DYNHYD5 HYDRODYNAMIC MODEL (VERSION 2.0) AND CHLORIDE WATER QUALITY MODEL FOR THE DELAWARE ESTUARY

Delaware River Basin Commission
DELAWARE • NEW JERSEY
PENNSYLVANIA • NEW YORK
UNITED STATES OF AMERICA

DELAWARE RIVER BASIN COMMISSION
WEST TRENTON, NEW JERSEY

December 2003

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Overall technical guidance and comments were provided by the PCB Model Expert Panel established by the Commission. The current and former members of the PCB Model Expert Panel during the model development process are (in alphabetical order):
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The efforts of the following persons and organizations are gratefully acknowledged (in alphabetical order):

Steve Bearer, intern of the Commission provided editorial effort.
Gail R. Blum of the Commission compiled and provided water temperature and specific conductance data.
Gregory J. Cavallo and John R. Yagecic of the Commission compiled and provided flow data.
Richard W. Greene of DNREC provided chloride data for the C &D Canal.
Dr. Shih-Long Liao of the Commission provided technical support.
Patricia McSparran of the Commission retrieved and compiled the PCS flow data.
Karen Reavy of the Commission provided all the GIS works in this document.
Edward D. Santoro of the Commission provided chloride monitoring data.
Robert D. Schopp of USGS provided tidal heights data of Burlington, NJ station.
Dr. Christopher K. Sommerfield of University of Delaware provided current velocity data.
Dr. David Velinsky of the Academy of Natural Sciences provided chloride data in Schuylkill River.
Dr. Kuo-Chuin Wong of University of Delaware and Dr. William C. Boicourt of the University of Maryland shared their knowledge on C & D Canal hydrodynamics through personal communications.

EXECUTIVE SUMMARY

A new hydrodynamic model was needed as a part of the development of Stage 1 TMDLs for polychlorinated biphenyls (PCBs) for the Delaware River Estuary. The downstream boundary of the existing DYNHYD5 hydrodynamic model (Version 1.0) was updated to establish a hydrodynamic and mass transport link to the ocean boundary. High resolution of Zone 6 would require a more comprehensive data collection effort and result in unacceptable increases in simulation time. Alternatively, introducing nine junctions to represent Zone 6 allowed for improved simulations, resulting from this linkage to the ocean boundary, while minimizing impacts to simulation time and model stability. Furthermore, since PCBs TMDLs to be derived using this hydrodynamic model applies only to Zones 2 through 5, a more coarse representation in Zone 6 was acceptable. The newer version of the hydrodynamic model (Version 2.0) extends the downstream boundary to the mouth of the Delaware Bay (Zone 6), and consists of 105 junctions and 111 channels.

The concept of a rolling calibration was used. In rolling calibration, as more data becomes available, the simulation period of the model is sequentially extended, and the model is re-calibrated to the expanded data set for each extension. The final calibration covers the period from September 1, 2001 to March 31, 2003, which is19 months or 577 days.

The tidal datum for the C&D Canal, Chesapeake City, MD, was modified to correctly simulate the magnitude and the amount of net flow through the C&D Canal. Version 2.0 DYNHYD5 hydrodynamic model was calibrated against tidal heights to ensure that the model correctly simulated the advective water mass movements within the Estuary. The simulated tidal heights were compared with the hourly observed tidal heights at six locations along the Estuary. Linear regression yielded slopes ranging from 0.945 to 1.027, and intercepts ranging from -0.087 to 0.035 with R-squared values of 0.930 to 0.994, respectively. The cumulative frequency distribution comparisons showed good agreement between the simulated and the observed tidal heights throughout the ranges of the tidal heights. Lastly, temporal comparisons confirmed that the model reasonably simulated both the amplitudes and the phases of the tidal heights throughout the calibration period. The predicted current velocities were also compared with the limited observed data to further confirm the Model. Based upon these results, the DYNHYD5 hydrodynamic model for the Delaware River Estuary (Version 2.0) correctly generates the advective movement of the water mass throughout the Delaware Estuary for the entire calibration period.

A TOXI5 (water quality) model consisting of 87 water column segments was then linked with the outputs from the calibrated DYNHYD5 hydrodynamic model and calibrated against the chloride concentrations. The main objective in this calibration process was the determination of an advection factor and a set of dispersion coefficients for the water quality model to correctly simulate the dispersive mixing within the Estuary. Review of comparison plots and the results of regression analyses indicated that the model was able to reproduce the temporal and spatial trends, and the magnitude of the chloride concentrations, within a reasonable range throughout the tidal portion of the Delaware River. It was therefore concluded that the calibrated model properly simulates the advective and dispersive movement of the chloride for the entire Estuary.

