comparison of the Tidal Frequencies Signals

The tidal frequency signals are estimated by subtracting the low-passed time series from the hourly time series, attributing the resultant residual time series to the tidal (and super-tidal) signal. This tidal residual information was further scrutinized for astronomically-driven harmonic responses by analyzing the time series using the T_TIDES software, applied in Octave (Pawlowicz, Beardsley and Lentz, 2002). The tidal harmonic analysis is performed for each station for each year individually, for the period of overlap when the Pea Patch Island station was active in 2014 (141 days[(1)]) and 2016 (195 days). The results for the 17 tidal constituents that exhibited the largest amplitudes and the highest signal-to-noise ratios in the T_TIDE results are shown in Figure 2-9 below (S/N generally > 3, with 3 cases > 1.5; M8 was allowed in for Pea Patch Island 2016 for completeness, even though the S/N was 0.67).

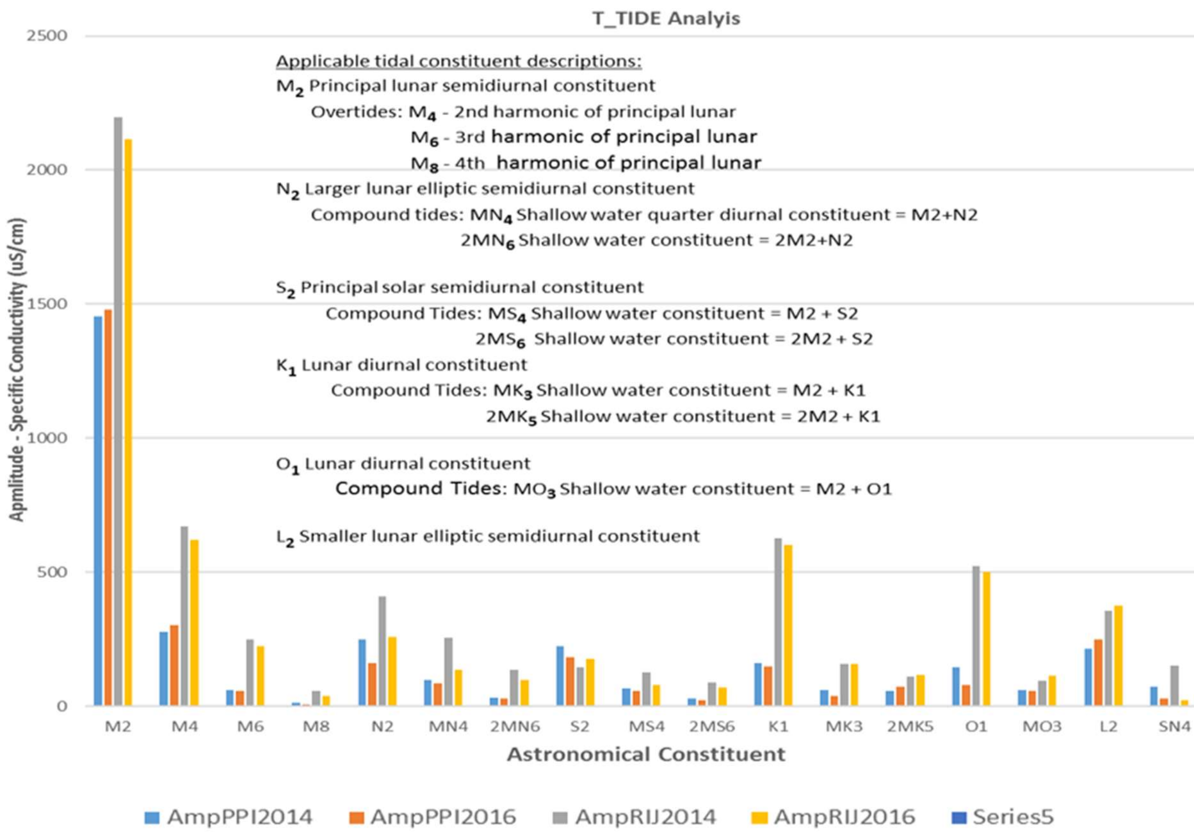


Figure 2-9: Amplitude of specific conductivity for tidal constituents: 2014 and 2016 at Reedy Island Jetty (RIJ) and Pea Patch Island (PPI)

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(1) Note that the data acquired before early June of 2014 was not used in this analysis because the high volume of river inflow associated with the Spring freshet during that period caused the tidal-frequency signal sinusoidal pattern at Pea Patch Island to be clipped. For valid results, the harmonic analysis (T_TIDE) software expects full range sinusoids, i.e., a random, ergodic stationary sinusoidal signal.

The results of the tidal harmonic analysis indicate that the relationships of tidal-frequency amplitude between the two monitoring periods are quite similar for each station. While in general the amplitudes of the Specific Conductivity signal for each constituent at Pea Patch Island are damped relative to that at Reedy Island Jetty (which is assumed to be attributable to the location of Pea Patch Island further upstream, closer to the principal sources of fresh water runoff), they fairly consistently exhibit similar constituent-to-constituent patterns in amplitude. In addition, the differences in phase for the tidal constituents between Pea Patch Island and Reedy Island Jetty (phases are shown in Figure 2-10 below) generally are quite small for the principal constituents that actually are the result of a celestial motion (i.e., M_2, N_2, S_2, K_1, O_1 and L_2). For instance, the M_2 constituent phase at Reedy Island Jetty only differs from the phase at Pea Patch Island by a few degrees. The only primary constituent with a large station-to-station and year-to-year variance was N_2, but on closer inspection the amplitude is small and that is the only constituent with large phase errors reported by T_TIDE, in fact the phase error exceeded the values of the phase. But overall for the principal constituents, the signals are similar in their respective response to whatever forcings are driving them at tidal frequencies, demonstrating that the Reedy Island data makes a reasonably good surrogate for the Pea Patch Island signal at tidal frequencies.

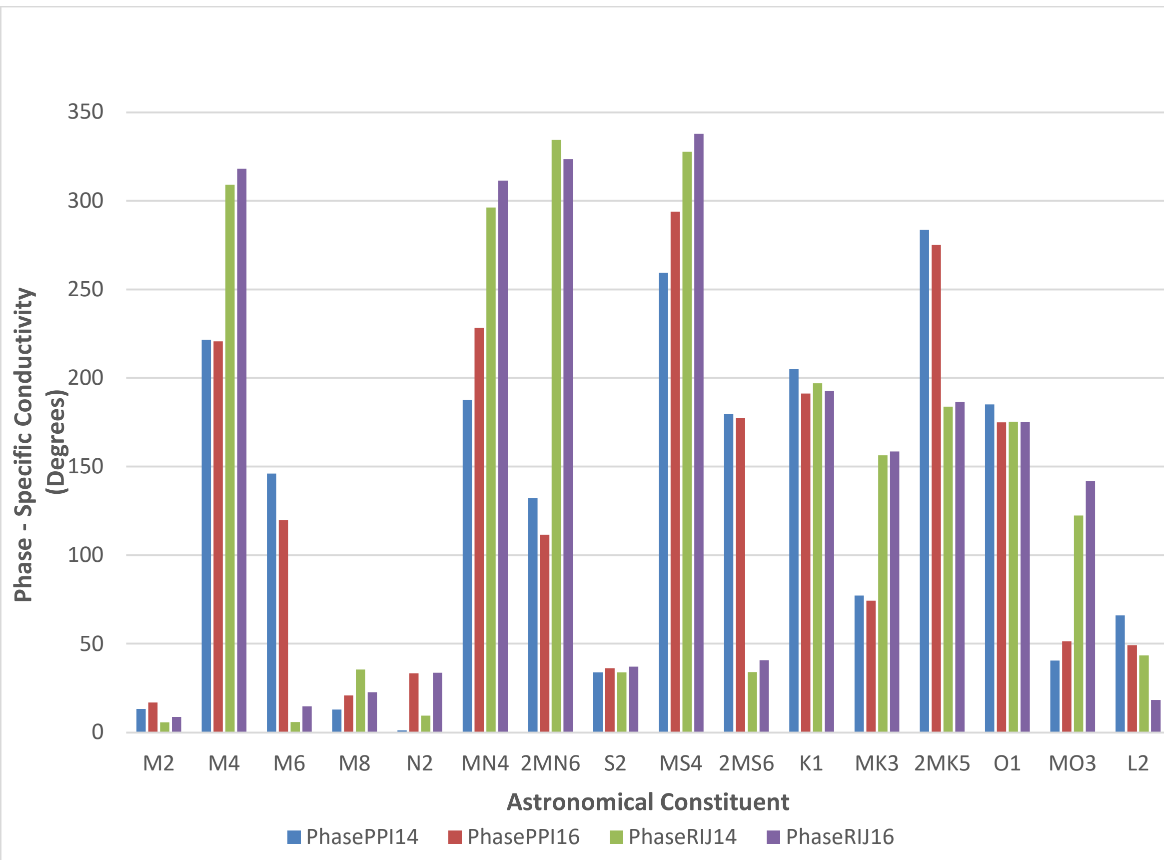


Figure 2-10: Phase of Specific Conductivity for Tidal Constituents: 2014 and 2016

2.5.2.4 Developing a Predictive Equation - Estimating Specific Conductivity at Pea Patch Island from Reedy Island Data

As discussed previously, preliminary work led to the result that all subsequent modeling would be performed on a two-variate basis, decomposing the times series of Specific Conductivity into a subtidal (low-pass filtered) signal and, by subtraction, a residual signal that includes tidal frequencies. The subtidal signal was estimated by applying a modified Lanczos filter as described above. The tidal-frequencies signal was created by subtracting the low-passed filtered signal from the original time series, essentially creating a high-passed series that includes the tidal-frequencies and any higher frequencies.

2.5.2.5 Preliminary Investigations Seeking a Predictive Equation

Initially, a series of regression analyses were performed, first with the low-passed, subtidal-frequency hourly Specific Conductivity series at Buoy P, versus the subtidal-frequency hourly Specific Conductivity series at Reedy Island Jetty, and then with the addition of residual-frequency (high-passed, tidal frequencies and greater) hourly Specific Conductivity at Buoy P versus the residual-frequency hourly Specific Conductivity at Reedy Island Jetty. These regressions were performed on the 2014 data, with the 2016 data used for validation. Initial indications from this work was encouraging, with the low-passed signal at Reedy Island Jetty explaining about 90% of the variance of the low-passed signal at Buoy P/Pea Patch Island in 2016, and the high-passed signal from Reedy Island Jetty explaining about 50% or more of the residual high-passed signal at Pea Patch Island in 2016. The predictions for the total signal at Pea Patch Island for 2016 yielded root mean square errors in the range of 900-1,000 µS/cm (0.4-0.5 ppt salinity).

When the T_TIDE analyses were performed on the two tidal-frequency series, it admitted the opportunity to use the harmonics-predictive capabilities of T_TIDE to provide an input-output model for the tidal frequency signals. That line of investigation was explored, but the resulting root mean square error estimates increased over those yielded by the preliminary regression work, typically by about an additional 500 µS/cm or more. An important underpinning of the harmonic analysis approach is that the time series is stationary in a statistical sense, and there are no temporal modal fluctuations in the mean, and no non-tidal trends in the data. Scrutiny of the graphical results readily revealed that a harmonic prediction approach loses the ability to reflect modal changes in Specific Conductivity that, one assumes, is a result of forcings such as changes in fresh water flow or other meteorological factors, and mixing dynamics, that were not removed by the filter. It is not unreasonable to assume that the reason such relatively short-duration modal shifts can remain in the high-passed filtered tidal-frequencies may belie the inherent numerical inefficiency of the filter to eliminate all the energy from the near-tidal periods (filter “leakage” around the cut-off, 24-72-hours). When these ephemeral fluctuations appear in the record, they cannot be reproduced by a harmonic analysis approach. However, the regression analysis approach readily accommodates directly linearly transferring such fluctuations from the Reedy Island Jetty to the Pea Patch Island output signal. Therefore, a regression approach is favored.

2.5.2.6 Common problem with regression analysis for a water quality parameter: the negative intercept

The initial work on a regression approach described in the previous section revealed a problem that often occurs when working with regression analyses of most water quality parameters. That is, when a parameter's valid realizations only can be positive (no negative Specific Conductivity), and that parameter is used as an endogenous variable in a least squares regression, it admits the possibility that, when the resultant equation is used in a predictive setting, a negative value for the intercept could lead to invalid predictions of negative values for the water quality parameter. That is in fact the experience in the cases explored in the early work here.

A number of approaches can be taken either to avoid this issue altogether, or to remediate the effect by secondary actions on the predicted time series. The most obvious method of avoidance is to suppress the computation of the intercept in the least squares code, and to allow the regression analysis to estimate coefficients for the exogenous variables only. This often leads to a loss in the amount of variance explained (lower correlation coefficient, r^2) over the case that allows the intercept, and poor representations of the predicted values when they are small, approaching the approximate value of the intercept. Curiously, when this approach was attempted here, the r^2 actually increased when the intercept was suppressed, but on close inspection of the observed-predicted graphs, as expected, there was a bias in the results, with the lower levels of Specific Conductivity experiencing over-prediction. Another unusual result of this exercise was that while the suppression of the intercept led to a slightly higher correlation coefficient result, the overall root mean square error (RMSE) between the observed and the-predicted series increased when the intercept was suppressed. This demonstrates an object lesson in least squares regression work: reduced measures of explained / unexplained variance (increased r^2) is not the same thing as a lowest gross error (smaller RMSE).

Another approach to avoid the negative intercept problem is to transform the variables so negative values cannot occur, for instance by taking the log of the variables. While that ensures a non-negative (and non-zero) result, the success of using such a transform is very dependent upon the nature of the variables and how they relate to one another. For parameters that exhibit limited range, such as most water quality parameters that exhibit a 1-log total variation or less, the effect of using a log transform can be very limiting and lead to poor regression fits (as opposed to working with a parameter like bacteria where multiple log ranges are involved and log transforms are common practice).

A third approach to avoid the negative intercept problem, is to post-process the application of the prediction equation to limit the minimum predicted value to some lower (positive) limit, that is based on an informed understanding of the behavior of the endogenous parameter. In this application for instance, several factors support taking this approach. First and most importantly, the objective is to create the boundary condition for 2014 and 2016, when only predicting Specific Conductivity for the first few and last few months of the year. The periods of the observations in 2014 and 2016 cover some of the periods of the highest fresh water inflows, which are the periods of lowest Specific Conductivity that occurred in those years. In addition, the months when observed data is available are the periods of the most interest in water quality modeling, spring through fall, making issues with estimation methods in the remaining periods less critical. Second, there are numerous occasions in the spring of each of these years when the Specific Conductivity is quite low, enabling a reasonable estimate of the minimum value that should be allowed by the application of the regression results. In 2014, the minimum observed value was approximately 220 µS/cm, and the minimum observed in 2016 was approximately 500 µS/cm. That knowledge allows the establishment of a starting point to inform the input-output modeling process to yield a minimum error estimate. This approach is described below.

One possible problematic aspect of using a minimum allowable cutoff value for predicting an endogenous variable with a typically sinusoidal pattern (not unusual for water quality parameters in a tidal situation) is that it "bottom-clips" the sinusoidal signal, causing abrupt changes in the time-slope of the predicted parameter. When that clipped series is used as a boundary condition, or otherwise as a time-series input to in a numerical model, it can lead to numerical stability issues. It is anticipated that this situation will be buffered as the model takes these hourly values and interpolates them up to the computational time step, softening the numerical effects of the breaks. Also, the effect is occurring at very low salinities (<~0.5 ppt) when abrupt changes may not have an impact on the model numerical scheme. However, if it does surface as an issue here, the predicted time series again can be post-processed, running a short-period filter over the low-salinity portions time series where the clipping has occurred, smoothing the transitions.

2.5.2.7 Selecting a Predictive Equation

The regression approach was chosen for the development of an input-output model needed to establish the continuous Specific Conductivity boundary condition. The regression result for the selected model is summarized in the table below.

Table 2-7: Regression Results

Model	No. of Obs.	Adj. R^2	Reddy Is. Jetty LP Coefficient	Reedy Is. Jetty Tidal Coefficient	Intercept
PPI Hourly vs. RIJ LP & RIJ Tidal 2014 & 2016	8,011	0.91	0.818	0.525	-2,418.8

2.5.2.8 Setting a Minimum Allowable Value: The Negative Intercept

As discussed above, the application of the prediction equation includes post-processing to limit the minimum predicted value to some lower (positive) limit that is based on an informed understanding of the behavior of the endogenous parameter, the predicted hourly average Specific Conductivity at Pea Patch Island. While simply selecting the minimum (hourly averaged) observed value in a year might at first appear to be the most direct approach, a better overall estimate likely will result from setting the minimum value to the mean of all observed values for periods when the predicted value falls below the minimum observed value. The table below shows the results of a SAS routine that illustrate the effects of a range of minimum allowable values on the root mean square error during the monitoring periods between the hourly mean of the observed data and the values predicted using the selected regression equation. For this application a lower limit is set for 2014 and another is set for 2016, and the root mean square error (RMSE) is calculated for each year and the two years taken together. The table below shows the selected values for the 2014 and 2016 adjustment factors. These are the values resulting from taking the mean of all hourly-averaged observed values that occurred for all hours when the resultant of the prediction equation fell below the annual minimum hourly values (2014: 218.4 µS/cm; 2016: 498.8 µS/cm).

Table 2-8: Adjustment factors for 2014 and 2016

Low Limit 2014	Low Limit 2016	RMSE 2014	RMSE 2016	RMSE Overall (2014 & 2016)
551.4	1,652.3	976.2	997.8	987.7

2.5.2.9 Application of the Predictive Equation

The selected model equation is:

PPI_HrSC = (0.818 x RIJ_LPHrSC) + (0.525 x RIJ_TFHrSC) – 2,418.8

For 2014, if the value of *PPI_HrSC is < 218.4 µS/cm*, then *PPI_HrSC = 551.4 µS/cm*.

For 2016, if the value of *PPI_HrSC is < 498.8 µS/cm*, then *PPI_HrSC = 1,652.3 µS/cm*.

Where:

PPI_HrSC = Predicted Pea Patch Island/Buoy P hourly Specific Conductivity, µS/cm

RIJ_LPHrSC = Reedy Island Jetty hourly subtidal/low-passed Specific Conductivity, µS/cm

RIJ_TFHrSC = Reedy Island Jetty hourly tidal-frequency /high-passed Specific Conductivity, µS/cm.

This prediction equation, with the limits applied as discussed above, is used to synthesize the continuous Pea Patch Island Specific Conductivity in the units of µS/cm, for 2014 and 2016, for all hours in those years when there is no observed data. For 2014, there are 4,128 hours during May to October when observed data are available, and 4,632 hours during January to May, and October to December, when the predicted equation is used. Of those 4,632 hours in 2014 when predictions are required, there are 972 hours, or 11.1% of the total number of hours in that year, when the predicted value is limited to the minimum value of 551.4 µS/cm. For 2016 (a leap year), there are 4,680 hours during April to October when observed data are available, and 4,104 hours during January to April, and October to December, when the predicted equation is used. Of those 4,104 hours in 2016 when predictions are required, there are 340 hours, or 3.9% of the total number of hours in that year, when the predicted value is limited to the minimum value of 1,652.3 µS/cm.

2.5.3 CSOs

Time series of flows and dissolved salts loads from multiple combined sewer overflow (CSO) areas are explicitly represented in the PWD salinity model, which are listed as follows:

- City of Philadelphia Pennsylvania – Philadelphia Water Department (PWD)
- City of Camden New Jersey, Gloucester City New Jersey – Water Department, and one Camden County Municipal Utilities Authority (CCMUA) owned outfall

- City of Chester Pennsylvania - Delaware County Regional Water Quality Control Authority (DELCORA)
- City of Wilmington Delaware - Department of Public Works

The Trenton Sewer Utility in Trenton New Jersey has one permitted CSO outfall (DSN002A), which, based on a review of publicly available discharge monitoring report tables and the National Pollutant Discharge Elimination System (NPDES) permit description, overflows infrequently when compared to typical CSO configurations. Specifically, this CSO operates as an interceptor relief overflow when the hydraulic capacity of the wastewater treatment plant of 27 MGD is exceeded and the wet weather detention basin (in service since 1982) at the plant is full. For example, the administrative files for the Trenton Sewer Utility indicates that there has been a total of seven (7) discharges at DSN002A between January 2003 and December 2012. Given the infrequency of the overflows and difficulty in representing them for this system, this CSO area is excluded from the model representation.

Additional CSO areas, tributary to the Delaware River and Estuary and located upstream of non-tidal USGS gaging stations, are not explicitly represented. Instead, these CSO contributions are represented within tributary flows and loads without special consideration. A short example of these CSO areas include but are not limited to: Lansdale, Norristown, Bridgeport, Bethlehem, and Easton.

2.5.3.1 CSO Flow Estimates

Time series of CSO flows are estimated for the above mentioned CSO areas in Figure 2-11. Different methodologies are developed for each area, based on available tools, reference materials, the relative importance of each source, and other factors.

CSO flows for the city of Philadelphia are predicted by SWMM models maintained by PWD. These models are driven by precipitation measured by the PWD rain gage network. The predicted overflows are loaded to the PWD salinity model on a 15-minute-interval time series basis.

CSO flows for the city of Camden, New Jersey, Gloucester City, New Jersey – Water Department, and one Camden County Municipal Utilities Authority (CCMUA) owned outfall are predicted by the NetStorm model developed by PWD, which is driven by hourly precipitation measured at the Philadelphia International Airport. The estimated overflows are loaded to the PWD salinity model on a 1-hour-interval time series basis.