Even though Version 2.0 of the DYNHYD5 hydrodynamic model for the Delaware River Estuary could be further enhanced with additional data collection and refinements, the calibrated model demonstrates the capability to accurately simulate the advective and dispersive movement of a conservative substance in the Delaware River Estuary over a wide range of hydrologic conditions.

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1. INTRODUCTION

1.1 Background

A new hydrodynamic model was needed as a part of the development of Stage 1 TMDLs for the polychlorinated biphenyls (PCBs) for the Delaware River Estuary. Even though the development of the TMDLs for PCBs only covers Zones from 2 to 5 of the tidal portion of the Delaware River, the need to set the downstream boundary at the mouth of the Delaware Bay was inevitable (Figure 1-1). The purpose of inclusion of the Bay area or the setting the downstream boundary at the mouth of the bay is to generate realistic boundary conditions between Zones 5 and 6. Delaware River Basin Commission (DRBC) currently maintains two hydrodynamic models. One is DYNHYD5 (DRBC, 1995) and the other is ECOM (HydroQual, Inc., 1998). The downstream boundary for both of the models were set at the head of the Delaware Bay (Liston Point, DE at River Mile 49). The biggest difference between two models are the model dimensions. The DYNHYD5 model is basically a one dimensional model with available branching to simulate around the islands, and the ECOM is a z-level, three-dimensional model. The DYNHYD5 hydrodynamic model was linked with the water quality model (TOXI5) to develop the Total Maximum Daily Loads (TMDLs) for the volatile organic compounds in 1998 (DRBC, 1998a; 1998b). The DYNHYD5 model was chosen to be updated and used as a hydrodynamic model for the Stage 1 TMDLs for PCBs because of the limited data availability and the well known characteristics of the relatively well mixed Delaware Estuary system (Wong and Garvine, 1984).

The existing DYNHYD5 model was renamed for Version 1.0 and the newly developed DYNHYD5 is named Version 2.0 of the DYNHYD5 hydrodynamic model for the Delaware River Estuary.

Figure 1-1: Water Quality Zones of the Delaware River Estuary.

The segmentation of the existing DYNHYD5 hydrodynamic model has been extended to include the Delaware Bay (Zone 6) in this version of the DYNHYD5 hydrodynamic model (Version 2.0). In addition to the extension to the mouth of the Bay, one of the major differences in this newly developed hydrodynamic model is the length of the calibration period. Version 1.0 was calibrated over nine days and validated over six day period while Version 2.0 was calibrated over 19 months (577 days) covering wide range of flow conditions.

1.2 Study Objectives

As described in the Section 1.1, the hydrodynamic and water quality models were required to be extended to the mouth of the Delaware Bay to obtain the better temporal and spatial gradients of the chemicals of concern for the rest of the Estuary. The major objectives for this study are described below.

1. Development of the model segmentation to cover the Zone 6 of the Delaware Bay.
2. Calibration of the hydrodynamic model against the tidal heights to ensure that the model correctly simulates the advective water movements within the Estuary.
3. Calibration of the water quality model, linked with hydrodynamic model, against chloride to ensure that the model simulates the dispersive movement properly.

2. CONCEPTUAL APPROACH FOR THE MODEL CALIBRATION

The calibration of the hydrodynamic model basically requires two steps followed by a link with the water quality model to complete the calibration process. The detailed description of the two step calibration approach is discussed in this section.

Step 1

The DYNHYD5 model was calibrated against tidal heights. The hydrodynamic model was set up with all the forcing tides at the open boundaries and inflows from the tributaries and discharges. Groups of Manning's coefficients were determined to obtain the best match with the observed tidal heights at the gaging stations. Because of the lack of velocity data, the current velocities were not a calibration parameter in this calibration process. Rather, the current velocities and flows were checked and confirmed using best professional judgement and the limited available data. At the end of this process, the advective movements are set and calibrated.

Step 2

Once the hydrodynamic model is calibrated, the outputs of the calibrated hydrodynamic model are then linked with the water quality model as a part of the hydrodynamic model calibration process. The main purpose of this process is to set the proper dispersion coefficients and also to find the proper computational time step of the water quality model. It was almost inevitable that certain levels of the numerical dispersions were introduced into the water quality model because of the size of the segments and the computational time step. Dispersion coefficients and the advection factor were adjusted until the water quality model results were well matched with known, spatially and temporally varying, observed conservative chemical concentrations. Like many other estuary model calibration processes, chloride (or salinity) concentrations were used as a calibration parameter. The major sources of chloride were the two open boundaries. The dispersion coefficients between segments and an advection factor were then adjusted to obtain the best fit with the observed data sets. Calibrated dispersion coefficients and the advection factor were thus established at the end of this step. Utilizing the hydrodynamic model results along with these dispersion coefficients properly simulated both the advective and dispersive movement of the chemicals of concern in the water column.

Iterative approach using step one and two might be required to finalize the hydrodynamic model calibration, which was the case for this study.

2.1 Constraints for the Extension of the Model Segments

Version 1.0 of the DYNHYD5 hydrodynamic model consists of 94 junctions and 100 channels. The downstream boundary was extended to the mouth of the Delaware Bay (Zone 6) in the newer version of the hydrodynamic model. The extended model comprises a total of 105 junctions and 111 channels. A number of constraints were considered in this model domain extension. The major constraints of the inclusion of the Delaware Bay into the model domain are the stability of the model, the data availability, and overall simulation time. Because the PCB water quality model will have additional sediment layers, and there is a slower interaction between sediment layer and water column chemical exchanges, the overall simulation time was one of the critical elements in determining the number of extended portions of the model segments. Because the purpose of the inclusion of the Delaware Bay was to generate reasonable temporal variations of chemical concentrations at the intersection of the Zones 5 and 6, it was not required to have a relatively fine scale of segmentation in Zone 6. It was determined that nine segments would cover the Zone 6. This coarse segmentation will fulfill the main purpose of this work while minimizing the overall computational time in both hydrodynamic and water quality model simulations.

2.2 Concept of the Rolling Calibration and the Calibration Period

The newly segmented hydrodynamic model was then calibrated against tidal heights and chloride by utilizing the water quality model over a longer time period than used with Version 1.0. The final calibration covers the period from September 1, 2001 to March 31, 2003, which lasted for 19 months or 577 days. The concept of rolling calibration was used. In rolling calibration, as more data becomes available, the simulation period of the model is sequentially extended, and the model is re-calibrated or validated to the full available data set for each extension. Thus, rather than splitting the time period for the model calibration and validation period, a longer and single time period was used as a calibration time period. In consequence, a number of sensitivity runs performed before March 31, 2003 did not cover the whole calibration time period.

3. OVERVIEW OF THE MODELS

3.1 Overview of DYNHYD5 Hydrodynamic Model

The DYNHYD5 hydrodynamic model solves the one dimensional equations of continuity and momentum for a branching or channel-junction (link-node), computational network. The resulting unsteady hydrodynamics are averaged over larger time intervals and stored for later use by the water quality model (Ambrose et. al., 1993a).

3.1.1 Governing Equations

Even though more detailed descriptions of the governing equations for the DYNHYD5 hydrodynamic model are available from the User’s Manual (Ambrose et. al, 1993a), a number of key equations are listed in this section to help understand the DYNHYD5 model. The hydrodynamic model solves one-dimensional equations describing the propagation of a long wave through a shallow water system while conserving both momentum and volume. The equation of motion, based on the conservation of momentum, predicts water velocities and flows. The equation of continuity, based on the conservation of volume, predicts water heights (heads) and volumes. This approach assumes that flow is predominantly one- dimensional, Coriolis and other accelerations normal to the direction of flow are negligible, channels can be adequately represented by a constant top width with a variable hydraulic depth, wave length is significantly greater than the depth, and that bottom slopes are moderate.