CSO flows for the City of Chester, Pennsylvania and Wilmington, Delaware are predicted through simplified overflow spreadsheet models developed by PWD. Different calculation methodologies are developed for each area. Overflows for Chester are estimated using hourly precipitation measured at the Philadelphia International Airport. Overflows for Wilmington are estimated using hourly precipitation measured at the Wilmington-New Castle County Airport. The estimated overflows are loaded to the PWD salinity model on a 1-hour-interval time series basis.

2.5.3.2 CSO Dissolved Salts Loads Summary

Combined sewer overflow is not expected to be a significant source of dissolved salts (i.e. salinity) in the tidal Delaware River except during periods of road salt treatment in the winter.

Outside of periods of road salt treatment, wet weather runoff is expected to result in the dilution of dissolved salt in sewer systems and urban tributaries.

Wet weather sampling of dissolved salts and surrogates for dissolved salts at sewer trunks, regulating structures, or CSO outfalls is not available for the Philadelphia Combined Sewer System. Instead, sampling taken within the combined sewer systems of Camden and Gloucester City, New Jersey are assumed to be a representative estimate of dissolved salts concentration for all explicitly represented CSOs. The representative wet weather concentration derived from Camden and Gloucester City had a specific conductance value of 233 µS/cm, and a corresponding practical salinity value of 0.11 PSU, which was applied to the PWD salinity model as a constant concentration to the CSO flow time series. The following report subsection provides details on how these values are developed.

Comparisons made to the National Stormwater Quality Database version 1.1, confirm that stormwater runoff is typically relatively dilute of salts with an overall sample median value for specific conductance of 121 µS/cm. Continuous water quality sampling at USGS 01467087 Frankford Creek at Castor Avenue indicates that estimates from Camden and Gloucester City are within similar ranges during wet weather, which is a relevant comparison, since the majority of wet weather flow observed at Castor Avenue is CSO in origin for most rainfall spatial distributions. At Castor Avenue, outside of road salt treatment time periods, specific conductivity climbs during extended dry weather periods. Specific conductance values of 400 – 1000 µS/cm are common preceding a wet weather event, and then decline rapidly to values in the range of 80 – 300 µS/cm during a wet weather event.

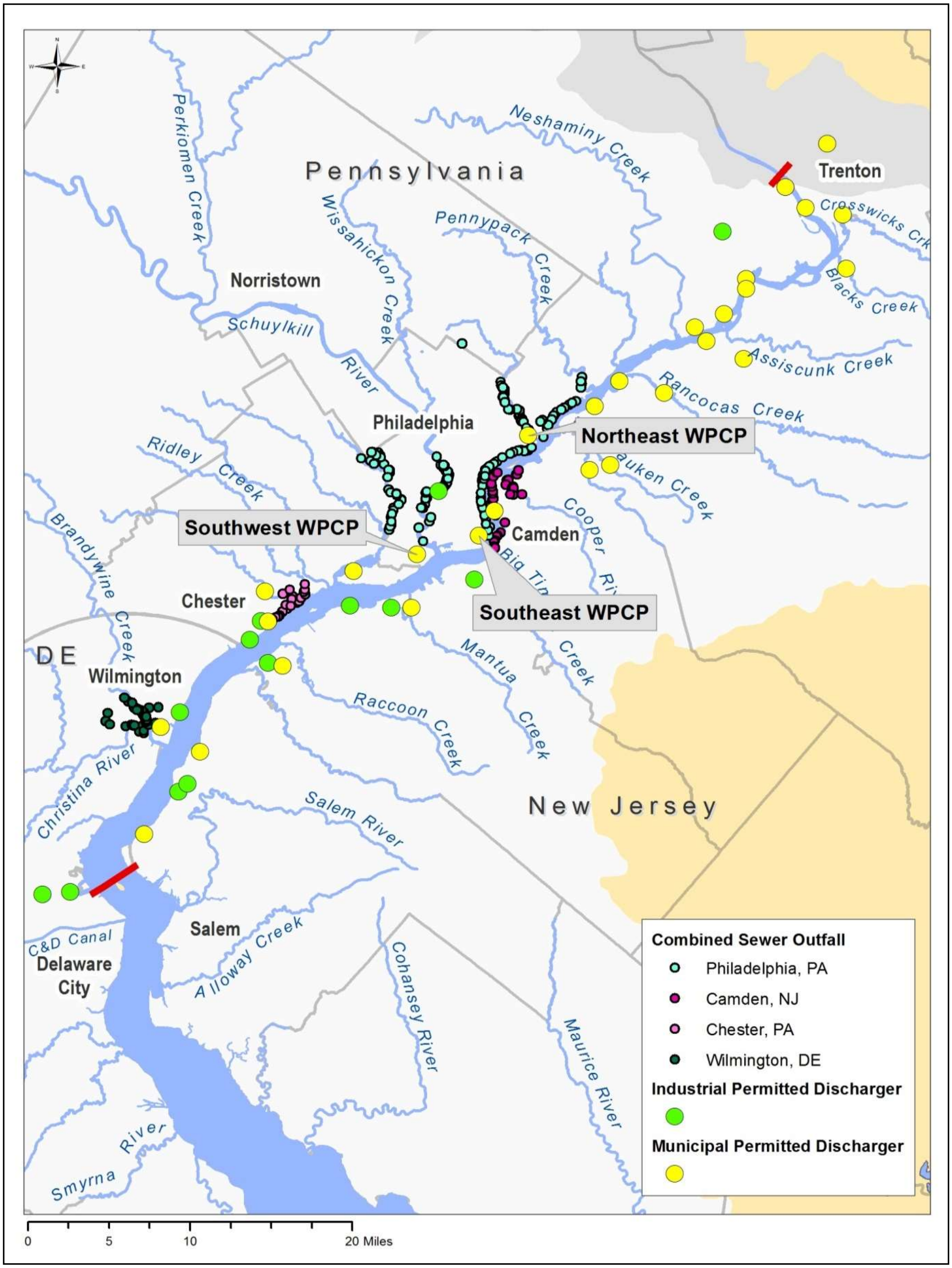


Figure 2-11: Permitted Discharges and Combined Sewer Outfalls

2.5.3.3 CSO Dissolved Salts Loads Development

In response to the New Jersey Sewage Infrastructure and Improvement Act, a 1999 CSO Monitoring Study Report was developed for the City of Camden, Gloucester City, and the Camden County Municipal Utilities Authority, which documented numerous flow and water quality sampling efforts conducted in the sewer systems in 1997. Wet weather grab samples were collected upstream of three combined sewer regulating structures, and analyzed for numerous water quality parameters including specific conductance and total dissolved solids (TDS). Sampling was conducted for two events at each site, staggered over three wet weather events, which are listed as follows: 8/4/1997 at Regulators C3 and C32; 8/17/1997 at Regulators G1, C3, C32; and 10/24/1997 at Regulator G1. Six combined sewer regulator site-events were collected. Continuous flow monitoring was recorded while five grab samples were collected per site and wet weather event, to characterize the water quality throughout an event. In total there were 30 grab sample observations, paired with flow monitoring time series, available to characterize the wet weather water quality conditions located upstream of CSO regulating structures.

Flow weighted wet weather event mean concentrations (EMCs) calculated for specific conductance and total dissolved solids, which can be used as surrogates to estimate salinity. The 1990 CSO Monitoring Study Report narrative discussed first-flush effects observed within the event pollutographs for the two events in August, which highlighted the importance of flow weighting the calculations. The report contained tabular summaries of flow weighted EMCs for select parameters, including TDS, but not for specific conductance. The report also contained the percent of event discharge volume associated with each grab sample, which were used to apply the same methodology used in the report to calculate flow weighted EMCs for specific conductance. In total, 6 site-event EMCs were provided for TDS, and 6 site-event EMCs were calculated for specific conductance. Subsequently, the means of the 6 site-event EMCs were calculated. The group mean EMC for TDS was 140 mg/L. The group mean EMC for specific conductance was 233 μS/cm.

The group mean of the flow weighted EMCs for TDS of 140 mg/L, converted through equation 2.2 (Section 2.4), results in a TDS as Absolute Salinity of 0.17 g/kg. The group mean of the flow weighted EMCs for specific conductance of 233 μS/cm (conversion from Section 2.4), assuming a temperature of 25°C, resulted in a Practical Salinity of 0.11 PSU. The salinities derived from TDS and specific conductance were very close in value, which suggests the report parameter, Salinity (μmhos/cm), was interpreted correctly. The Practical Salinity value of 0.11 PSU is selected and applied to the PWD salinity model as a constant concentration to the CSO flow time series.

2.5.4 Withdrawals and Discharges in the Model Domain

There are numerous intakes, industrial and municipal dischargers along the Delaware and Schuylkill Rivers and their tributaries. The discharger list used for this salinity model started with the list of dischargers used in the 2015 Tidal Waters Water Quality Model (Philadelphia Water Department 2015), referred to as the PWD WQ model. In the PWD WQ model, only facilities with discharge over one million gallons per day (MGD) were included. Additional intakes and discharges are added to the PWD salinity model due to their potential impact on spatial salinity concentration along the Delaware River. While there are only dischargers included in the PWD WQ model, the PWD salinity model takes four different categories into account: discharge only, withdrawal only, withdrawal and discharge, and return flow facilities.

Facilities discharging directly into the Delaware River, Schuylkill River, and their tributaries are "discharge only" class. These locations are not limited to a minimum discharge requirement as long as the discharge contains specific conductance, or total dissolved solids (TDS). Facilities withdrawing directly from the rivers and tributaries are "withdrawal only" class, such as water treatment plants. Many industrial facilities have both an intake and a discharge and a discharge at the same location and are classified as “withdrawal and discharge”. Lastly, facilities withdrawing from the rivers and tributaries, utilizing the water in processes, and discharging it back into the watershed are "return flow" class. Facilities that withdraw water for cooling purposes are also included in the return flow class. When a facility withdraws, utilizes, and then discharges water, the net loss of water is called consumptive use. This loss of water is often due to evaporation during a cooling or industrial process. There are different return flow classes: withdrawal and discharge, and withdrawal at one facility and discharge at another facility.

In order to identify facilities to include in the salinity model, searches for permitted withdrawal and discharge facilities in Pennsylvania, Delaware, and New Jersey are performed using the state compliance, EPA and DRBC databases and then mapped using GIS. Permitted facilities that withdrawal and discharge to the model domain and are located downstream of USGS streamflow and water quality sampling stations are then identified for further review. For the purposes of the salinity model, discharges upstream of USGS water quality and streamflow sampling stations are not included in the salinity model because it is presumed that their impact on water quality and streamflow are captured by the most downstream USGS sampling station. The USGS stations used as the most upstream boundary in this discharge and withdrawal screening process are depicted in Figure 2-2.

The follow subsections describe the discharge only, withdrawal only, withdrawal and discharge and return flow categories of water use within the model domain. While the PWD salinity model validation presented in this report is performed on 2014 and 2016, a detailed search for available discharge and withdrawal data was only performed for 2014. It is assumed that there are no significant changes in the withdrawals and discharges between 2014 and 2016, therefore maximum effort was directed at locating as much data for only one of the two validation years, 2014. A description and table are also provided of how these facilities are represented geographically and consolidated into model nodes.

2.5.4.1 Discharge Only

A search of 2014 publicly available DRBC information, the EPA-PCS database, NJDEP-OPRA database, Pennsylvania and Delaware resources identified 52 facilities classified as discharge only for the purposes of the PWD salinity model, Table 2-9 below. The majority of discharge only facilities identified are municipal wastewater treatment plants, however the list also includes some specialty industrial and manufacturing facilities that purchase water from another supplier but treat and discharge their own processing wastewater.

In order to represent these facilities in the PWD salinity model, a search for available information on 2014 discharge flow rate, TDS concentration, conductivity, or chloride was conducted. The objective of the data collection is to assemble a 2014 time series for each discharger that includes a monthly flow rate in cubic meters per second (CMS) and salinity in practical salinity units (PSU). All data collected is converted into these units. The monthly flow rate is taken directly from Discharge Monitoring Reports (DMRs) and is gap filled using a site-specific annual average.

Many facilities do not have available salinity data, including TDS, chloride, or conductance information to convert to salinity. However, it is not assumed there is no salinity in the discharge, just that the facility is likely not regulated for salinity and therefore not required to sample and report salinity in the DMRs. All 2014 salinity related data from DRBC information, the EPA-PCS database, NJDEP-OPRA database, Pennsylvania and Delaware resources are inventoried due to the availability issue mentioned above. The search identified DRBC data from 2011 to 2016.

In order to estimate salinity for discharge only facilities the following, procedure is used. If there are monthly average or daily maximum TDS or chloride data available, these data are used in the salinity loading. If there are one or two missing monthly values, these gaps are filled with the annual average. Longer gaps are filled with site-specific DRBC median values. If data is reported in three months intervals, then each data point represents a season. When monthly DMR data is unavailable from 2011 – 2016, DRBC data is used. Facilities with 2014 DRBC information use 2014 reported data and are gap filled with the annual average. For facilities without 2014 DRBC information, the salinity load is a median value based on all available 2011 – 2016 DRBC data.

Facilities with no DMR or DRBC information are divided into industrial and municipal classes and use either a municipal or an industrial salinity constant. Industrial facilities with no available TDS discharge concentration data are assumed to have a constant TDS discharge concentration equal to the median of all available TDS data from industrial discharges within the model domain. PWD was able to collect 224 data points from 17 facilities for 2014, and the median of this data is 628.2 mg/L TDS. In the model, a TDS concentration for discharges from the 3 industrial facilities without data is set to a constant of 628.2 mg/L. The municipal constant is an average of PWD plants and DELCORA median TDS concentrations.

Table 2-9: Discharge Only Facilities Included in PWD Salinity Model

State	NPDES	Name	Outfall	2014 Avg. Flow [MGD]	2014 Avg. Salinity [PSU]	Standard Deviation	Needs estimate of salinity?	Estimation category
DE	DE0020320	Wilmington WWTP	1	73.71	0.46	0.00	No	WWTP
NJ	NJ0004278	Air Products & Chemicals Inc. (COIM USA)	001A	0.07	0.21	0.21	No	Process
NJ	NJ0004391	RIMTEC Corp. (Colorite)	2	0.65	0.55	0.00	Yes	Polymer manf.
NJ	NJ0005002	PSE&G Fossil Generating Station	WTPA	0.03	0.50	0.61	Yes	Process
NJ	NJ0005185	Ausimont USA Inc.	001A	0.41	0.56	0.94	No	Specialty polymer
NJ	NJ0005401	Coastal Eagle Point Oil Co.	001A	1.50	0.52	0.69	Yes	Process (refinery)
NJ	NJ0020206	Allentown WWTP	001A	0.13	0.42	0.00	Yes	WWTP
NJ	NJ0020923	Trenton DPW Sewerage Authority	001A	11.38	0.19	0.00	No	WWTP
NJ	NJ0021598	Pennsville Twp. Sewerage Authority	001A	1.44	0.18	0.17	Yes	WWTP
NJ	NJ0021601	Carneys Point WWTP	001A	1.07	0.42	0.00	Yes	WWTP
NJ	NJ0021610	Riverton Boro. STP	001A	0.16	0.14	0.15	Yes	WWTP
NJ	NJ0021709	Burlington Twp DPW	002A	2.13	0.35	0.00	Yes	WWTP
NJ	NJ0022021	Swedesboro Boro. MUA WWTP	001A	0.23	0.42	0.00	Yes	WWTP
NJ	NJ0022250	Woodstown Boro. Water Dept.	001A	0.41	0.42	0.00	Yes	WWTP
NJ	NJ0022519	Riverside Twp.	001A	0.53	0.30	0.00	Yes	WWTP
NJ	NJ0023361	Willingboro Twp MUA	001A	3.82	0.25	0.00	No	WWTP
NJ	NJ0023507	Delran Sewerage Authority	001A	2.06	0.27	0.00	Yes	WWTP
NJ	NJ0023701	Florence Twp STP	001A	1.53	0.45	0.00	Yes	WWTP
NJ	NJ0024007	Cinnaminson Sewerage Authority	001A	1.33	0.30	0.00	No	WWTP
NJ	NJ0024015	Mount Holly Twp. MUA	001A	3.18	0.42	0.00	Yes	WWTP
NJ	NJ0024023	Pennsgrove Sewerage Authority	001A	0.39	0.14	0.25	Yes	WWTP
NJ	NJ0024449	Palmyra Boro	001A	0.49	0.39	0.00	Yes	WWTP
NJ	NJ0024660	Burlington City STP	002A	1.89	0.31	0.00	Yes	WWTP
NJ	NJ0024678	Bordentown Sewerage Authority	001A	1.85	0.34	0.00	No	WWTP
NJ	NJ0024686	Gloucester County Utility Authority	001A	18.45	0.67	0.00	No	WWTP

State	NPDES	Name	Outfall	2014 Avg. Flow [MGD]	2014 Avg. Salinity [PSU]	Standard Deviation	Needs estimate of salinity?	Estimation category
NJ	NJ0024821	Pemberton Twp. MUA	001A	1.78	0.42	0.00	Yes	WWTP
NJ	NJ0024996	Moorestown WWTP	001A	2.49	0.23	0.00	No	WWTP
NJ	NJ0026182	Camden County MUA	001A	55.40	0.39	0.00	No	WWTP
NJ	NJ0026301	Hamilton Twp WPCF	001A	8.12	0.36	0.00	No	WWTP
NJ	NJ0027481	Beverly City Sewer Auth.	001A	0.46	0.15	0.17	Yes	WWTP
NJ	NJ0027545	Logan Twp MUA	001A	1.31	0.19	0.19	Yes	WWTP
NJ	NJ0030333	Greenwich Twp. STP	001A	0.51	0.42	0.00	Yes	WWTP
NJ	NJ0069167	Maple Shade POTW	001A	2.59	0.42	0.00	Yes	WWTP
PA	PA0011533	Phila. Energy Solutions (Sunoco) Girard Pt.	15	6.63	1.88	0.25	No	Process (refinery)
PA	PA0013323	Boeing	1	0.21	0.97	0.38	No	Process
PA	PA0013463	US Steel Fairless Hills Works	103	1.67	0.48	0.13	No	Process
PA	PA0023949	Brookhaven WWTP - discharge only	0	0.19	0.42	0.00	Yes	WWTP
PA	PA0024121	Little Washington STP	1	1.44	0.42	0.00	Yes	WWTP
PA	PA0026450	Bristol Twp WWTP	1	2.78	0.42	0.00	Yes	WWTP
PA	PA0026468	Lower Bucks County JMA	1	7.49	0.31	0.00	No	WWTP
PA	PA0026662	PWD - Southeast WPCP	SEOUT	*	0.43	0.11	No	WWTP
PA	PA0026671	PWD - Southwest WPCP	SW123E	*	0.48	0.12	No	WWTP
PA	PA0026689	PWD - Northeast WPCP	NEOUT	*	0.45	0.13	No	WWTP
PA	PA0026701	Morrisville Boro Mun. Auth-STP	1	5.24	0.51	0.00	No	WWTP
PA	PA0027103	DELCORA	1	31.27	0.55	0.10	No	WWTP
PA	PA0027294	Bristol Boro WSA	1	1.46	0.34	0.02	No	WWTP
PA	PA0027383	Southwest Delaware County MUA	2	4.23	0.42	0.00	Yes	WWTP
PA	PA0028380	Tinicum Twp WWTP	1	1.05	0.24	0.23	Yes	WWTP
PA	PA0043818	Waste Management (Falls Twp. landfills)	0	0.30	5.02	1.73	No	Process
PA	PA0045021	Brightsmith LLC Morrisville	1	0.02	0.19	0.14	No	Coil coating
PA	PA0051713A1	Evonik - discharge only	0	0.85	0.55	0.00	No	Process

**Data Source: A combination of publicly available DRBC dockets, DMR reports, the EPA-PCS database and NJDEP-OPRA database are used to identify 2014 information, with the exception of PWD facilities in which internal data is used.*

2.5.4.2 Withdrawal Only

An extensive search of DRBC dockets, reports and other publicly available material identified thirty facilities classified for PWD salinity model purposes as withdrawal only, Table 2-10. Facilities identified as having a withdrawal only include water suppliers as well as manufacturing or industrial facilities that do not treat their own wastewater, and instead interconnect with a wastewater treatment facility. Some facilities identified as withdrawal only have NPDES permits, but they are for stormwater only outfalls. Groundwater withdrawals identified by the geographical screening process described at the beginning of this section are included here. Given the USGS gages are located at the head of tide on the tributaries, and the identified groundwater withdrawals are made downstream of these locations, it is assumed that they have an equivalent hydrological impact as a surface water withdrawal.

To represent the withdrawals in the PWD salinity model, the annual average withdrawal for each facility identified in publicly available information is used as the amount of water withdrawn by the model at the location of the facility. For facilities where no information on the average annual withdrawal could be found, the permitted withdrawal or water allocation for the facility is used. The largest withdrawal only facility is the PWD Baxter Water Treatment Plant located along the Delaware River at River Mile 110 in the Torresdale neighborhood of Philadelphia. Special considerations for the Baxter withdrawal are made and detailed below due to the intake configuration.

PWD Baxter Water Treatment Plant

On average the PWD Baxter Water Treatment Plant takes in 140 MGD (based on 2014 daily data), which corresponds to about 200 CFS or a small tributary. The water withdrawn from the Baxter intake is returned to the Delaware River from the three PWD Water Pollution Control Plants. Withdrawing this water by a simulated upstream intake in the model will prevent the same volume of water from being added to the model twice; once by the municipal discharges and once by omission of an intake node.

PWD opens the tidal Baxter intake gate to take in water during the incoming flood and closes the gate at high tide to prevent water from flowing out. For a realistic representation of this tidal intake, a time series is generated in which the daily withdrawal is distributed over time periods when the Delaware River water level elevation surpasses the Baxter raw water basin (RWB) elevation, thus allowing flow from the Delaware River to the RWB.