3.1.2.1 The Equation of Motion

The equation of motion is given by:

$$\frac{\partial U}{\partial t} = -U\frac{\partial U}{\partial x} + a_{g,\lambda} + a_f + a_{w,\lambda}$$

where,

$\frac{\partial U}{\partial t}$ = the local inertia term, or the velocity rate of change with respect to time, m/sec^2

$U\frac{\partial U}{\partial x}$ = the Bernoulli acceleration, or the rate of momentum change by mass transfer; also defined as the conservative inertial term from Newton’s second law, m/sec^2

$a_{g,\lambda}$ = gravitational acceleration along the λ axis of the channel, m/sec^2
a_f = frictional acceleration, m/sec^2
$a_{w,\lambda}$ = wind stress acceleration along axis of channel, m/sec^2
x = distance along axis of channel, m
t = time, sec
U = velocity along the axis of channel, m/sec
λ = longitudinal axis

Gravitational acceleration is driven by the slope of the water surface. The acceleration along the longitudinal axis is

$$a_{g,\lambda} = -g\sin S$$

where,
g = acceleration of gravity = 9.81 m/sec^2
S = water surface slope, m/m

with small water surface slope (S), the term [sin S] can be replaced with S. The slope can be expressed as the water surface elevation changes along the distance of the channel. The gravitational acceleration term can be now expressed as:

$$a_{g,\lambda} = -g\frac{\partial H}{\partial x}$$

where,
H = water surface elevation, or head (height above an arbitrary datum), m

The frictional acceleration term can be expressed using the Manning equation for steady uniform flow:

$$U = \frac{R^{2/3}}{n} \frac{\partial H^{1/2}}{\partial x}$$

where,

R = hydraulic radius (approximately equal to the depth for wide channel), m
n = Manning roughness coefficient, sec/m$^{1/3}$
$\frac{\partial H}{\partial x}$ = the energy gradient, m/m

The wind effect was not considered in the hydrodynamic model calibration for the Delaware River Estuary.

3.1.2.2 The Equation of Continuity

The equation of continuity is given by:

$$\frac{\partial A}{\partial t} = -\frac{\partial Q}{\partial x}$$

where,

A = cross sectional area, m^2
Q = flow rate m^3/sec

For rectangular channels of constant width B, the equation of continuity can be expressed as:

$$\frac{\partial H}{\partial t} = -\frac{1}{B}\frac{\partial Q}{\partial x}$$

where,

B = width, m
H = water surface elevation (head), m
$\frac{\partial H}{\partial t}$ = rate of water elevation change with respect to time, m/sec
$\frac{1}{B}\frac{\partial Q}{\partial x}$ = rate of water volume change with respect to distance per unit width, m/sec

3.1.2 Model Network

The solutions of the equations give velocities (U) and heads (H) throughout the water body over the duration of the simulation. The "link-node (or channel-junction)" network solves the equations of motion and continuity at alternating grid points. At each time step, the equation of motion is solved at the links, giving velocities for mass transport calculations, and the equation of continuity is solved at the nodes, giving heads for pollutant concentration calculations.

3.2 Overview of TOXIWASP5

(see DRBC, 2003a, b, c; Ambrose et. al., 1993b, c; for the detailed model description)

4. CALIBRATION OF THE HYDRODYNAMIC MODEL

4.1 Model Bathymetry and Geometry

4.1.1 Bathymetry

The bathymetry data for the extended portion was downloaded from the National Ocean Service (NOS) web site (http://spo.nos.noaa.gov/servlet/BuildPage?template=bathy.txt&parm1=M090). This hydrographic information for the Zone 6 was established using the Digital Elevation Model (DEM) and GIS. The downloaded bathymetry data was based on the mean low water (MLW) datum whereas, the existing model's datum was National Geodetic Vertical Datum of 1929 (NGVD1929). Because of lack of a information on the relationship between MLW and NGVD29 for the Bay area, limited station information was used to convert the datum of the downloaded bathymetry to NGVD29 datum. Another note to the downloaded bathymetry data was that the bathymetry data were derived from seventeen hydrographic surveys conducted between 1945 and 1993. On the other hand, the existing model's bathymetry was derived from single shore to shore survey performed by U.S. Army Corps of Engineers (USACE) in late 1980s to early 1990s. The bathymetry data for the Version 2.0 of the hydrodynamic model was from the USACE for the Zones 2 through 5 and from the NOS for the Zone 6.

4.1.2 Model Geometry and the Segmentation

The newer version of the hydrodynamic model extends the downstream boundary to the mouth of the Delaware Bay (Zone 6), and consists of 105 junctions and 111 channels. The minimal number of junctions were added to represent the Zone 6 of the Delaware River Estuary to improve the simulation results and to minimize impacts on the overall computational time.

Minor modifications were also performed to junctions and channels of the Version 1.0 model to improve the model stability. Most of the numbering systems were kept to maintain the comparability between the models. One of modifications in Version 2.0 model was the addition of boundary junctions for all four drinking water intake withdrawals. By assigning the boundary junctions for the intake withdrawals, the mass of chemical of concern would be withdrawn along with the water mass in the hydrodynamic and water quality modeling.

Another modification to the Version 1.0 hydrodynamic model was the relocation of the Chesapeake and Delaware Canal (C&D Canal) downstream boundary. The downstream boundary for the C&D Canal was at the Old Town Point Wharf, MD in the earlier version of the model. In this version, the boundary was moved about 9 km east from the Old Town Point to the Chesapeake City, MD for several reasons. First, the Chesapeake City location has a more confined channel configuration compared to the location at the Old Town Point Wharf, which is potentially influenced by the Elk River. Second, tidal heights were not gaged for both of the locations, rather, relationships to estimate the tidal heights for both locations were already developed by NOAA. The tidal heights for the Old Town Point Wharf were derived from the observed tidal heights at Baltimore, MD, which is over 80 km away. Whereas, the tidal heights for the Chesapeake City were derived from the Reedy Island Station's observed data, which is only about 21 km apart. Therefore, Chesapeake City would be based on more accurate tidal height calculations. Junctions and channels of the C&D Canal were redefined, while the total number of segments and the numbering system remained same as the Version 1.0 Model.

The finalized segmentation for the Version 2.0 of the DYNHYD5 hydrodynamic model for each Zone is presented in Figure 4-1 (a) to (e). The schematic diagram of segmentation for the entire Delaware Estuary is presented in Figure 4-1 (f). The individual junction information for the model input is summarized in Table 4-1 and the channel geometries are summarized in Table 4-2.