Table 2-10: Withdrawals Included in PWD Salinity Model

Facility Name	State	Surface Water or Groundwater	Annual Average, MGD*
Aqua - PA Neshaminy	PA	Surface	15*
Aqua NJ Gloucester	NJ	Groundwater	4.50
Aqua PA Bristol	PA	Surface	5.71
Artesian Water Company	DE	Groundwater	20.00
Borough of Haddonfield	NJ	Groundwater	1.53
Borough of Wenonah	NJ	Groundwater	0.17
Burlington City	NJ	Surface	1.20
Deptford Twp.	NJ	Groundwater	2.46
Greenwich Twp.	NJ	Groundwater	0.82
Haddon Twp.	NJ	Groundwater	0.90
Inversand Company	NJ	Groundwater	0.40*
Kimberly Clark	PA	Surface	7.10
Lower Bucks Jt. Municipal Authority	PA	Surface	8.03
Mafco Worldwide Corp.	NJ	Surface	0.14
Maple Shade	NJ	Groundwater	1.87
Mount Laurel	NJ	Surface	4.50
New Castle PWS	DE	Groundwater	0.60
NGC Industries Inc.	NJ	Surface	0.14
NJ American Delran	NJ	Surface	21.73
Pennsgrove Water Supply Company - Bridgeport	NJ	Groundwater	0.09
Pennsville Twp. Sewer Auth. Heron Ave. WTP	NJ	Surface	0.94
PWD**	PA	Surface	Time Series
South Jersey Water Supply Co. - Harrison Twp.	NJ	Groundwater	0.61
Sunoco Logistics Tank Farm	NJ	Surface	8.62*
Uniqema (Croda)	DE	Surface	5.02
United Water - Stenton	DE	Surface	16.56
West Deptford	NJ	Groundwater	1.30
Wheelabrator Falls	PA	Surface	0.75
Willingboro	NJ	Groundwater	5.01
Wilmington-Brandywine WTP	DE	Surface	11*
Total	-	-	**286.3**

** Water allocation used given lack of information on annual average withdrawal*
*** PWD Baxter withdrawals are described in detail below, annual average approximately 140 MGD*
Data Source: A combination of publicly available DRBC dockets, reports, and interactive maps were used to identify this information, with the exception of PWD.

2.5.4.3 Withdrawal and Discharge

A search for facilities that both withdrawal and discharge to the model domain identified thirty such facilities, comprised mainly of industrial, manufacturing and refinery facilities, Table 2-11. In order to correctly capture the withdrawal and return of water from these facilities, DMRs as well as DRBC dockets were reviewed for consumptive use, withdrawal and discharge information.

Table 2-11: Consumptive Use of Withdrawals and Discharges

Name	NPDES	Water Allocation (MGD)	Water Withdrawal Ave. (MGD)	Consumptive Use - Facility (%)	Consumptive Use (MGD) Based on Allocation	Consumptive Use (MGD) Based on Avg.
Axeon	NJ0064921	0.64	0.19	25.00	0.16	0.05*
Bordentown City White Horse WP	NJG0028649	3.93	2.01	20.00	0.79	0.40(NA)
BP Oil Co. Paulsboro	NJ0005584		0.22			0.02*
Coastal Eagle Point Oil Co.	NJ0005401	3.67	2.88	19.00	0.70	0.55*
Conoco Phillips Refinery (Outfall 201)	PA0012637	156.70		1.23	1.93*	
Delaware City Refinery (Outfall 601)	DE0000256	467.17	367.78	1.15	5.37	4.23*
Dupont Edgemoor (Outfall 1 AND Outfall 3)	DE0000051	11.50	6.31	2.90	0.33	0.18*
E I Dupont De Nemours & Co. (Outfall 662)	NJ0005100		41.76	10.40	4.34*	
E I Dupont De Nemours & Co. Repauno	NJ0004219	22.93	6.28	16.00	3.67	1.01(NA)
Ferro Corp.	NJ0005045					
FPL Energy Marcus Hook	PA0244449	11.00	3.91	70.40	7.74	2.75*
General Chemical Del. Valley Works	DE0000655					NA
GEO Specialty Chemicals (Hercules)	NJG0005134		0.18		NA	NA
Hess Corp. Pennsauken (001A)	NJ0004383			40.00		
Hess Corp. Pennsauken (002A)	NJ0004383					NA
Holman RMP Enterprises	NJG0105449	0.24	0.12	1.00	0.00	0.00(NA)
Laidlaw Env. Services	NJ0005240	0.60				NA
Moorestown Twp. Hartford Rd. WTP	NJG0029548		1.58	10.00		0.16(NA)
National Park Boro. SLF	NJ0025844	0.40	0.27	10.00	0.04	0.03
NJ American Green Street WTP	NJG0004731		0.14	10.00		NA
Occidental Chemical Corp.	DE0050911					NA
Phila. Electric Eddystone	PA0013714	863.07		0.40	3.45*	
Phila. Energy Solutions	PA0012629	22.77		38.00	8.65*	
Polyone Corp.	NJ0004286	1.49	0.92	44.00	0.65	0.40*
PSE&G Mercer Generating Station	NJ0004995	714.23	640.22	0.60	4.29	3.84*
Quality Distribution Inc.	NJG0105589		0.29			NA
Rohm & Haas Bristol	PA0012769		4.80	5.10		0.24*
Solvay Solexis	NJG0005185		0.61	10.00		0.06*
US Steel Fairless Hills Works (Outfall 103)	PA0013463	242.93	41.93	3.00	7.29	1.26*
Valero Refining Co. (Outfall 1)	NJ0005029	13.33	7.60	31.00	4.13	2.36*

2.5.4.4 Return Flow

Eleven facilities that consume water for cooling purposes are located within the model domain (Table 2-12). This means that they remove water from the river with the ambient salinity and discharge water as a return flow with higher salinity after part of the volume evaporated during the cooling process. While these flows are relatively low, PWD decided to incorporate them as a potential source of salt for the sake of completeness.

Table 2-12: Return Flow Facilities

Facility	Withdrawal [MGD]	Discharge [MGD]	% Return	Located at River Mile
Deepwater Generating Station (Pepco, Connectiv)	90.15	89.70	99.50	68.5
Chambers Cogen - Carneys Point	3.33	3.00	90.09	69.2
Calpine Edgemoor	1100.00	1089.00	99.00	72.4
Calpine Hay Road	5.60	5.54	99.00	72.4
Dupont Edgemoor (Outfall 3)	6.31	6.13	97.15	72.4
Logan Generating Co	12.76	6.80	53.29	76.5
Sunoco Logistics Marcus Hook	2.67	2.64	99.00	78.5
Liberty Energy	12.92	12.91	99.90	84.8
Wheelabrator Gloucester	4.37	4.28	97.94	95.2
PGW Port Richmond	2.31	0.08	3.46	103.5
Exelon Schuylkill	99.40	98.41	99.00	Schuylkill

The EFDC model contains a module for power plant return flow that uses the intake flow rate, the percentage of evaporation and the difference in concentration between intake and discharge of the respective transport parameter, in this case the difference in salinity ΔS in PSU. Constant intake and discharge flow rates were available research of publicly available facility information, such as DRBC dockets, from which the percentage of evaporation could be calculated. To determine ΔS an iterative approach using the model was used. Initially, a model run without return flows was performed with salinity time series outputs at the return flow locations to provide the ambient salinity. This time series was used to calculate the total salt load [kg] within the intake volume per time increment, which was then redistributed into the lower discharge volume, leading to a higher concentration. In a final step the intake salinity was subtracted from the discharge salinity to determine the difference ΔS that is used as input for the return flow module.

2.5.5 Boundary Conditions Summary

A quantitative summary of model salinity boundary condition inputs for 2014 is shown below as mass loading of chloride and percent chloride loadings in Figure 2-12 and Table 2-14. This summary includes all tributary, DMR, direct runoff, and CSO inputs but excludes the ocean end boundary.

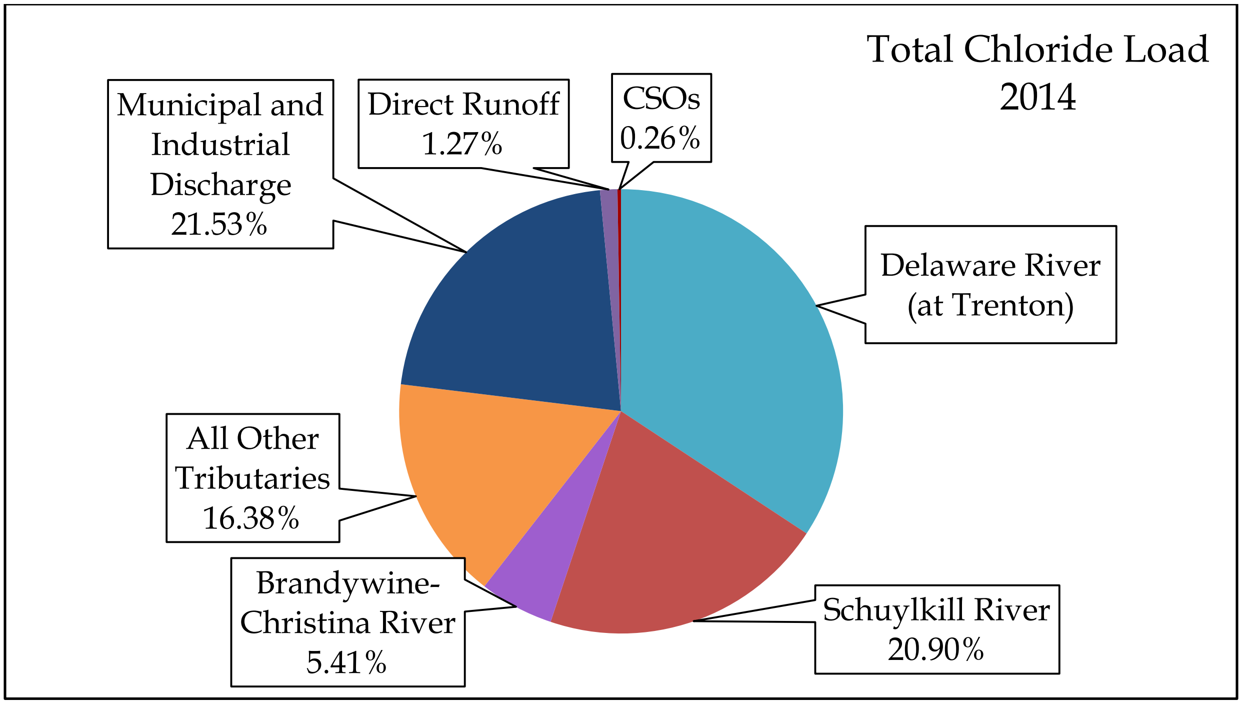


Figure 2-12: Summary of chloride distribution from model discharge inputs as a percent excluding the ocean end open boundary

The largest source of salt by weight in the model, excluding the ocean end open boundary, is the Delaware River. All tributaries to the model domain are responsible for 78.2% of the total salt load. Municipal and industrial discharges are responsible for 21.5% of the salt load in the model domain.

Table 2-13: Summary of chloride distribution from model discharge inputs excluding the ocean end open boundary

Source	Total Chloride Load [kg/year]	Percentage
Delaware River (at Trenton)	5.06 E+08	34.25
Schuylkill River	3.08 E+08	20.90
Brandywine-Christina River	7.99 E+07	5.41
All Other Tributaries	2.42 E+08	16.38
Municipal and Industrial Discharge	3.18 E+08	21.53
Direct Runoff	1.88 E+07	1.27
CSOs	3.81 E+06	0.26
Total	**1.48 E+09**	**100.0**

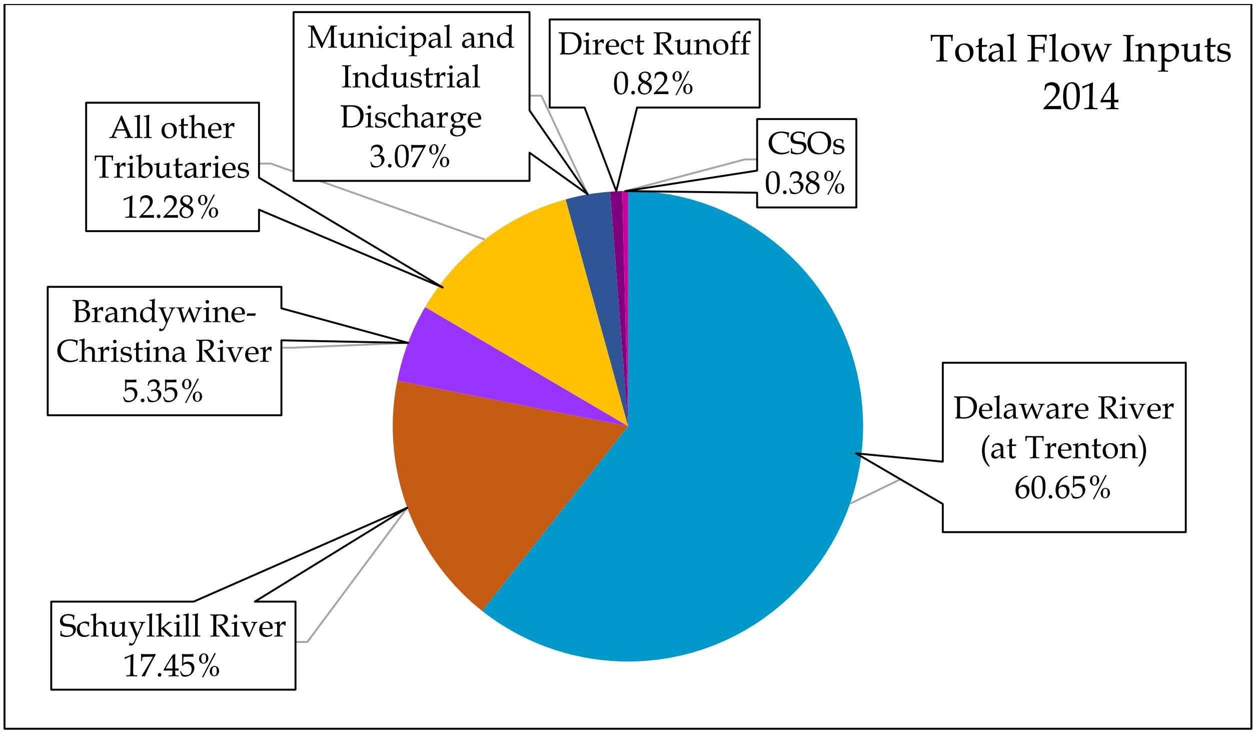


Figure 2-13: Summary of streamflow distribution from model inputs as a percent excluding the ocean end open boundary

The largest source of streamflow to the model domain is the Delaware River with the Schuylkill River the second largest. All tributaries to the model domain are responsible for 95.7% of the streamflow input. While the municipal and industrial discharges contribute a small percentage of streamflow (3%), they contribute 20.9% of the salt.

Table 2-14: Summary of chloride distribution from model discharge inputs excluding the ocean end open boundary

Source	Total 2014 Volume [Cubic Meters]	Percentage
Delaware River (at Trenton)	1.00 E+10	60.65
Schuylkill River	2.88 E+09	17.45
Brandywine-Christina River	8.82 E+08	5.35
All Other Tributaries	2.03 E+09	12.28
Municipal and Industrial Discharge	5.07 E+08	3.07
Direct Runoff	1.36 E+08	0.82
CSOs	6.24 E+07	0.38
Total	**1.65 E+10**	**100.0**

2.6 Initial Conditions

2.6.1 Temperature

The initial temperature is set spatially constant to the temperature measured at NOAA's Philadelphia station at start time of the model run.

2.6.2 Salinity

The initial salinity is determined based on main stem continuous specific conductance data from USGS and PWD stations. The salinity at time of start of the model run at Pea Patch Island (PWD), Buoy C (PWD), Chester (USGS), Buoy B (PWD), Ben Franklin Bridge (USGS), Pennypack at Baxter (USGS), and Trenton (USGS) are taken and salinity in between is linearly interpolated onto the model grid using the respective river mile locations.

2.7 Grid and Bathymetry

The model grid contains 75 miles (120 km) of the Delaware River, 8 miles (13 km) of the Schuylkill River (from the Delaware River confluence to the head of tide at Fairmont Dam), the full tidal extents of Cobbs Creek (5.6 miles or 9 km), Frankford Creek (1.85 miles or 3 km) and Pennypack Creek (1.85mi or 3km), all of which receive CSO discharges. The grid contains 9,746 horizontal elements with edge lengths ranging from 17 m to 650 m, and 5 vertical layers.

The original fine grid used for the model hydrodynamic calibration was based mainly on bathymetry measured by NOAA through 2005. In the meantime, changes such as the 45 ft deepening of parts of the navigational channel and natural erosion/deposition have occurred. A bathymetry update based on US Army corps of engineers (USACE) regular bathymetry surveys of the navigational channel reaches and its adjacent shoals was performed which includes all changes measured up to the year 2014 (Figure 2-14).

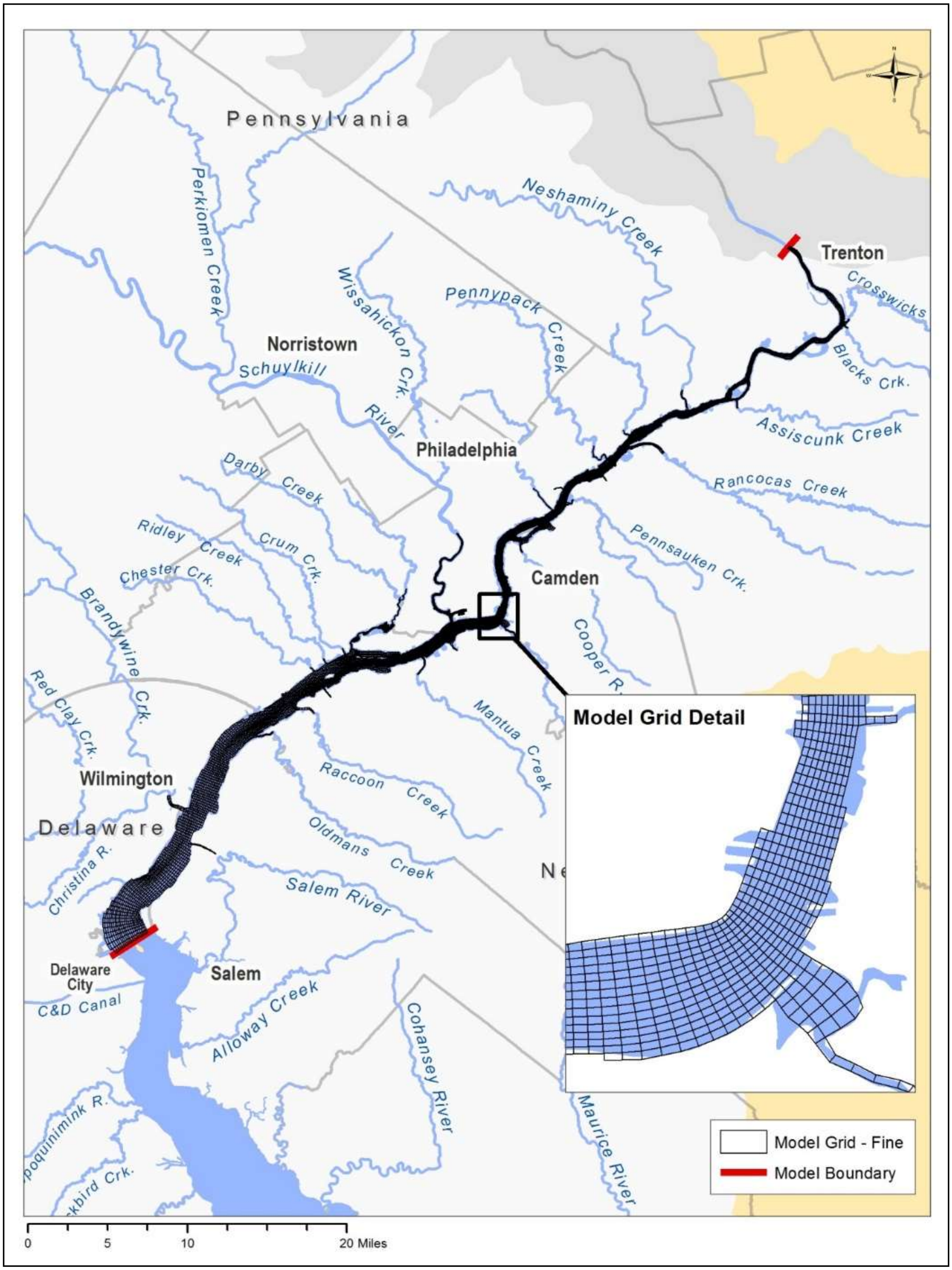


Figure 2-14: Model fine grid

3.0 Sensitivity Studies

To better understand the factors influencing salt transport in the EFDC model, several sensitivity studies are performed. These help to determine if certain processes matter for improvement of salinity in the model domain and to calibrate a final version. The following sections compare model results at Buoy C and Buoy B (see Figure 2-2) for different model scenarios to show the sensitivity of salt transport to adjustment of related model parameters and inputs. This comparison is performed in a validation period defined by the presence of a salt intrusion event during the low streamflow fall period and by the availability of observed salinity data at the open boundary and reference stations. The period selected for both 2014 and 2016 was September 1 through October 26, results for 2014 are shown as an example. The flow at the USGS Delaware River Trenton gage for this period reached a minimum of 2,550 and mean of 3,781 CFS during 2014 and a minimum of 2,150 and mean of 3,098 CFS during 2016. Peak observed surface salinity at Buoy C for this period reaches 3.3 PSU during 2014 and 4.3 PSU during 2016.

Subtidal signals, where the tidal signal was filtered out of continuous observed and modeled time series, demonstrate the model's ability to simulate currents and water level changes that reflect net non-tidal transport. This supports evaluation of whether the model can reproduce stratified currents with opposing direction as seen under strain-induced periodic stratification (SIPS) conditions. Subtidal time series are produced for this analysis by applying a Lanczos filter, a mathematical formula that only allows signals below a certain cutoff frequency to pass (low-pass filter), to modeled and observed velocity and salinity (Emery & Thomson, 2004). For time series with a 6 minute interval, a cut off period of 34 hours is used. The cutoff frequency is calculated as $2*\pi*0.1/34$, where 0.1 is the sampling frequency (6/60), and the half window width is calculated as $2*10*34$, where 10 is the sampling period (10/hour).

The following parameters are identified as having an impact on salinity in the area of interest:

- Bottom roughness
- Turbulent diffusion and turbulence closure settings
- Salt loading at open boundary and tributaries
- Grid resolution

Final choices for parameter settings (for details see following sections):

- Bottom roughness: Starting model roughness lowered by 50% in the channel and raised on the shoals by 200% from the model open boundary near Delaware City (RM 61.25) to just below Petty Island (RM 101.25). The depth threshold for channel/shoal demarcation is 6 m.
- Turbulence closure settings: CTE3=5.0
- Salt loading at open boundary:
    - Observed Surface Salinity at open boundary multiplied by 1.15 to account for increased load due to higher salinity at bottom (not monitored) during salt intrusion events.
    - Mixed vertical distribution: exact stratification unknown, stratification in area of interest established by model not very sensitive to mixed or stratified input at open boundary.

- Salt loading at tributaries: estimated values calibrated for best match with observed data.
- Grid resolution: fine grid selected due to slight model improvement vs. coarse grid in comparison to observed data.

The figures in the following sections show a comparison of results with the final settings to observed data with the respective test parameter turned off or set to a formerly used value/setting.

Bottom roughness, turbulence closure settings, and loading at the southern open boundary had a significant impact on model performance and will be described in more detail. A summary of the remaining parameters will be given, which had a minor impact and were used for fine adjustment.

Bottom roughness and turbulence closure settings have a similar impact on salinity in the area of interest. In order to come close to the salinity peak observed in October at Buoy B, both improved settings need to be in place. Turning off either the newly determined bottom roughness or the correct turbulence setting will have a significant negative impact on transport to the Philadelphia area.

3.1 Bottom Roughness

Bottom sediments of the Delaware River in the model area range from fine sediment and mud at the lower boundary close to the estuarine turbidity maximum (ETM) to coarse sediment and bed rock in the upper model extent. Validation data available to inform roughness coefficients include findings from a 2003 sediment inventory study of the upper Delaware River (Sommerfield & Madsen 2003), local knowledge of the bed composition, and Tetra Tech industry experience.

A hydrodynamic sensitivity study to optimize the model hydrodynamic performance by adjusting bottom friction values was conducted for a previous model. This study did not include salinity in the model and followed the process below. The results confirm that the variability in bottom conditions make a spatially variable roughness distribution necessary.

Due to the uncertainties inherent in bottom roughness treatment in hydrodynamic models, an attempt was made to use as simple a treatment of bottom roughness as possible. A uniform roughness height of 0.004 m was used throughout the model domain with the exception of the Trenton area near the head of tide where a higher roughness was applied, and the downstream area near the model's open boundary where a lower roughness was applied. The shipping channel was also assigned a different roughness than the shallower portions of the River. These areas were assigned a roughness value specific to surveys and local knowledge and were deemed necessary to maintain realistic tidal energy transport within the model domain. The final roughness distribution is shown in Figure 3-1. The figure shows that the model roughness increases with distance upstream. This measure ensures tidal energy dissipation reflective of observations. The figure also shows higher roughness in the shipping channel than in the shallows, which reflects likely sedimentation of fines in the shallows.

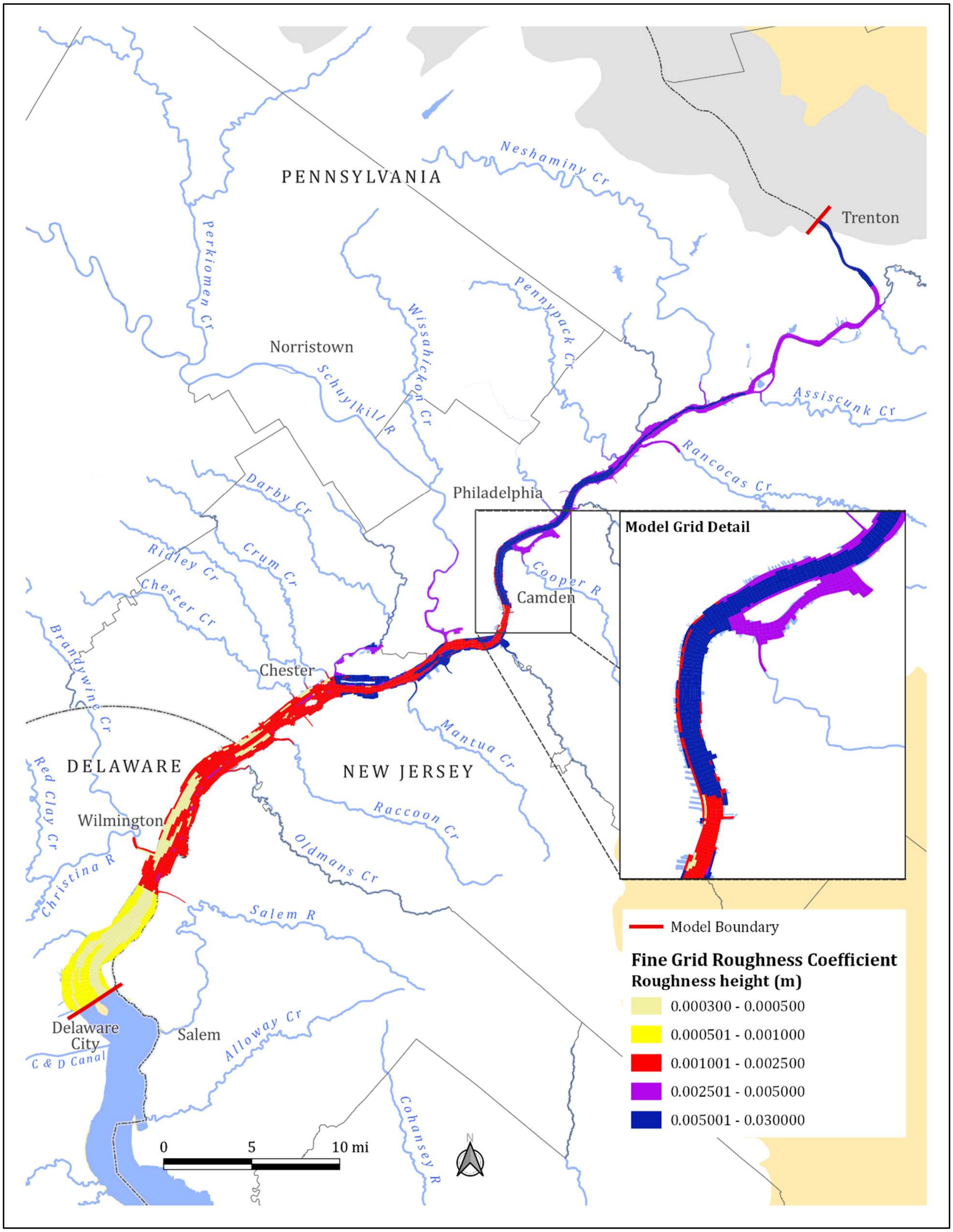


Figure 3-1: Validated roughness distribution

An additional sensitivity study to optimize salt transport by adjusting bottom friction values involved raising or lowering friction in different spatial combinations throughout the model domain. The process was designed to achieve optimal salt transport with the least compromise of hydrodynamic performance. The study found that the best results were achieved by lowering friction values by 50% in the channel and raising friction on the shoals by 200% from the model open boundary near Delaware City (RM 61.25) to just below Petty Island (RM 101.25). The depth threshold for channel/shoal demarcation was 6 m. Figure 3-2 and Figure 3-3 show the improved results for Buoy B and Buoy C, respectively. The maximum bottom to surface salinity difference is 1.08 psu for the adjusted roughness case and 0.30 psu for the original case at Buoy C. This is an important measure for the existence of stratified flow that allows for a temporary upstream transport of salt and the establishment of the salinity peak in October at Buoy B. This roughness distribution was used for the final set up.

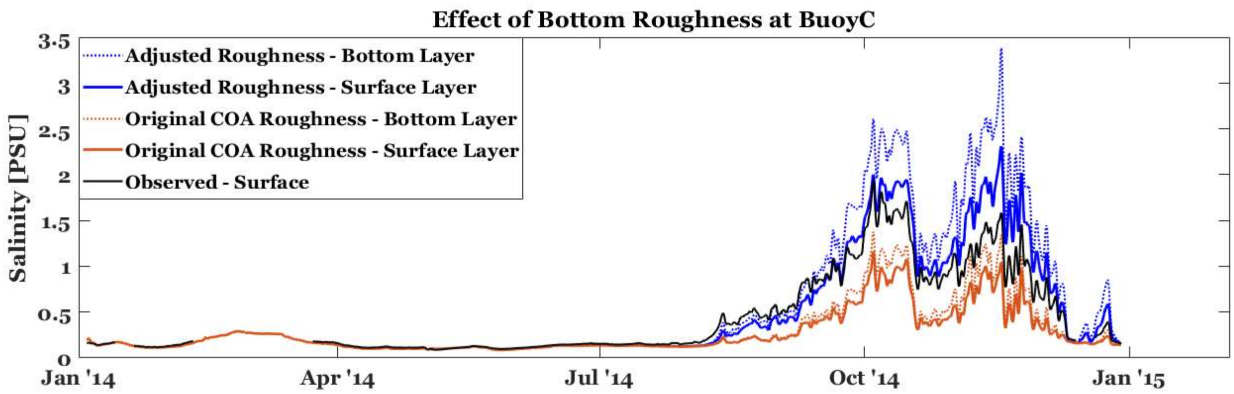


Figure 3-2: Original COA vs. adjusted bottom roughness – Buoy C. Maximum bottom to surface salinity difference is 1.08 psu for adjusted roughness case and 0.30 psu for original case.

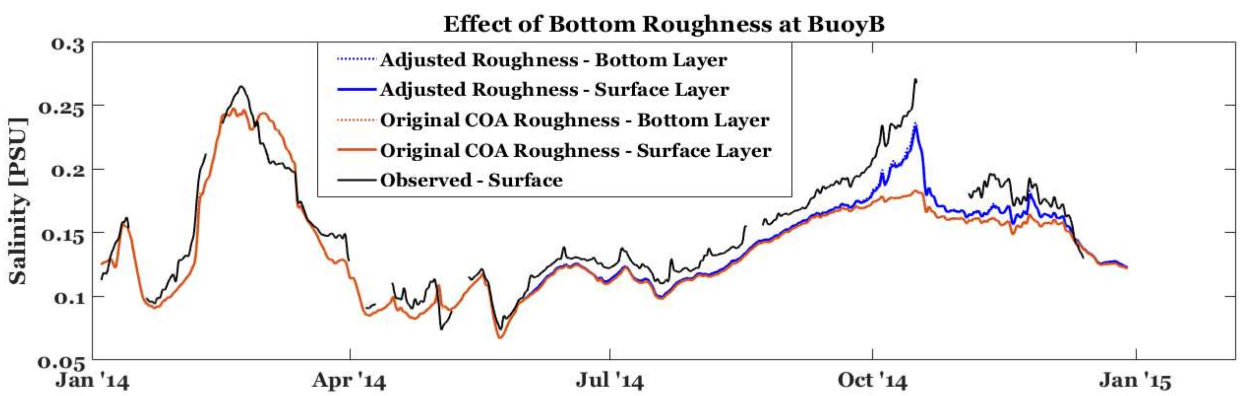


Figure 3-3: Original vs. adjusted bottom roughness – Buoy B

3.2 Turbulent diffusion and turbulence closure settings

In order to understand how the EFDC model handles the transport of salinity in the model through diffusion and turbulent mixing, several scenarios were tested to explore the impact of changes made to the turbulent diffusion and turbulence closure settings that are recommended in the EFDC User Manual. Several test simulations were run changing the values for minimum kinematic eddy viscosity and minimum eddy diffusivity, activating horizontal momentum diffusivity with side wall log law roughness height, and applying a range of values to the maximum turbulent intensity Richardson number for stable conditions as recommended in Ralston (2007). However, none of these settings had a measurable impact on down-gradient salt transport.

Simulations using an alternate setting for the turbulence constant E3 buoyancy term in the Q*Q*L equation of the EFDC turbulence closure scheme, Mellor-Yamada 2.5 (MY2.5), were then explored. This setting conforms to the findings of Burchard (2001) that addresses a limitation in MY2.5 due to equal contributions of shear and buoyancy production in the turbulent length scale equation and names the additional coefficient E3. Found on Card 13 of the efdc.inp file, this setting allows for a separate coefficient for the buoyancy term (E3), in which CTE3 = 5.0, rather than 1.8. While Burchard, 2001 does not propose an exact value for this parameter, it successfully tests a value of "E3 ≈ 5" in three cases in coastal waters. The EFDC manual suggests the optional value by indicating it in the comments for Card 13 with "1.8/5." above the CTE3 parameter, and the metadata identifying CTE3 as the equivalent for E3 with "CTE3: Turbulence constant E3 … buoyancy term in Q*Q*L equation" (Tetra Tech, 2001). This setting markedly improved down gradient salt transport, especially for the area around Buoy B. Figures of comparison runs for Buoy B and C follow (Figure 3-4 and Figure 3-5). The maximum bottom to surface salinity difference is 1.08 psu for the alternate case and 0.39 psu for the default case at Buoy C, which similar to the improved roughness distribution facilitates upstream transport and the peak at Buoy B.

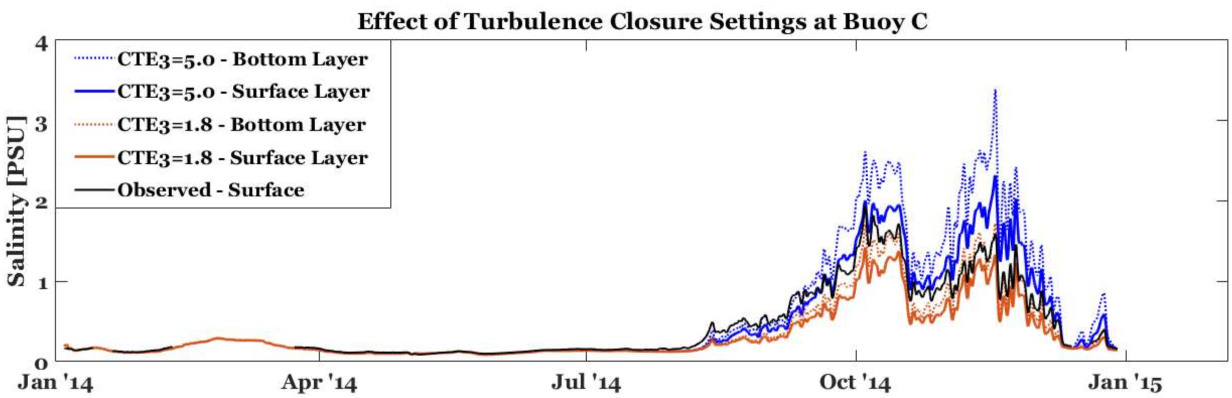


Figure 3-4: Buoy C – default turbulence closure setting vs. alternate setting of CTE3=5.0. Maximum bottom to surface salinity difference is 1.08 psu for alternate case and 0.39 psu for default case at Buoy C.

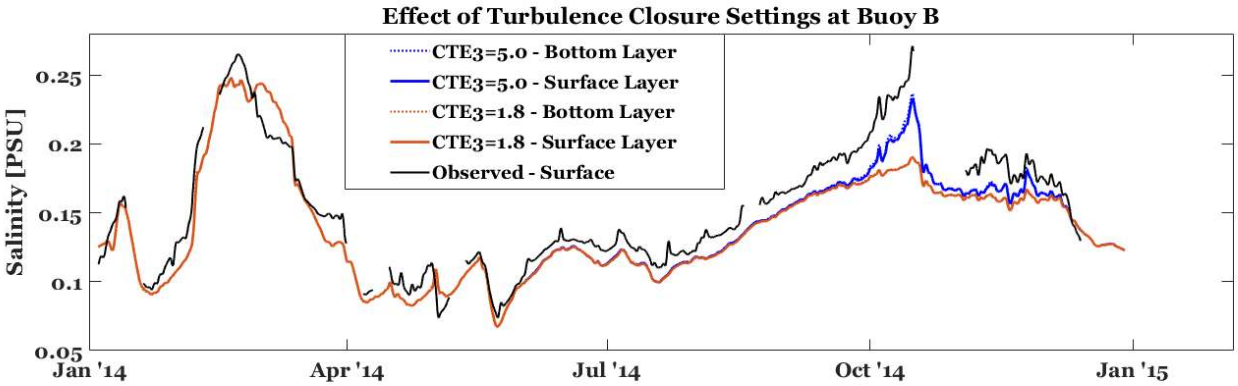


Figure 3-5: Buoy B – default turbulence closure setting vs. alternate setting of CTE3=5.0.

3.3 Open Boundary Loading

As described in Section 2.5.2, PWD placed a specific conductance sensor (Buoy P) close to the open boundary of the model domain to obtain data for realistic boundary conditions. The initial set up only included a sensor close to the surface (year 2014). Subsequent information from a salinity monitoring study a few miles downstream (Aristizábal & Chant, 2014) indicates vertical stratification during salt intrusion events with surface salinity greater than 8-9 PSU is a possibility in this location.

3.3.1 Loading adjustment for stratification

Surface observations at Buoy P (orange) reached up to 9 PSU in 2014 and 10 PSU in 2016 (blue) during salt intrusion events (Figure 3-6).

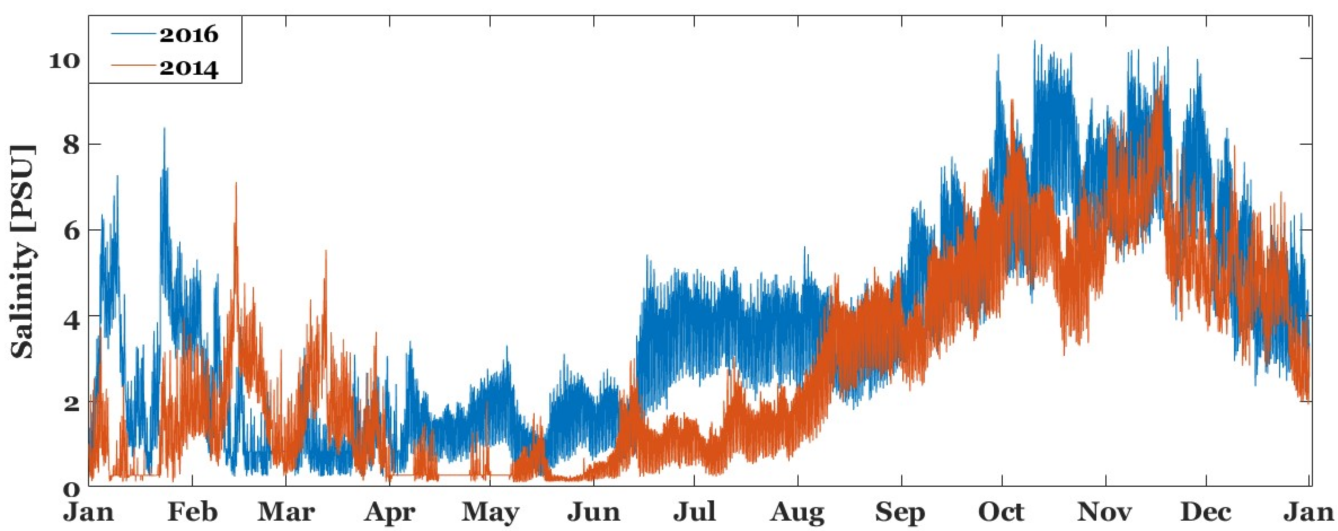


Figure 3-6: Observed salinity 2014 (orange) and 2016 (blue) at Buoy P

An along-channel survey of salinity conducted by Aristizábal & Chant (2014) on June 11th, 2011 showed that when surface salinity reaches 9 PSU distinct stratification can be observed, with a higher salinity on the bottom (Figure 3-7).

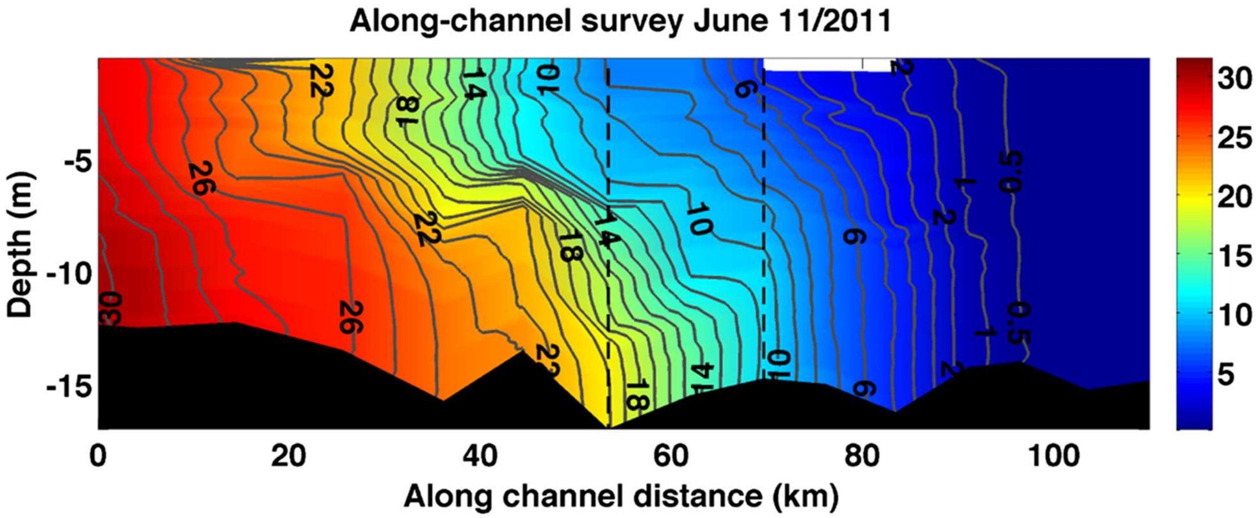


Figure 3-7: Along Channel Salinity Survey 2011 (Aristizábal & Chant, 2014)

Early model runs steered with only the observed surface salinity (x 1.0) in 2014 resulted in an underestimation of salinity during salt intrusion events. Based on the previously cited findings it is assumed that when salinity reaches high enough levels at the open boundary, stratification can be expected, which would overall lead to a higher total salt load as compared to vertically constant conditions at the value of the observed surface salinity. To determine the model sensitivity to salt loading, the surface salinity was multiplied by adjustment factors of up to 1.2.