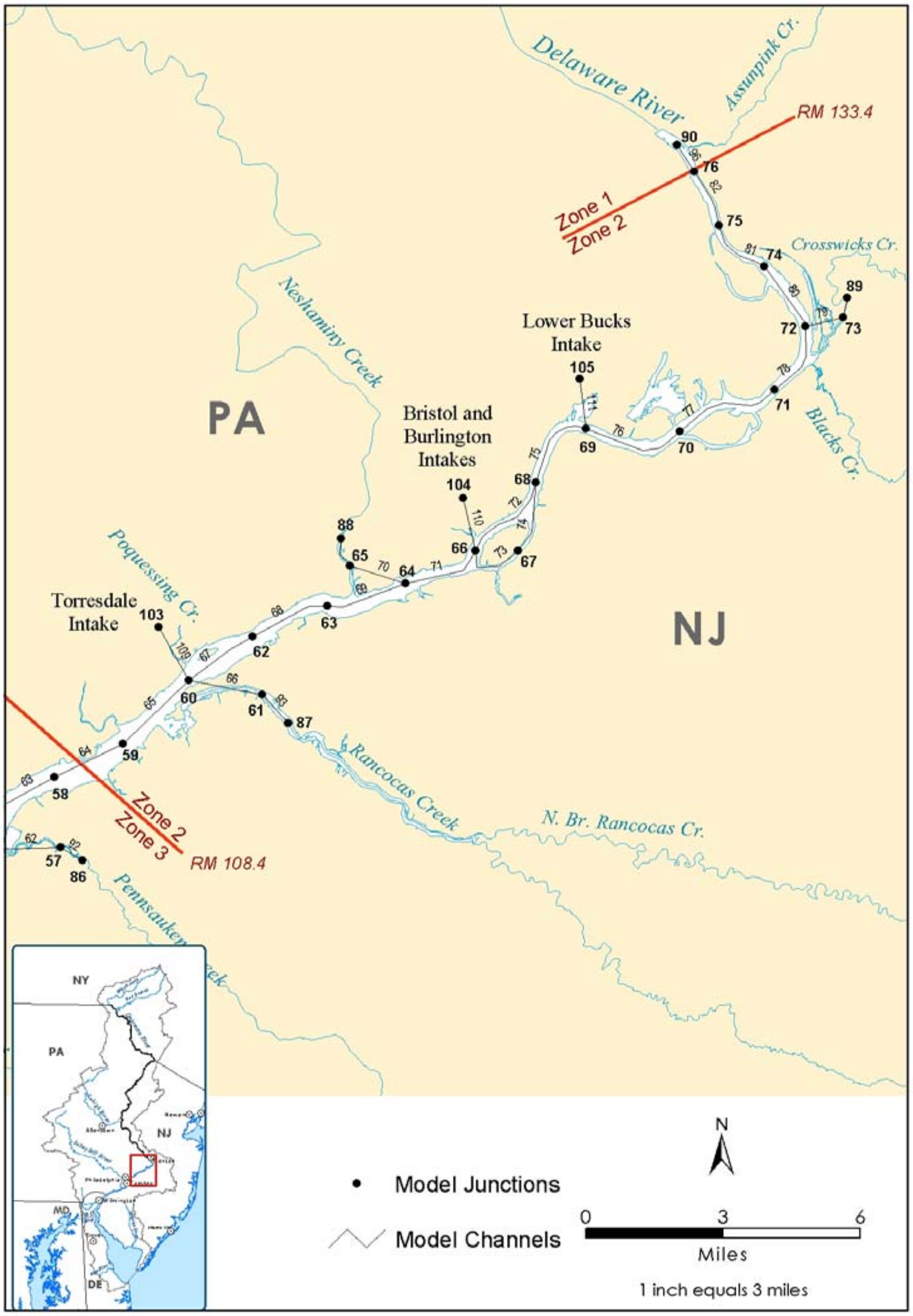


Figure 4-1(a): Schematic diagram of the segmentation for the DYNHYD5 hydrodynamic model (Version 2.0): Zone 2