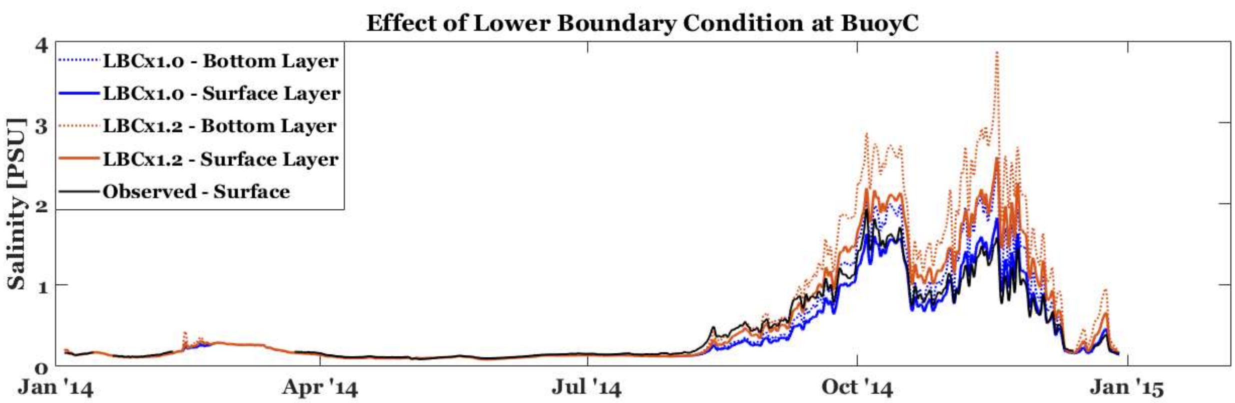


Figure 3-8: Buoy C – Lower Boundary Salinity x 1.0 (LBCx1.0) vs Salinity x 1.2 (LBCx1.2)

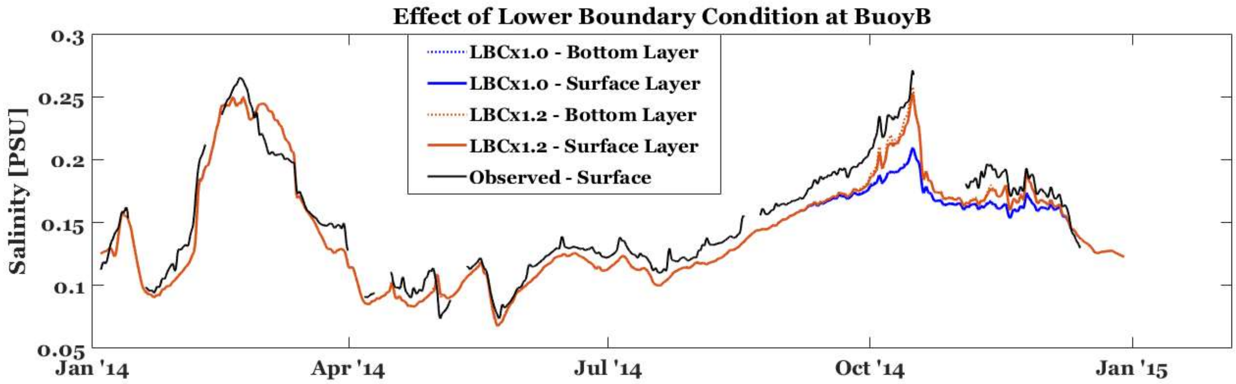


Figure 3-9: Buoy B – Lower Boundary Salinity x 1.0 (LBCx1.0) vs Salinity x 1.2 (LBCx1.2)

Figure 3-8 and Figure 3-9 show the model sensitivity to salt load at the boundary. A 20% increase in load (x1.0 to x1.2) significantly increases the salinity at Buoy C (Figure 3-8). At Buoy B a significant peak during the maximum salinity intrusion period in October only appears with the increase in salt load (Figure 3-9). This peak can be seen in the respective observed salinity at Buoy B. A factor of 1.15 produced good agreement of modeled to observed salinity for both, 2014 and 2016 and was used in the final set up.

3.3.2 Mixed vs stratified input

This sensitivity analysis is performed to determine if it matters for results within the area of interest if the open boundary salinity is provided as a constant value multiplied by the afore mentioned adjustment factor or if an estimate for stratification is needed. For the stratified case the bottom two layers were loaded with observed surface salinity x1.3, the middle layer used a factor of 1.15 and the upper two layers the original salinity, which compares to an average factor of 1.15.

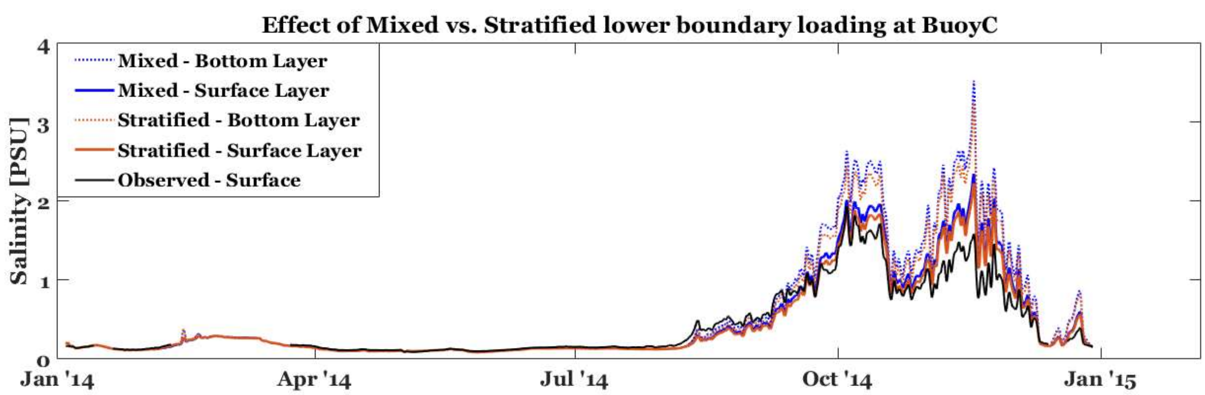


Figure 3-10: Buoy C - mixed vs stratified salinity boundary condition. Maximum bottom to surface salinity difference is 1.18 psu for mixed case and 1.05 psu for stratified case.

The results show that salinity at Buoy C with a mixed condition at the lower boundary (Figure 3-10) is slightly higher. The maximum bottom to surface salinity difference is 1.18 PSU for the mixed case and 1.05 PSU for the stratified case. For Buoy B this means that we get a slightly higher spike during the intrusion event for mixed conditions (Figure 3-11), which is favorable since salinity at Buoy B during intrusion is still underestimated by the model.

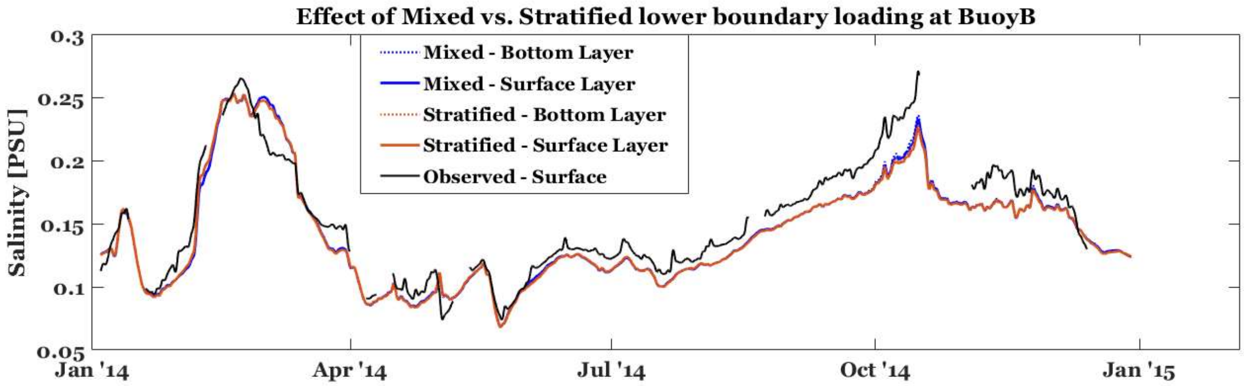


Figure 3-11: Buoy B - mixed vs stratified salinity boundary condition

Estimating stratification based only on a surface measurement also introduces uncertainty. Therefore it was decided to use the mixed boundary condition for the final set up, and let the model adjust itself for stratification within the model domain.

3.4 Grid Adjustment

3.4.1 Fine vs. coarse grid

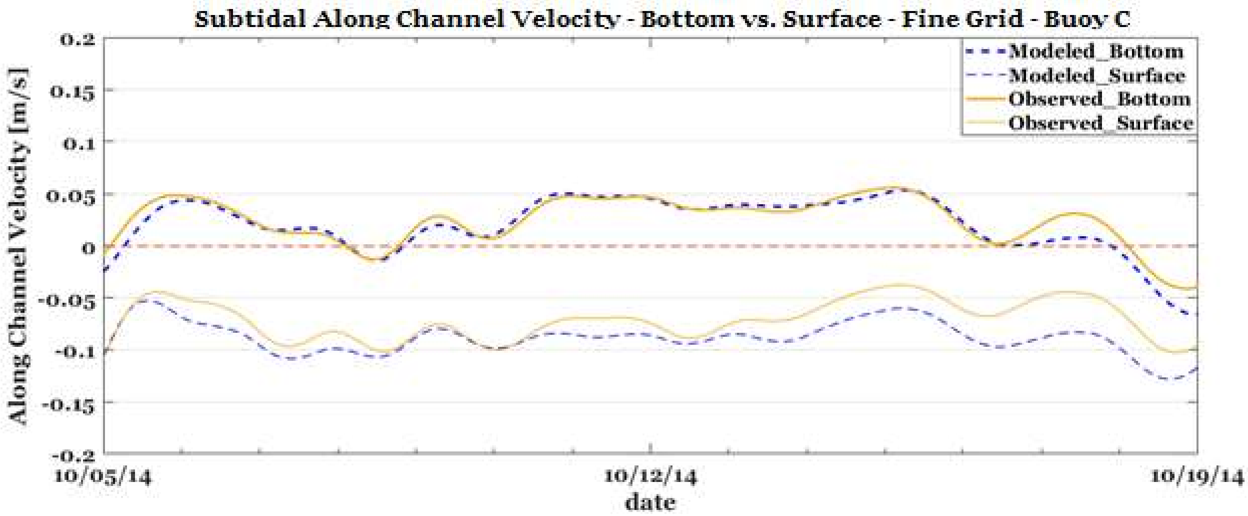
To conserve runtime, initially a coarse version of the PWD model grid was considered for the salinity model. While the modeled salinity at downstream stations Buoy C and Chester compared well to observed data, use of the coarse grid appeared to underestimate salinity at Philadelphia stations Buoy B and upstream during salt intrusion events, which was improved by using the fine grid. Sensitivity tests identified the turbulence closure setting CTE3 as the real cause and not the grid resolution. Adjusting the setting to CTE3=5.0 led to similar results in the fine vs. the coarse grid version, especially in the area of the City of Philadelphia. There are improvements in stratification and two-layer flow in the high salinity area around Buoy C, therefore a slight improvement overall for the fine grid, which will be used for the salinity model.

Details of model grid dimensions can be found in Table 3-1.

Table 3-1: Model grid metrics

Grid Parameter	Fine grid	Coarse grid
Cell count	9,746	2,860
Edge length range	17 – 650 m	33 – 1,142 m
Mean lateral dimension	95 m	178 m
Mean axial dimension	150 m	285 m

A finer grid with better resolved bathymetric features appears to be important for matching observed stratification. Figure 3-12 shows the bottom (bold) and surface (fine) layer, modeled (blue) vs observed (yellow) subtidal along channel velocity for the fine grid (upper) and coarse grid (lower) model runs. Surface and bottom labels refer to mean of top two and bottom two layers of the model respectively. The along channel velocity is used as the most representative component of velocity in this location. For this the component aligned with the channel geometry is determined from the x/y (Easting/Northing) components of the velocity vector using trigonometric equations. The red, dashed line marks zero velocity, with flood velocity being positive and ebb negative. Both model runs show similar agreement to the observed velocity in the surface layer, but the coarse grid model underestimates the upstream directed velocity in the bottom layer, which is in better agreement to observed data for the fine grid model run, which therefore was chosen for the final set up.



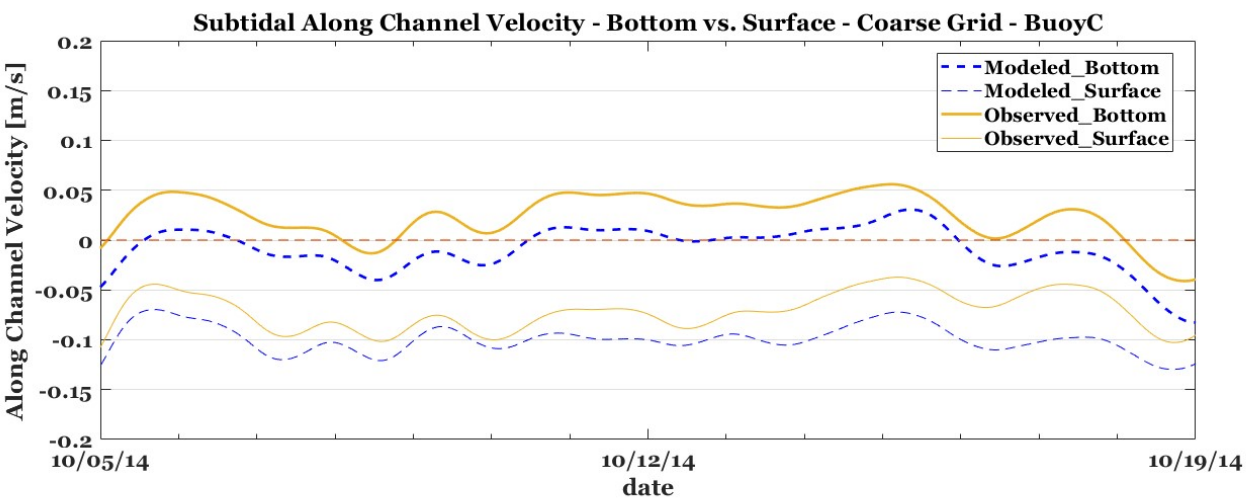


Figure 3-12: Subtidal model results for along channel velocity at Buoy C for Fine Grid (upper) and Coarse Grid (lower) show improved match to observations for fine grid as opposed to coarse grid. Surface and bottom labels refer to mean of top two and bottom two layers respectively.

The effect can also be seen in Figure 3-13 and Figure 3-14, where the fine grid simulation reaches a higher salinity during the salt intrusion period in fall.

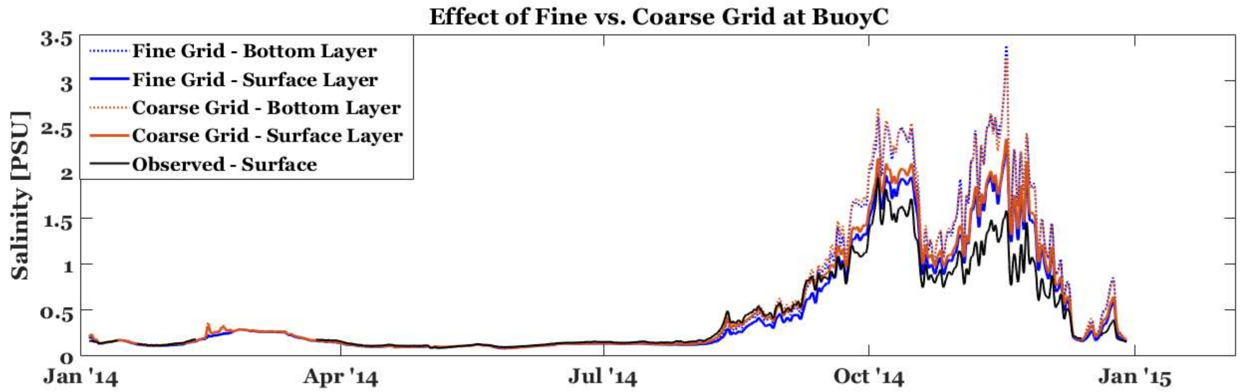


Figure 3-13: Subtidal model results for salinity [PSU] at Buoy B show improved match to observations for fine grid as opposed to the coarse grid

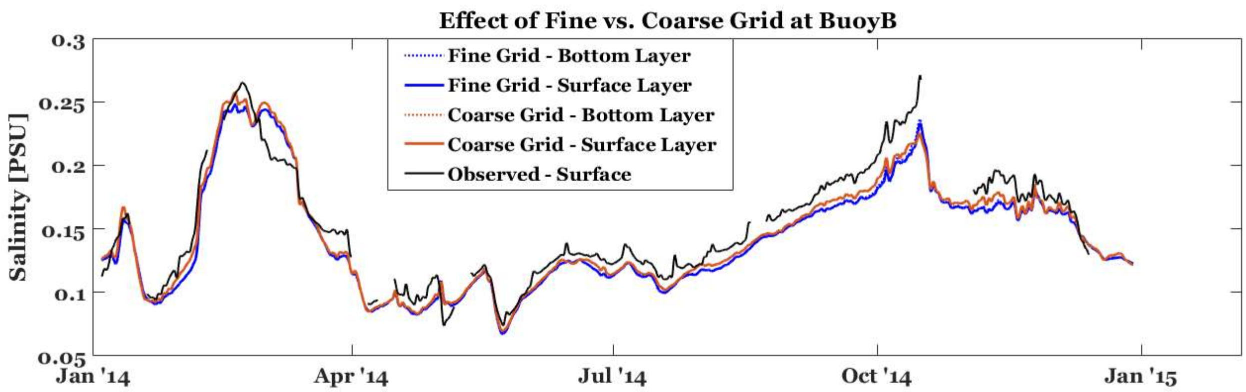


Figure 3-14: Subtidal model results for salinity [PSU] at Ben Franklin Bridge (lower) show improved match to observations for fine grid as opposed to the coarse grid

The coarse grid is still suitable for simulation of dissolved oxygen, which puts a higher demand on run time due to the use of 21 water quality parameters.

3.5 Tributary loading

Of the 43 tributaries included as flow and salinity inputs to the model, 21 are ungaged. In addition, discharge from watershed areas below the USGS stations and areas that discharge directly to the Delaware River between tributaries are also ungaged (Figure 2-2). Flow and salinity loads are estimated for all ungaged areas as described in Section 2.5.1. However, since these tributary loads are estimated based on observations from neighboring gages, this leaves some room for error and justifies adjustments to the tributary loadings during calibration. Further refinements to the flow and salinity load estimates are discussed in this section.

3.5.1 Tributary Flow Estimates

Most tributaries are gaged above the head of tide, often leaving as much as half of the watershed ungaged. A simple area ratio approach is used to account for flow from the ungaged areas. The ungaged areas closer to the Delaware River confluence likely have a lower yield than the upper watershed, and they are not corrected for the presence of surface water, which is especially important for areas with wetlands, likely leading to an overestimate of flow. Due to this uncertainty in the flow estimates for the ungaged tributaries, flow is used as a calibration parameter to match the modeled salinity with salinity observed at Buoy B. Sensitivity analysis of the tidal salinity model suggests that by refining the fresh water inputs to the model by reducing the ungaged tributary flows, the simulated salinity results have a better agreement with observed salinity during low flow intrusion periods. Therefore, salinity during salt intrusion events was validated by adjusting flow estimates and assumptions. These occur during times of very low flow, which are more prone to gage errors, another source of error. An overestimate of tributary flow limits potential salt intrusion, which is a key input necessary for accurately simulating salinity in the vicinity of Philadelphia.

Flows are adjusted to improve agreement between modeled vs. observed salinity during low flow periods when the marine salt signal is still noticeable at Buoy B. Figure 3-15 shows an increase, and therefore improvement, in salinity during the intrusion event from flow reduction at Buoy B. Changes in flow barely changed the salinity at Ben Franklin Bridge, which already was in good agreement with observed data (Figure 3-16).

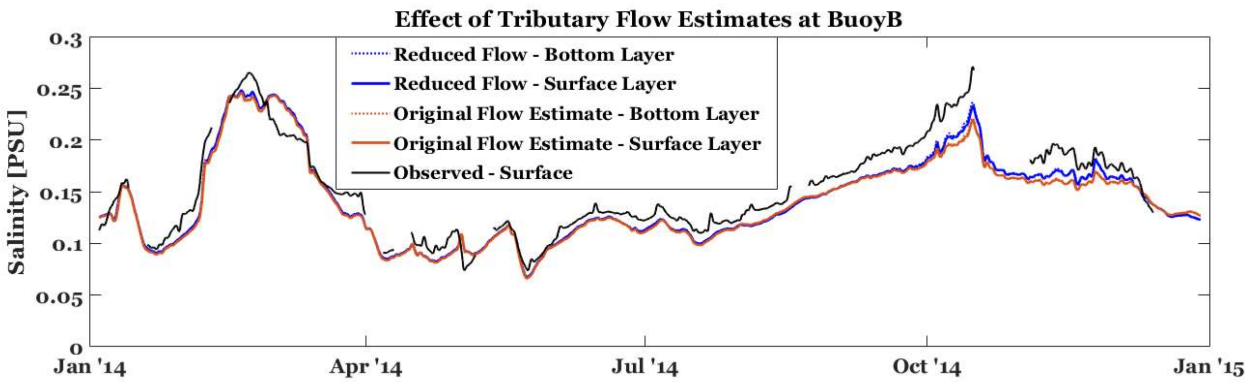


Figure 3-15: Salinity at Buoy B original flow estimate vs. reduced flow

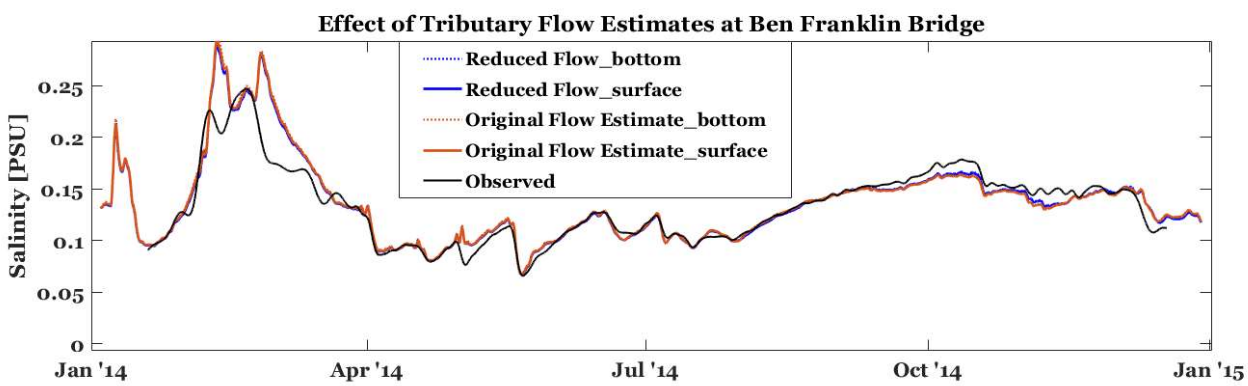


Figure 3-16: Salinity at Ben Franklin Bridge original flow estimate vs. reduced flow

For the 2014 intrusion period (Aug – Nov) it is determined that reducing the tributary flows by approximately 375 CFS generated the best salinity results. This reduction is within 10% of the total tributary flow to the model during the intrusion period, including the upstream flow from Delaware River at Trenton. This is a reasonable adjustment taking into account the uncertainty of USGS gages in recording flow, as well as the uncertainty in extrapolating observed flow to unmonitored (ungaged) watershed areas. The method of adjusting the estimated tributary flow inputs to the model is discussed below.

The following method was developed in which tributary flow inputs were modified to represent the targeted flow reduction. Average daily USGS flows are summarized for 2014 and 2016, and for the critical months in the fall of 2014 and 2016. The monthly averaged daily flows are determined for the ungaged lower tributary areas below the gages based on the watershed area ratio method. In similar fashion, the average monthly flows are summarized for all the ungaged tributaries and the direct runoff areas. These ungaged areas are analyzed to sum their total flow input to the model. A table is created that designates the flow contribution from each tributary or direct runoff area as an estimate or observed. A spreadsheet tool is used to aid in determining what reduction factors to apply to the model inputs for an overall targeted reduction in tributary and direct runoff flow for salinity validation. These flow estimates are used to adjust the water balance to the model for salinity calibration.

Flow reduction factors are generated by the adjustment tool to apply to the model tributary flow boundary conditions in the qser.inp file to account for a reduction in the ungaged flow assumption. In the tool, flow is removed from the ungaged tributaries globally by a percentage. Flow reduction targets and associated percent reduction in ungaged flow are shown in Table 3-2. For example, if a 500 CFS removal of flow is targeted, it is necessary to reduce the ungaged tributary flow by 67% everywhere to meet that target. Likewise, the direct runoff area flows are also reduced by 67% to achieve the desired reduction in tributary flow inputs. Flow reduction factors are calculated by the tool to update the tributary flow inputs to the model in the qser.inp file based on the assumed proportion of gaged and ungaged area to achieve the desired flow reduction for each tributary. In this method only the estimated (ungaged and direct runoff) flows are adjusted and all observed flows at the USGS gages are held constant.

Table 3-2: Flow Reduction Targets

Flow Reduction Target (CFS)	% Reduction in Ungaged Flow
200	25%
250	33%
375	50%
500	67%
550	75%

3.5.2 Final adjustment of generated tributary salt loads

In Section 2.5.1 methods to estimate salinity of ungaged tributaries are described. Long term grab sample data is the main source used to determine a constant, seasonal or wet/dry salinity value for each ungaged tributary. Comparison of a model run steered only with Delaware River at Trenton salinity (for sensitivity purposes) to a run with the initial estimates (Table 2-3) shows that tributaries near Baxter and Buoy B must provide enough low salinity water to dilute the ambient water of the Delaware River in this region.

It turns out that some long-term grab samples show much lower salinity than what can be observed in the main stem. This is likely because they were taken further upstream in more pristine areas before traveling through more developed areas. For example on the Rancocas

Creek, the lowest grab sample value is 0.02/0.09 PSU for the northern and southern branch, respectively (Table 2-4), which, after the branches combine, includes 5 WWTPs along the approach to the confluence with the Delaware River. Thus, Rancocas flow is likely higher in salinity by the time it reaches the Delaware River than what the grab sample data suggests. Given this common pattern, adjustments are made to the salinity of tributaries with significantly lower values than the salinity in the developed areas (~0.2-0.3 PSU) to a constant salinity on the order of main stem salinity (Rancocas, Cooper, Newton, Big Timber and Woodbury Creeks). This adjustment shows significant improvement at Baxter (Figure 3-17).

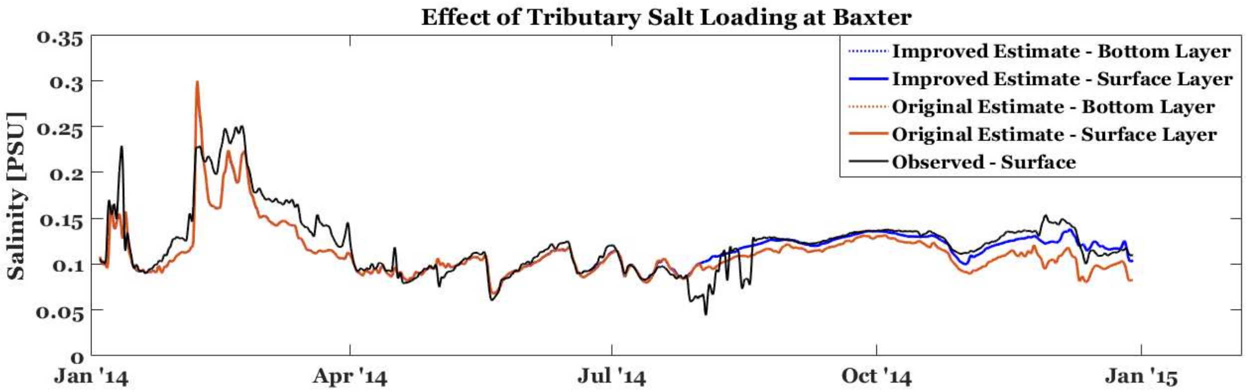


Figure 3-17: Salinity at Baxter – original vs. adjusted tributary salinity estimates vs. observed

3.6 Salt load analysis

In addition to the sensitivity studies above, additional general tests with respect to salt load are performed. An analysis by source in which only tributaries, tributaries and municipal/industrial point sources, and tributaries and CSOs contribute to salt load resulted in the following: during low flow periods, higher salinity areas up to Chester are dominated by the marine salt signal, and are not very sensitive to sources from tributaries, CSOs, and municipal/industrial point sources. Tributaries provide the main salinity signal in the lower salinity area upstream of Ben Franklin Bridge, as has been shown by the tributary salt load sensitivity study 2.5.5. CSO inputs barely matter in terms of salinity, but municipal/industrial point sources contribute. Therefore, further adjustment of point source estimates could be an additional tool for future runs to improve model results, especially for different years.

4.0 Salinity Model Validation

This section presents the salinity model results for the best performing simulation in both 2014 and 2016 model years. Water level, current and salinity results for each best simulation are presented as both visual comparison with plots of model versus observed parameter and as statistical metrics for each parameter against observed data as reference. As explained in Section 3.0, the validation period is generally defined by the presence of a salt intrusion event during the low flow fall period and by the availability of observed salinity data at the open boundary and reference stations. The availability of observed data for each validation parameter requires that different range of dates need to be selected to accommodate any periods which lack observations. The water level and current validation period for 2014 is September 1 – November 31. Due to blasting for channel deepening near Marcus Hook and the end of the deployment of PWD ADCPs at Buoy C and Buoy B, the water level and current validation period for 2016 was April 1 to June 30. For salinity, the range chosen for both years spanned September 1 to October 26, the later date being the end of the Buoy C CTD sonde deployment in 2016.

4.1 Validation configuration - 2014

To represent the range of conditions appropriate for production run conditions, a final group of validation scenarios are tested. Due to the feedback loop between upstream freshwater discharge and lower open boundary salinity, these runs are chosen to bracket the expected range of salinity at the lower open boundary and tributary flow adjustments. The settings that are most important in reproducing the appropriate estuarine exchange flow and salt intrusion include bottom friction, lower open boundary salt adjustment, and ungaged tributary flow adjustment.

From the sensitivity analysis discussed in Section 3, several settings are chosen that create the optimal balance of hydrodynamic and salinity intrusion performance. The basic scenario settings for the years 2014 and 2016 are identical and include 1) fine grid option, 2) vertically mixed lower boundary (LBC) salinity, 3) bottom roughness height adjustment using the 50/200 case, and correcting salt loading to increase salinity in tributaries with unrealistically low concentrations. For both 2014 and 2016, the best combination of settings is represented in the flow reduction of 50% and lower open boundary salt factor of 1.15. These results are discussed in the following subsections.

The EFDC model configuration used for the validation scenario runs follows the standard recommendations that are documented in the Environmental Fluid Dynamics Code User Manual, US EPA Version 1.01. Beside the alternate turbulence closure setting discussed in the previous section, additional exceptions to default values used in the final simulations that were suggested by the model developer follow on Table 4-1.

Table 4-1: EFDC model settings

Description	Card #	Parameter	Value
Anti-numerical diffusion correction	C6	ISADAC	1
Add flux limiting to above	C6	ISFCT	1
Coriolis parameter	C8	CORIOLIS	0.00009336
Background molecular diffusivity	C12	ABO	1E-6
Minimum eddy diffusivity	C12	ABMN	1E-5

4.1.1 River Discharges

As discussed in Section 2.5.1, USGS stream gage data is only available for approximately half of the tributaries included in the model domain. Time series for the ungaged extents of tributaries, fully ungaged tributaries, and direct runoff areas are developed using the watershed area ratio and discharge time series of a gaged adjacent or similar watershed, as described in Table 2-2. Flows are then slightly reduced to improve agreement between observed and modeled salinity in the city area, as described in Section 3.5.

4.1.2 Water Level

The NOAA tide gage at Delaware City, DE, provides observed water levels to drive the southern open boundary. It is reported in 6min intervals and no gaps were detected for the years 2014 and 2016.

4.1.3 Salinity

River salinity is based on observed continuous and grab sample data as described in Section 2.5.1. Final adjustments to estimates of ungaged tributaries are made based on sensitivity studies (Section 3.5). CSO salinity is set to a constant 0.11 PSU (Section 2.5.3). Withdrawals and discharges are set to values detailed in Section 2.5.4. Salinity at the open boundary is based on continuous observations at Buoy P, a PWD monitoring station explicitly deployed to provide data for open boundary conditions. Missing time periods (2014) and gaps (2014 and 2016) are filled using the methods discussed in section 2.5.2. Observations were taken from the surface layer, hence, the salinity was increased by 15% to adjust for load under stratified conditions where higher salinity values are expected at the bottom.

4.1.4 Wind

Philadelphia Airport (NCDC) wind data is for model steering, which has been validated in former model versions.

4.1.5 Grid and bottom roughness

The fine model grid (Section 2.7) was necessary to correctly reproduce the complex hydrodynamics observed in the region of high salinity intrusion (up to RM 80) as observed in the vertical velocity distribution at Buoy C (RM75). The spatially varying bottom roughness used in a previous PWD model was adjusted by increasing roughness on shoals and decreasing it in the shipping channel to improve the transport of marine salt upstream into the system as described in Section 3.3.

4.2 Validation Metrics

This section presents the metrics for the best performing simulations from 2014 and 2016, and summarizes statistics for mean error, root mean square error, and skill factor. These metrics are selected from the NOAA-sponsored guidelines for model benchmarking, the Model Evaluation Environment (MEE) (Patchen, 2007) that was established for the Delaware Estuary. After exercising the salinity model in both 2014 and 2016 during the sensitivity simulations described in Section 3.0, each model iteration was evaluated according to these metrics.

Distributed as part of the MEE, Zhang *et al.* (2006) summarizes the qualitative and quantitative metrics that are used to evaluate model validation. This technical report recommends an acceptable error of 0.15 m/s for water level and 0.26 m/s for velocity, when evaluating performance. The water level and current validation period for 2014 was September 1 – November 31. Due to blasting for channel deepening near Marcus Hook and the end of the deployment of PWD ADCPs at Buoy C and Buoy B, the water level and current validation period for 2016 was April 1 to June 30. For salinity, the range chosen for both years spanned September 1 to October 26, the later date being the end of the Buoy C CTD sonde deployment in 2016.

4.2.1 Mean Error, RMSE and Skill Factor

The results are analyzed with respect to Mean Error (Eq. 4-1), Root Mean Square Error (Eq.4-2 and Skill factor by Willmott (1981) (Eq. 4-3):

Mean Error
$$ME = \frac{1}{N}\sum_{i=1}^{N}\left(y_{i,m} - y_{i,o}\right)$$
Eq. 4-1

Root Mean Square Error
$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} e_i^2}$$
Eq. 4-2

Skill Factor
$$Skill = 1 - \frac{\sum |y_m - y_o|^2}{\sum(|y_m - \bar{y}_o| + |y_o - \bar{y}_o|)^2}$$
Eq. 4-3

with m=modeled and o=observed values.

A perfect model would have Mean Error, RMSE and Skill factor results of zero, zero and one, respectively.

4.2.2 Tidal Analysis Method

T_TIDE, a MATLAB based analysis package (Pawlowicz, et al., 2002), is used to isolate tidal constituents and evaluate modeled tidal amplitude and phase, which is a common practice in oceanographic model evaluation. This is accomplished using classical harmonic analysis, which models a tidal timeseries as the combination of a finite number of frequencies forced by gravitational modulation from the astronomical motions of the earth, moon and sun, using a least-squares fit. A modeled tidal signature is broken into various tidal components, and the amplitude and phase of each tidal constituent is compared with an observed tidal signature.

4.3 Validation Results

4.3.1 Hydrodynamics

4.3.1.1 Water Level

Table 4-2 shows Mean Error, RMSEs and Skill Factors for stations where observed data is available for the validation period. These stations include Marcus Hook, Philadelphia, Burlington, and Newbold. NOAA Marcus Hook station was removed from service during 2016 due to nearby blasting to deepen the navigation channel. The water level RMSE ranges from 0.038 m at the most downstream location to 0.119 m upstream at Newbold, where model resolution decreases. All stations are well below the acceptable error of ±0.15 m, especially Philadelphia and below. Skill factors range from 0.999 to 0.995, with 1.0 being a perfect result.

Table 4-2: Modeled Water Level Mean Error, RMSE and Skill Factor

Station	Mean Error [m]		RMSE [m]		Skill Factor [-]	
	2014	2016	2014	2016	2014	2016
Marcus Hook	-0.020	NA	0.038	NA	0.999	NA
Philadelphia	-0.026	-0.026	0.081	0.069	0.996	0.997
Burlington	-0.042	-0.048	0.113	0.112	0.995	0.995
Newbold	0.001	0.014	0.119	0.112	0.995	0.996

Harmonic analysis was performed on water level model timeseries for the respective validation periods of 2014 and 2016. Tables 4-3 and 4-4 show the amplitude and phase error between the modeled and observed water level constituents M2, S2, N2, K1, M4, O1, and M6. Negative amplitude errors are under predictions of the observed amplitude, and positive errors are over predictions. A negative phase lag shows that the PWD salinity model is leading the observed data, meaning the respective high water occurs earlier than observed. A positive phase error therefore indicates that the PWD salinity model is lagging. Results are shown for stations, Marcus Hook, Philadelphia, Burlington, and Newbold. Most amplitude errors are below 0.08 m, which is still well within accepted error margin of 0.15 m for water level (Zhang, 2006). The majority of phase errors fall below 12 minutes. Larger phase errors of up to 1.05 hr occur for the K1 and O1 phase, which are still relatively small in comparison to their period close to 24 hours and the amplitude of those constituents are small in comparison to M2.

Table 4-3: Water Level Tidal Analysis for 2014. Validation period of 9/1 – 11/30.

Station	Tidal Const	Period [hr]	Amplitude Ref [m]	Amplitude Model [m]	Amplitude Error [m]	Phase Ref [hr]	Phase Model [hr]	Phase Error [hr]
Marcus	M2	12.42	0.747	0.781	0.034	0.09	0.10	0.01
Hook	S2	12.00	0.105	0.106	0.001	0.92	0.96	0.05
	N2	12.66	0.119	0.122	0.004	11.70	11.73	0.03
	K1	23.93	0.093	0.096	0.002	12.56	12.45	-0.11
	M4	6.21	0.078	0.085	0.006	4.58	4.65	0.07
	O1	25.82	0.078	0.082	0.004	12.04	11.96	-0.08
	M6	4.14	0.036	0.039	0.003	0.98	0.83	-0.15
Philadelphia	M2	12.42	0.811	0.902	0.091	1.40	1.24	-0.16
	S2	12.00	0.102	0.117	0.015	2.33	2.28	-0.05
	N2	12.66	0.121	0.132	0.011	0.36	0.23	-0.13
	K1	23.93	0.093	0.104	0.011	13.78	13.35	-0.43
	M4	6.21	0.078	0.078	0.000	5.54	5.61	0.07
	O1	25.82	0.082	0.085	0.004	13.27	12.90	-0.37
	M6	4.14	0.051	0.046	-0.005	1.99	1.89	-0.11
Burlington	M2	12.42	1.004	1.086	0.083	2.42	2.25	-0.17
	S2	12.00	0.133	0.145	0.012	3.53	3.51	-0.02
	N2	12.66	0.142	0.152	0.010	1.48	1.34	-0.14
	K1	23.93	0.105	0.112	0.007	14.77	14.17	-0.60
	M4	6.21	0.098	0.120	0.023	0.84	1.07	0.23
	O1	25.82	0.083	0.088	0.005	14.31	13.77	-0.55
	M6	4.14	0.034	0.037	0.003	3.17	2.80	-0.37
Newbold	M2	12.42	1.087	1.165	0.078	2.56	2.40	-0.16
	S2	12.00	0.140	0.159	0.019	3.65	3.68	0.04
	N2	12.66	0.154	0.163	0.009	1.64	1.51	-0.13
	K1	23.93	0.103	0.115	0.012	14.60	14.28	-0.32
	M4	6.21	0.124	0.163	0.038	0.99	1.22	0.22
	O1	25.82	0.087	0.090	0.002	14.32	13.90	-0.43
	M6	4.14	0.073	0.051	-0.022	3.587	3.172	-0.42

Table 4-4: Water Level Tidal Analysis for 2016. Validation period of 4/1 – 6/30.

Station	Tidal Const	Period [hr]	Amplitude Ref [m]	Amplitude Model [m]	Amplitude Error [m]	Phase Ref [hr]	Phase Model [hr]	Phase Error [hr]
Marcus	M2	12.42	0.776	0.785	0.009	0.04	0.08	0.04
Hook	S2	12.00	0.099	0.089	-0.010	1.03	0.93	-0.10
	N2	12.66	0.132	0.143	0.012	12.36	11.82	-0.54
	K1	23.93	0.098	0.114	0.016	12.17	11.11	-1.06
	M4	6.21	0.089	0.090	0.001	4.56	4.60	0.04
	O1	25.82	0.080	0.068	-0.012	12.66	13.25	0.59
	M6	4.14	0.037	0.040	0.003	0.94	0.76	-0.18
Philadelphia	M2	12.42	0.828	0.903	0.075	1.25	1.22	-0.03
	S2	12.00	0.084	0.098	0.014	2.16	2.18	0.02
	N2	12.66	0.145	0.162	0.017	0.32	0.32	0.00
	K1	23.93	0.115	0.119	0.004	12.30	12.05	-0.25
	M4	6.21	0.083	0.081	-0.002	5.42	5.59	0.17
	O1	25.82	0.064	0.069	0.005	14.47	14.09	-0.38
	M6	4.14	0.052	0.047	-0.005	1.83	1.85	0.01
Burlington	M2	12.42	1.008	1.082	0.074	2.38	2.22	-0.16
	S2	12.00	0.103	0.117	0.013	3.48	3.32	-0.16
	N2	12.66	0.171	0.189	0.018	1.53	1.36	-0.16
	K1	23.93	0.115	0.123	0.008	13.27	12.91	-0.36
	M4	6.21	0.109	0.132	0.023	0.81	1.02	0.20
	O1	25.82	0.063	0.068	0.005	15.41	14.78	-0.63
	M6	4.14	0.033	0.034	0.001	3.11	2.76	-0.35
Newbold	M2	12.42	1.097	1.157	0.060	2.53	2.37	-0.17
	S2	12.00	0.112	0.126	0.014	3.63	3.50	-0.14
	N2	12.66	0.187	0.201	0.015	1.67	1.54	-0.14
	K1	23.93	0.120	0.124	0.004	13.49	13.06	-0.43
	M4	6.21	0.138	0.177	0.039	0.98	1.16	0.17
	O1	25.82	0.066	0.068	0.003	15.68	14.91	-0.77
	M6	4.14	0.070	0.047	-0.023	3.563	3.195	-0.37

4.3.1.2 Velocity

To generate composite time series comprised of the ADCP 0.5 m vertical bins that can be compared to each vertical cell layer output of the model, a dynamic average of each bin within a vertical model layer per time step is calculated. MATLAB code was developed to average the fixed bin (0.5 m) current meter observations that fall within each varying vertical layer of the model as water level changes over time. Mean Error, RMSE and Skill Factor in Table 4-5 are based on velocity major mean depth average. The Buoy C CTD sonde was removed from service October 26, 2016, therefore the salinity validation period is on September 1 to October 26.