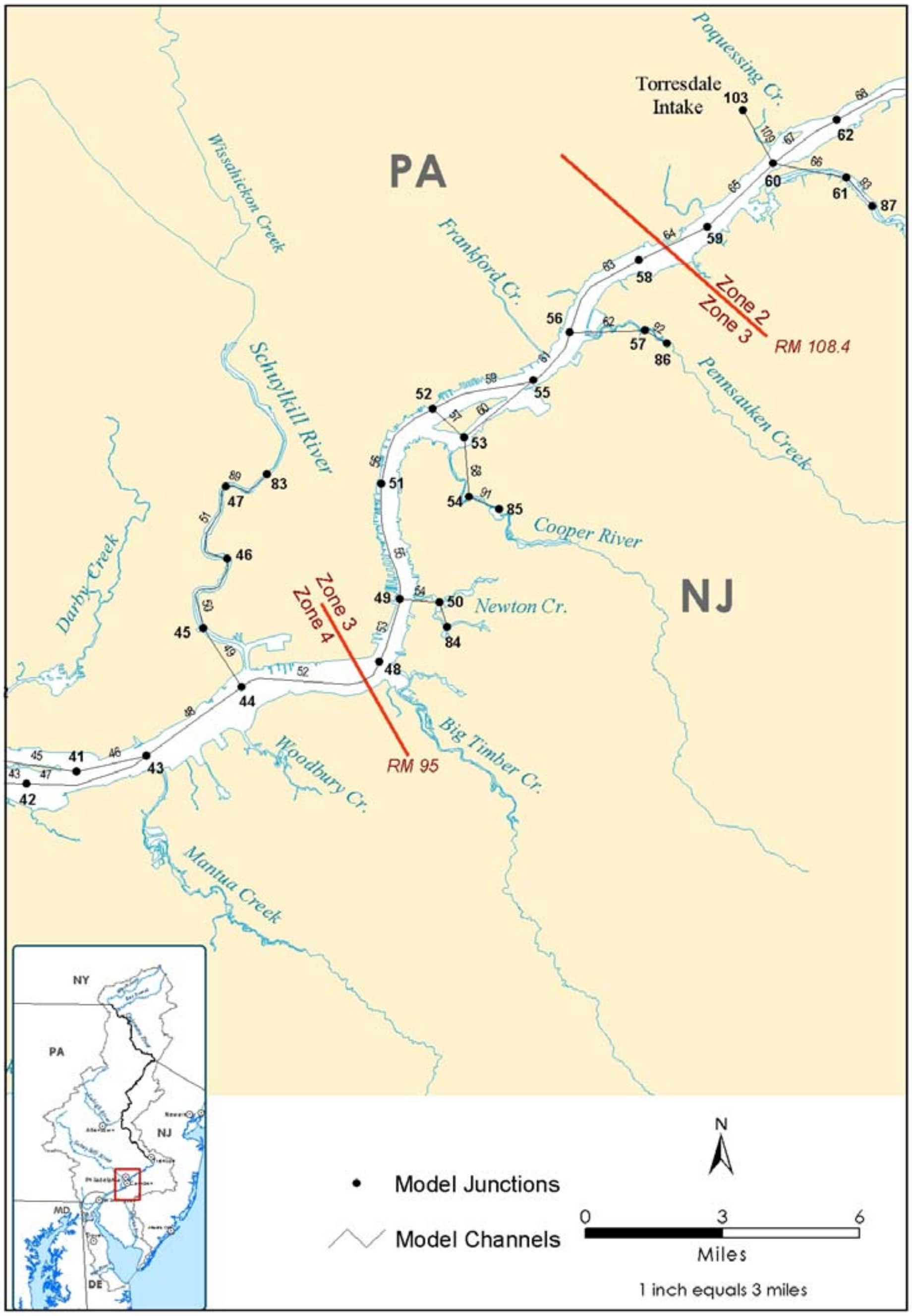


Figure 4-1(b): Schematic diagram of the segmentation for the DYNHYD5 hydrodynamic model (Version 2.0): Zone 3

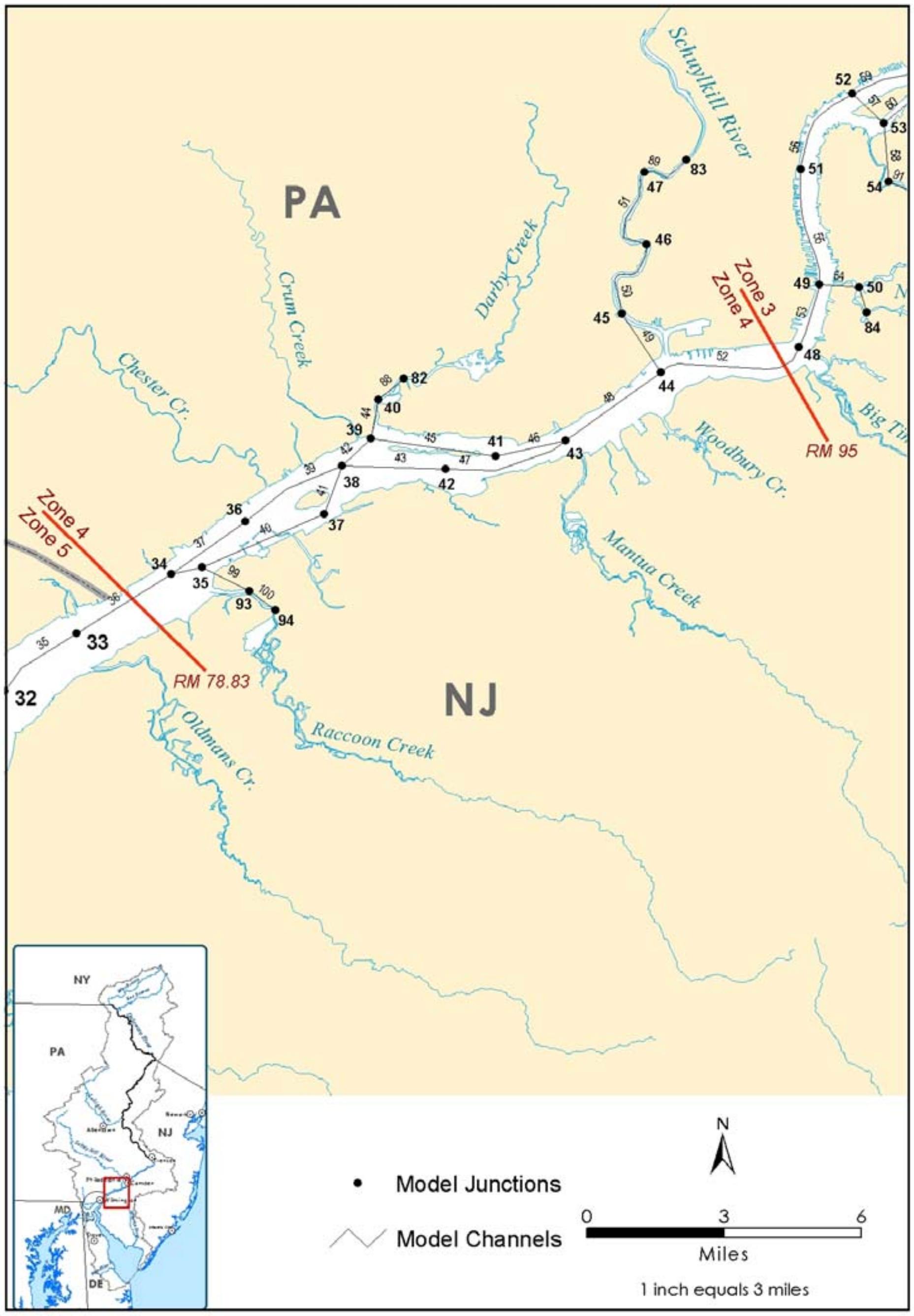


Figure 4-1(c): Schematic diagram of the segmentation for the DYNHYD5 hydrodynamic model (Version 2.0): Zone 4