Table 4-5 shows Mean Error, RMSEs and Skill Factors for stations where observed data is available for the validation period. These stations include Buoys B and C. RMSEs range from 0.082 m/s to 0.132 m/s, well within the acceptable error of ±0.26 m/s. All skill factors are close to 1, ranging from 0.976 to 0.994.

Table 4-5: Modeled Velocity Mean Error, RMSE and Skill Factor

Station	Mean Error [m/s]		RMSE [m/s]		Skill Factor [-]	
	2014	2016	2014	2016	2014	2016
Buoy C	-0.015	-0.016	0.094	0.066	0.988	0.996
Buoy B	-0.001	0.056	0.082	0.132	0.989	0.985

Tables 4-6 and 4-7 show amplitude and phase error at Philadelphia, and Buoys B and C. The largest amplitude error is present at Buoy B. This error is well below the threshold of ±0.26 m/s discussed in Zhang *et al.* (2006). As demonstrated in the along-channel comparison, there is also significant variation in observed amplitudes and phases of velocity tidal signatures. Phase errors of 1.87 hours occur for the K1 constituent, but this will have minimal impact on mean velocity error since their amplitudes are small compared to M2.

Table 4-6: Current Tidal Analysis for 2014. Validation period of 9/1 – 11/30.

Station	Tidal Const	Period [hr]	Amplitude Ref [m/s]	Amplitude Model [m/s]	Amplitude Error [m/s]	Phase Ref [hr]	Phase Model [hr]	Phase Error [hr]
Buoy C	M2	12.42	0.809	0.823	0.014	10.89	10.67	-0.22
	S2	12.00	0.107	0.109	0.003	11.49	11.34	-0.15
	N2	12.66	0.122	0.117	-0.005	10.05	9.86	-0.19
	K1	23.93	0.055	0.050	-0.004	7.77	7.22	-0.56
	M4	6.21	0.069	0.083	0.015	4.17	4.00	-0.17
	O1	25.82	0.047	0.039	-0.007	6.95	6.34	-0.61
	M6	4.14	0.066	0.058	-0.008	0.82	0.73	-0.09
Buoy B	M2	12.42	0.574	0.615	0.040	11.11	11.08	-0.03
	S2	12.00	0.080	0.081	0.001	12.02	11.92	-0.10
	N2	12.66	0.100	0.084	-0.015	10.23	10.30	0.07
	K1	23.93	0.034	0.034	0.000	14.23	12.36	-1.87
	M4	6.21	0.056	0.070	0.014	4.69	4.46	-0.23
	O1	25.82	0.029	0.026	-0.003	6.02	6.34	0.33
	M6	4.14	0.049	0.066	0.017	1.29	1.66	0.37

Table 4-7: Current Tidal Analysis for 2016. Validation period of 4/1 – 6/30.

Station	Tidal Const	Period [hr]	Amplitude Ref [m/s]	Amplitude Model [m/s]	Amplitude Error [m/s]	Phase Ref [hr]	Phase Model [hr]	Phase Error [hr]
Buoy C	M2	12.42	0.841	0.837	-0.004	10.81	10.67	-0.14
	S2	12.00	0.090	0.091	0.001	11.44	11.31	-0.13
	N2	12.66	0.143	0.145	0.002	10.06	9.92	-0.14
	K1	23.93	0.057	0.059	0.002	6.46	6.09	-0.37
	M4	6.21	0.090	0.082	-0.008	3.99	4.03	0.04
	O1	25.82	0.035	0.030	-0.005	7.98	7.50	-0.48
	M6	4.14	0.067	0.062	-0.005	0.72	0.71	-0.01
Buoy B	M2	12.42	0.660	0.610	-0.050	11.03	11.05	0.01
	S2	12.00	0.076	0.067	-0.009	11.86	11.79	-0.07
	N2	12.66	0.169	0.105	-0.064	10.68	10.35	-0.33
	K1	23.93	0.049	0.038	-0.011	10.77	11.21	0.45
	M4	6.21	0.055	0.077	0.022	4.82	5.08	0.26
	O1	25.82	0.034	0.023	-0.011	14.04	12.94	-1.10
	M6	4.14	0.042	0.063	0.021	1.81	1.59	-0.22

4.3.1.3 Subtidal current

A low-pass Lanczos filter is applied to model velocity in each vertical layer, then bottom and top layer subtidal currents are compared to corresponding observations.

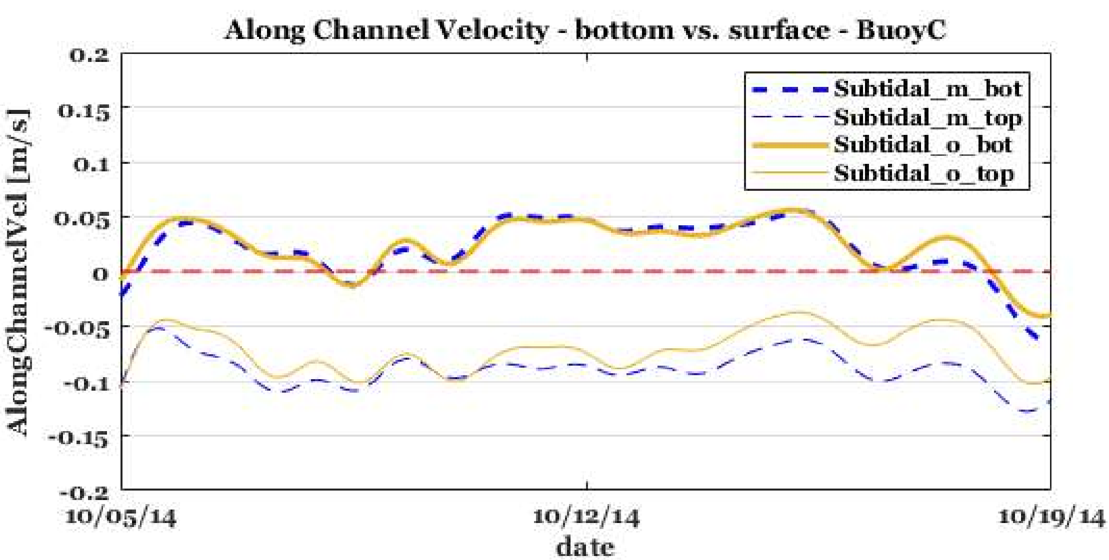


Figure 4-1: Low-passed current comparison for bottom and surface layers, 2014.

Figure 4-1 above is showing model vs. observations for Buoy C October 5-19, 2014. The qualitative comparison shows a close match with observed top and bottom subtidal currents demonstrating the model reproduces the estuarine exchange flow during this low flow event.

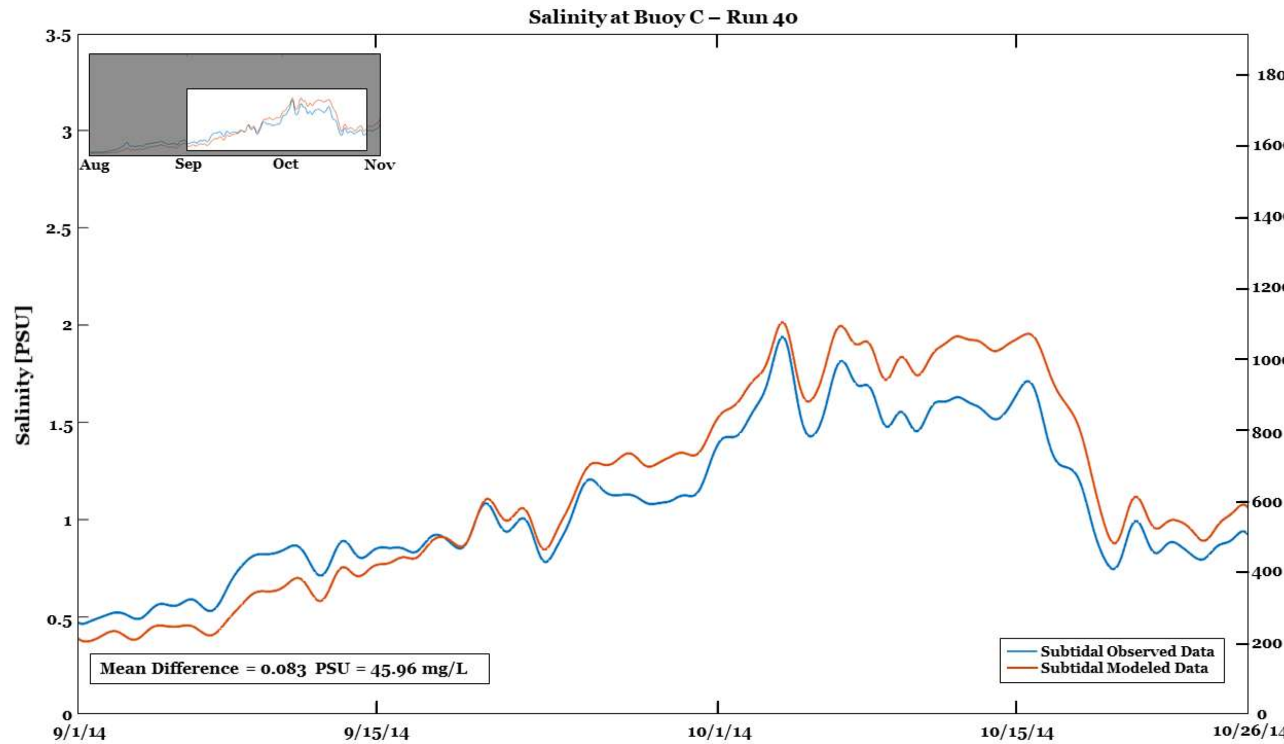
4.3.2 Salinity

Mean Difference of salinity is calculated for the period of September 1st to October 25th, for which observed data is available in 2014 and 2016. Mean salinity error is based on the intrusion event period of September 1st to October 26th, for which observed data is available in 2014 and 2016. (See Table 4-8).

Table 4-8: Salinity validation metrics in PSU and mg/L chloride

Station	Mean Error [PSU]		Mean Error [mgL]		RMSE [PSU]		RMSE [mg/L]	
	2014	2016	2014	2016	2014	2016	2014	2016
Buoy C	0.083	-0.034	45.96	-19.22	0.268	0.302	148.9	167.7
Chester	-0.0002	-0.066	-0.09	-36.59	0.143	0.170	79.7	94.5
Buoy B	-0.023	-0.049	-12.8	-27.11	0.025	0.053	14.0	29.6
Ben Franklin	-0.007	-0.014	-3.78	-7.57	0.009	0.017	5.3	9.6
Baxter	-0.002	-0.005	-1.32	-2.74	0.003	0.006	1.9	3.6

Figures 4-2 through 4-6 show modeled versus observed subtidal salinity for Buoy C, Chester, Buoy B, Ben Franklin Bridge and Baxter. The subtidal series, calculated in a similar manner as currents, are displayed to optimally compare mean salt transport. Qualitative inspection of the figures shows good match to observations. The model performs well in reproducing the low flow intrusion event from September through October. Figure 4-4 also shows the maximum daily observed salinity at Buoy B and the modeled maximum daily salinity for the entire transect at Buoy B, which demonstrates that the model captures the presence of salt longitudinally.



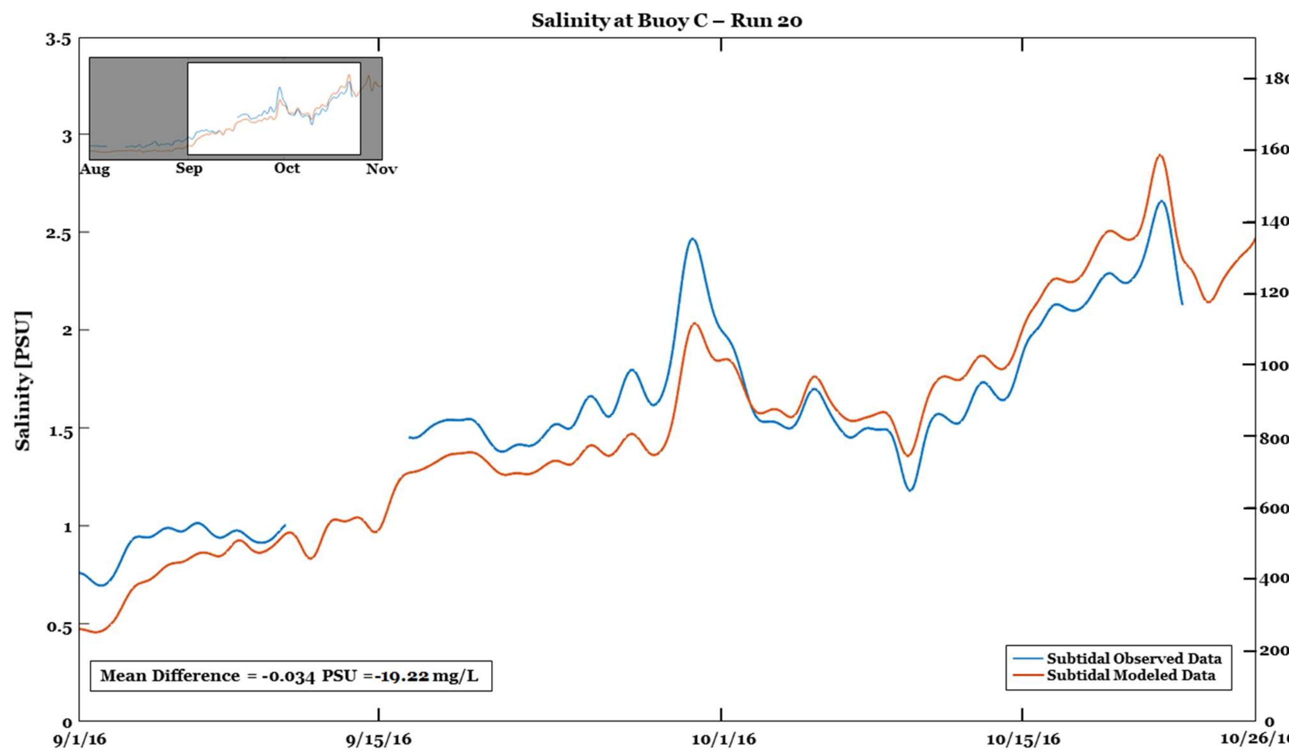
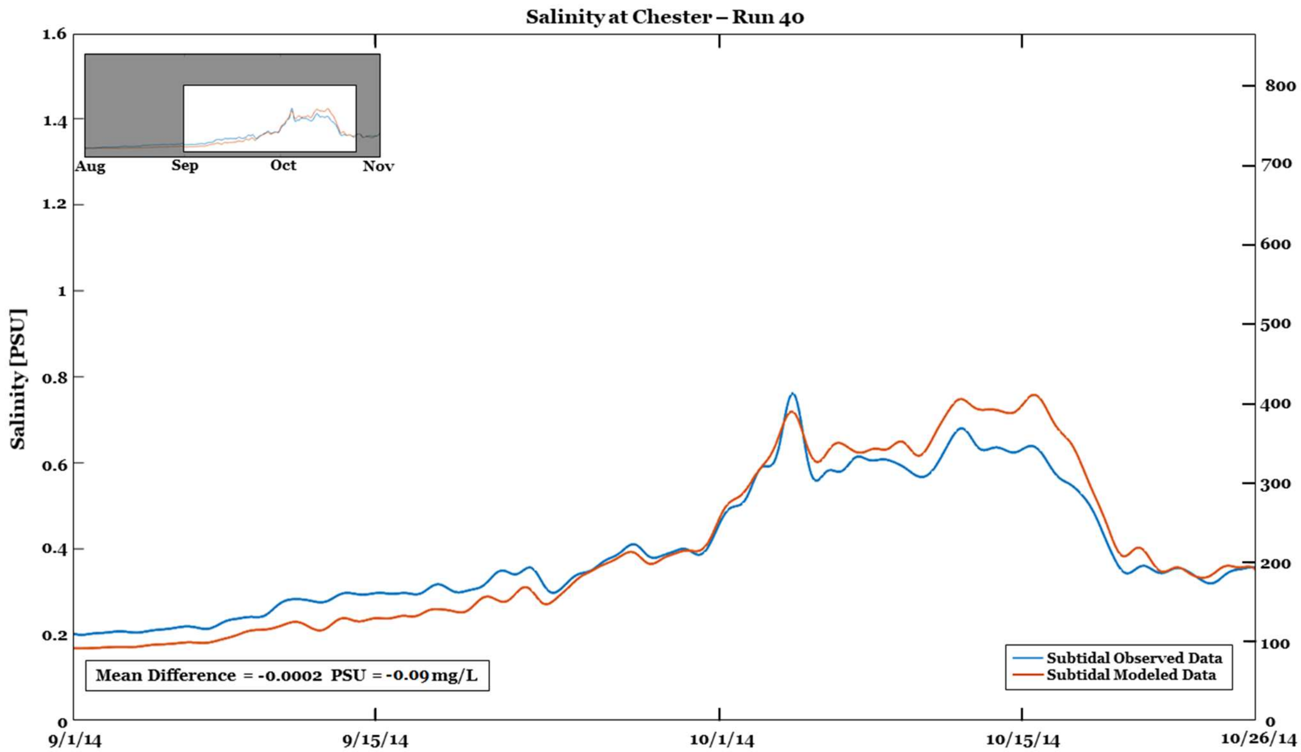


Figure 4-2: 2014 (upper) and 2016 (lower) low-passed salinity at Buoy C, validation period 9/1 – 10/26.



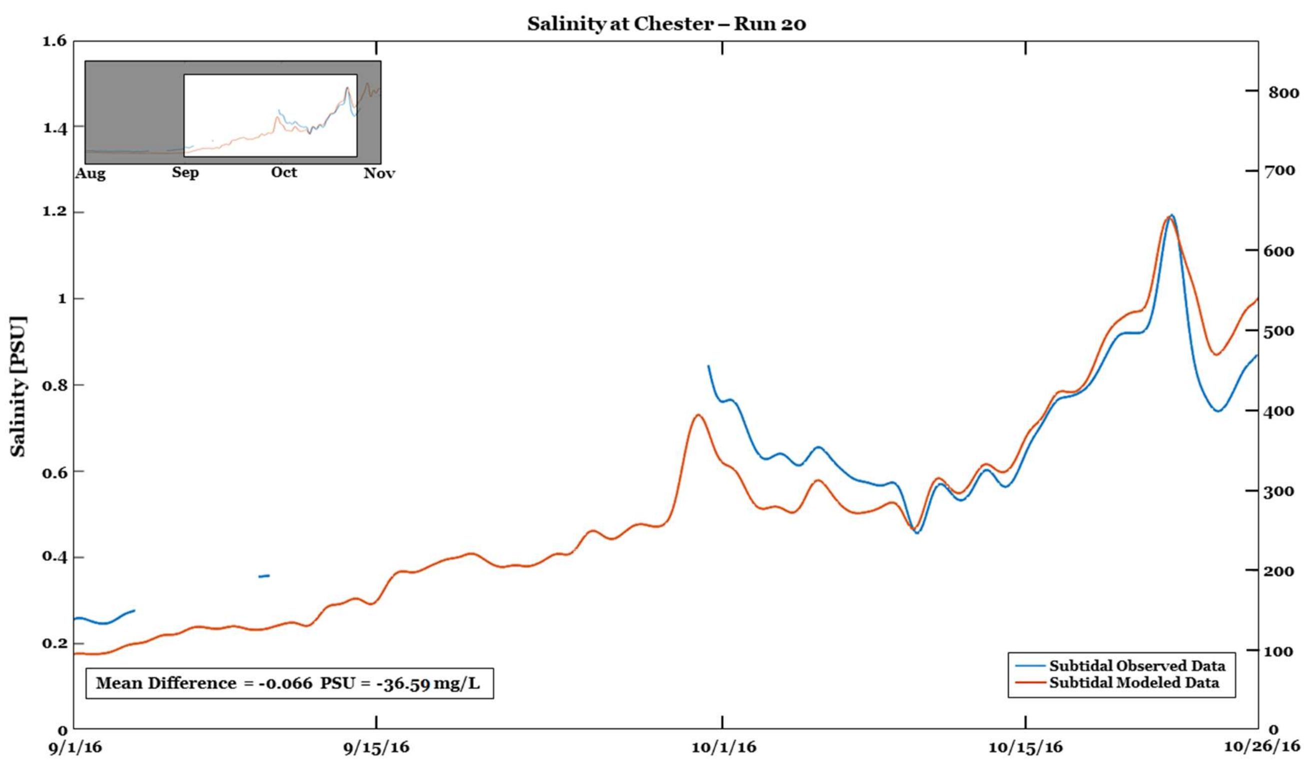
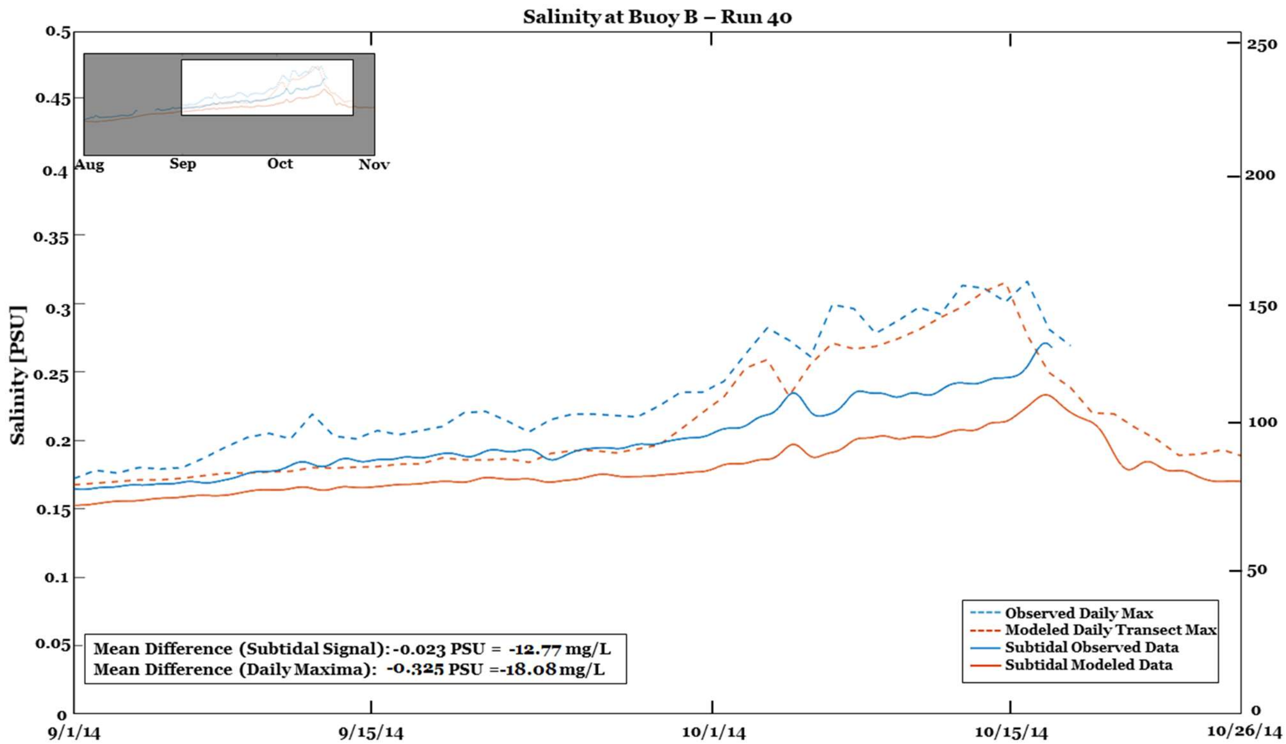


Figure 4-3: 2014 (upper) and 2016 (lower) low-passed salinity at Chester, validation period 9/1– 10/26.



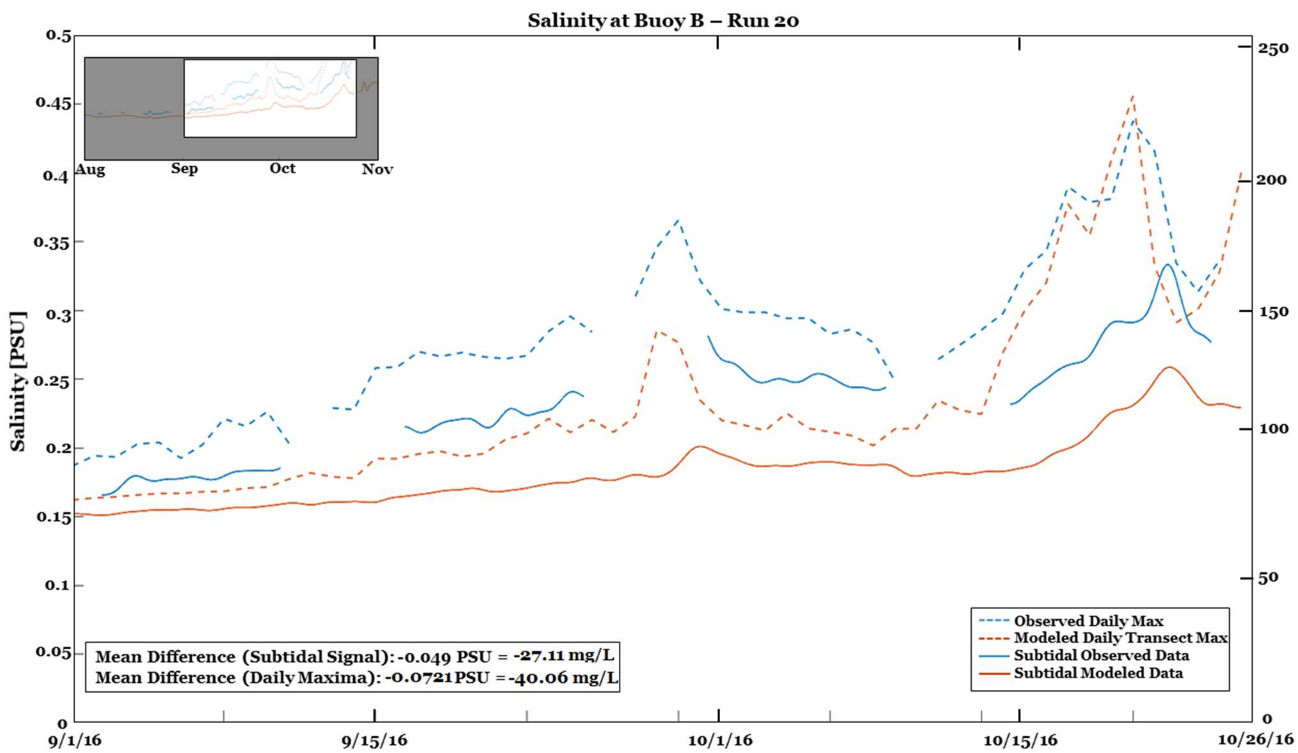
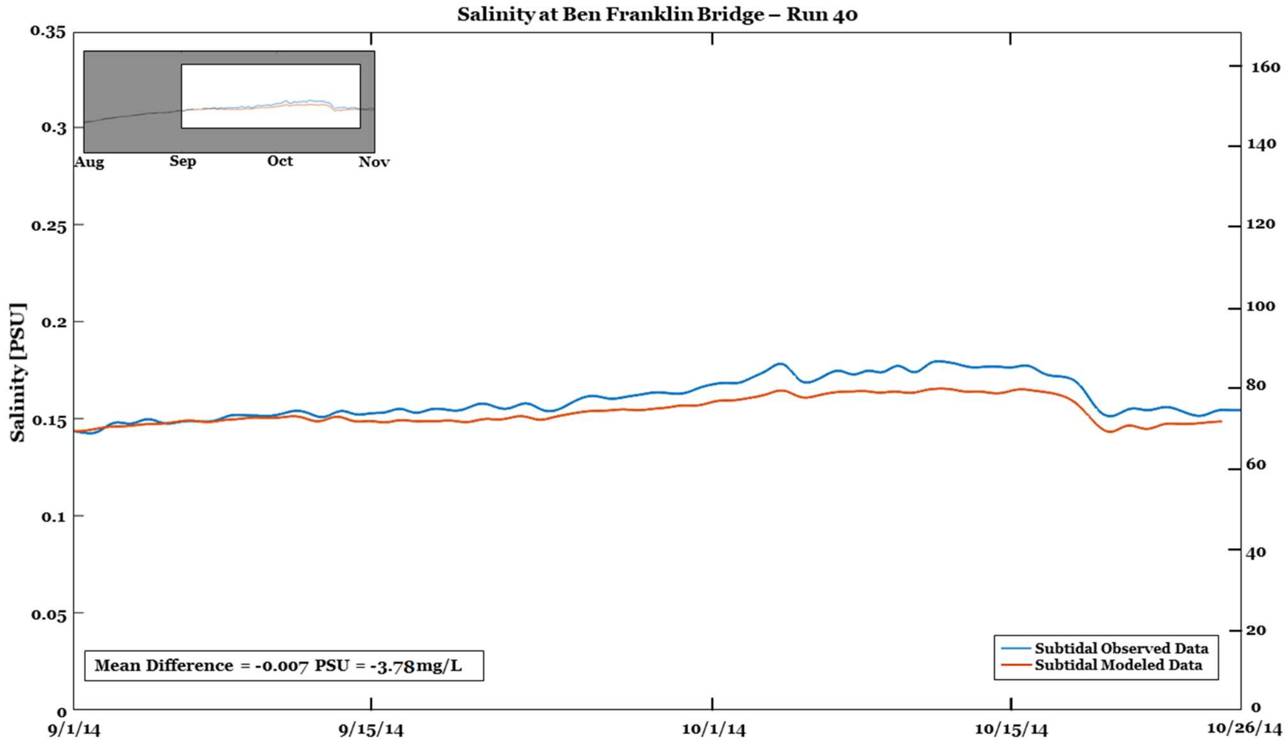


Figure 4-4: 2014 (upper) and 2016 (lower) low-passed salinity at Buoy B, validation period 9/1 – 10/26. Maxima for modeled and observed salinity show that model captures presence of salt longitudinally.



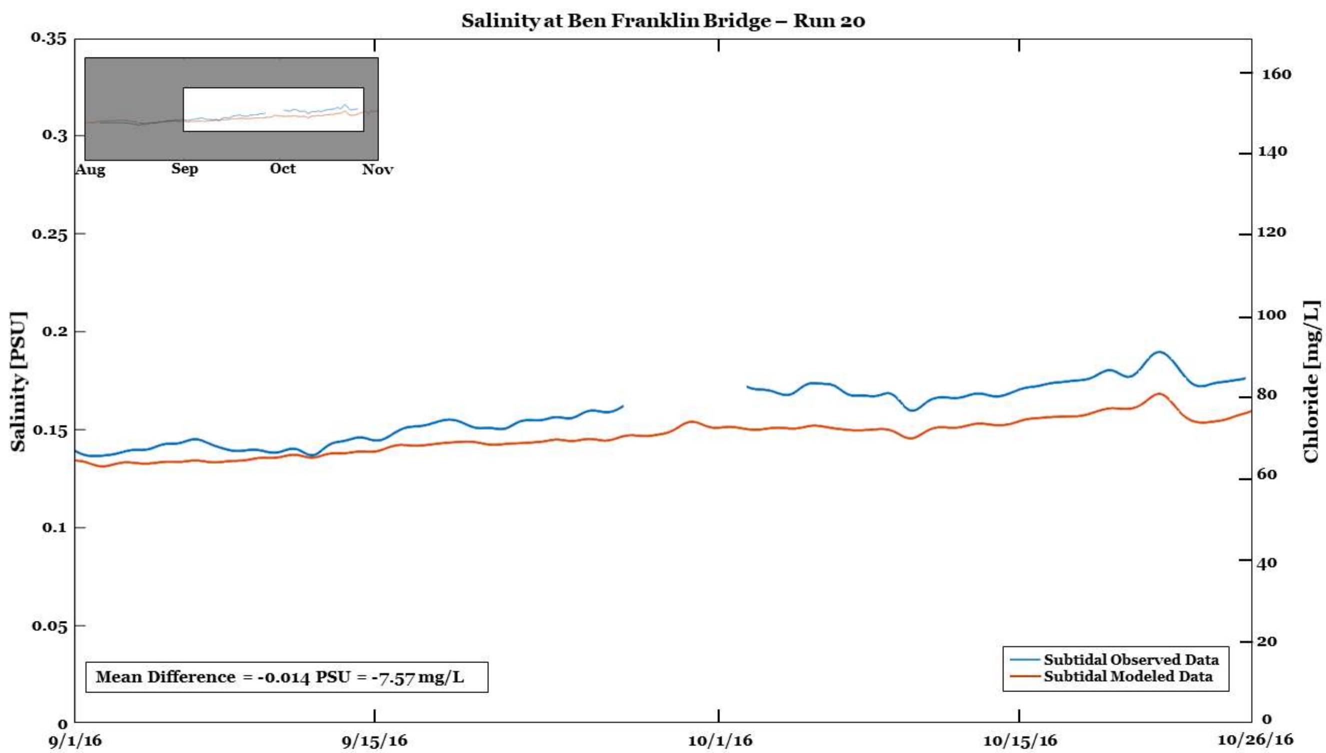
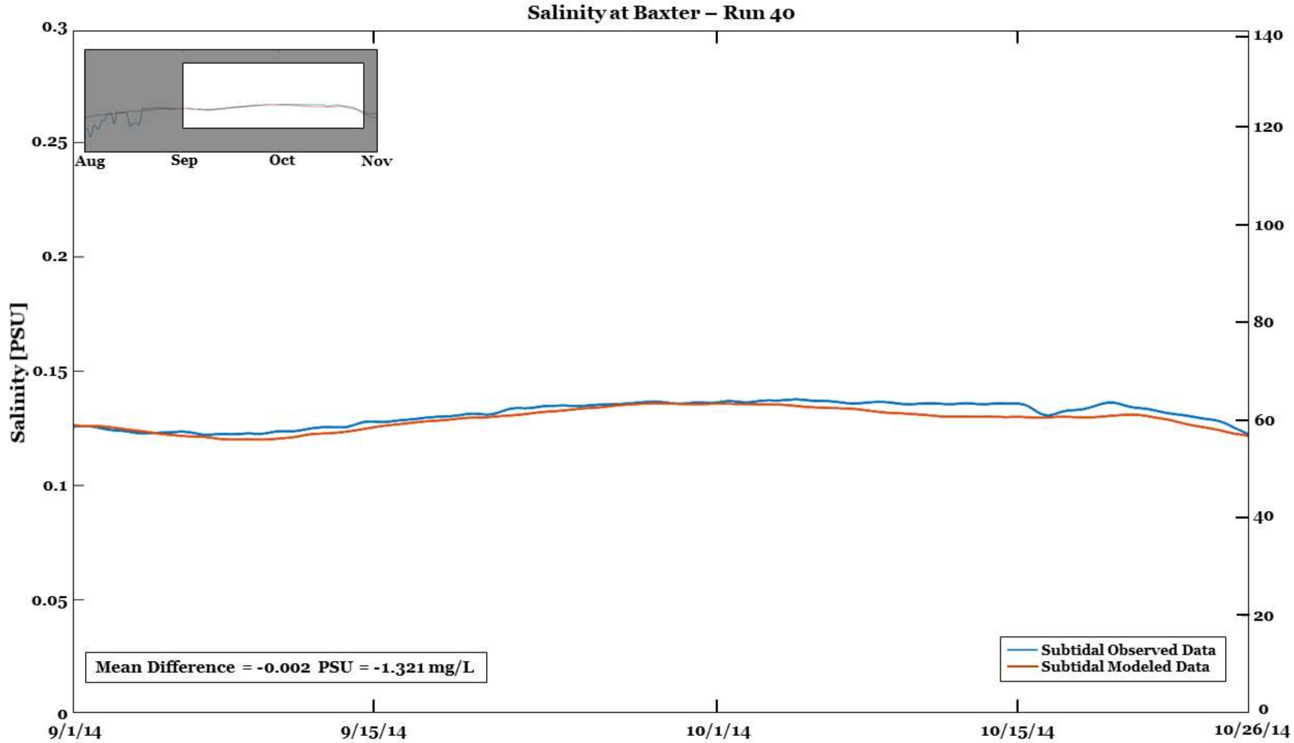


Figure 4-5: 2014 (upper) and 2016 (lower) low-passed salinity at Ben Franklin Bridge, validation period 9/1 – 10/26.



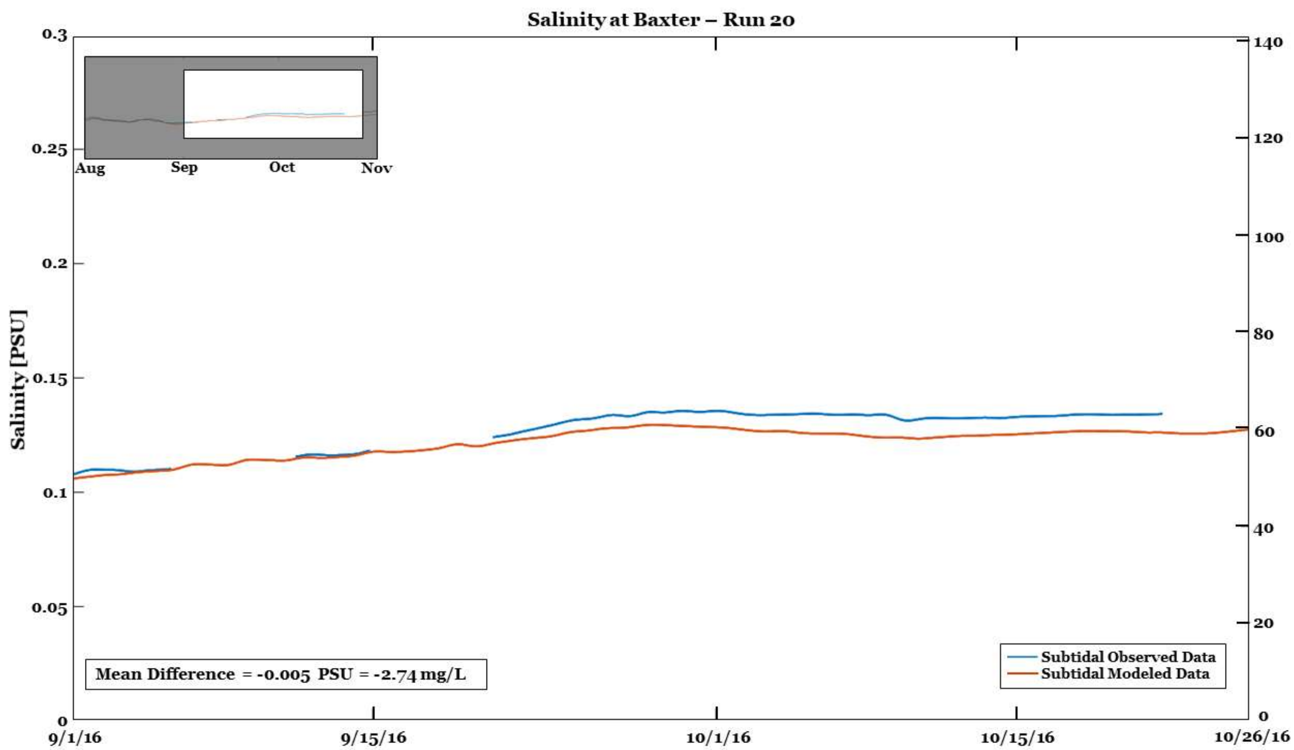


Figure 4-6: Low-passed salinity at Baxter, validation period 9/1 – 10/26.

5.0 Conclusions and Summary

To represent the range of conditions appropriate for production run conditions, the final validation configuration was tested and detailed in the prior discussion. Sensitivity analyses were performed on a range of model configurations and inputs that resulted in a combination yielding the optimal salinity results for 2014 and 2016.

Those features that had positive improvement in matching timeseries observations throughout the domain are detailed in Section 3. Using a fine model grid with higher spatial resolution vs. a coarse grid resulted in a close match to observed vertical velocity profile including two-layer exchange flow and a better match to salinity observations. Comparative runs were also performed by spatially varying bottom friction heights inferred from the Sommerfield & Madsen (2003) bottom morphology study. A combination of doubling roughness height on the shoals (depth < 6 meters) and decreasing by half those in the channel improved the hydrodynamic velocity performance and best matched salinity observations.

A range of enhancement factors for the salinity forcing at the lower boundary were tried to best represent a realistic salt flux at the lower boundary. Observations of surface value salinity at Pea Patch Island were available for the model years, but a factor ranging from 1.1 to 1.2 was applied to this data assuming that values at the bottom of the water column were higher than the surface during salt intrusion events. It was found that a factor of 1.15 was best for both years. As well, comparative runs tested whether a stratified lower boundary salinity forcing was superior to vertically mixed and found that the vertically mixed case performed best.

Tributary flows were enhanced by an area weighted factor (total tributary watershed area to gaged watershed area) to make up for potentially underestimating actual tributary flows but did not account for sub-watersheds that do not contribute additional flow. The sensitivity of overall salinity transport to these estimated flows was tested by lowering the total additional flow by a range of values between 25% to 75%. The reduction that improved matching of salinity observations was 50%. Tributary salt loadings that were generated from grab samples where there were no continuous conductivity observations were biased by monitoring in the more pristine upper end of these streams. Increasing these loadings to a constant salinity concentration close to that of the main stem Delaware River improved the match of salinity to observations in the upper domain of the model.

Sensitivity of the modeled salinity transport to adjustments in turbulent diffusion settings was found to be low by lowering/raising constant settings. These included minimum kinematic eddy viscosity and minimum eddy diffusivity, activating horizontal momentum diffusivity with side wall log law roughness height, and applying a range of values to the maximum turbulent intensity Richardson number for stable conditions, but none of these had a measurable impact on up-river salt transport. Using the alternate setting (CTE3 = 5.0) for the turbulence constant E3 buoyancy term in the Q*Q*L equation of the EFDC turbulence closure scheme suggested in the EFDC User Manual markedly improved down gradient salt transport.

For both 2014 and 2016, the best combination of settings is represented in the flow reduction of 50% and lower open boundary salt factor of 1.15 including additional adjustments summarized above. Pending field results to characterize the lower open boundary, an increased salt factor may be justified to improve 2016 results that are underestimating.

6.0 References

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