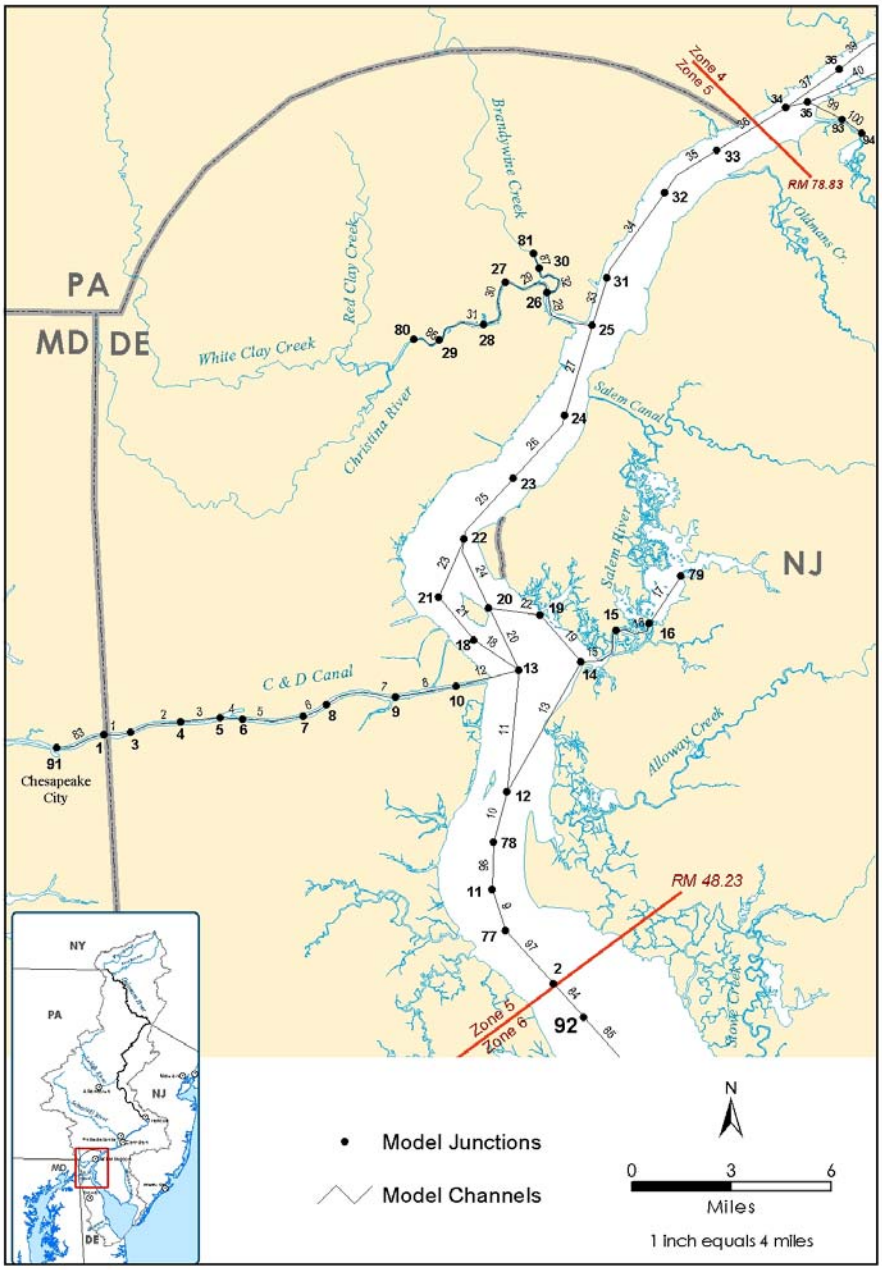


Figure 4-1(d): Schematic diagram of the segmentation for the DYNHYD5 hydrodynamic model (Version 2.0): Zone 5

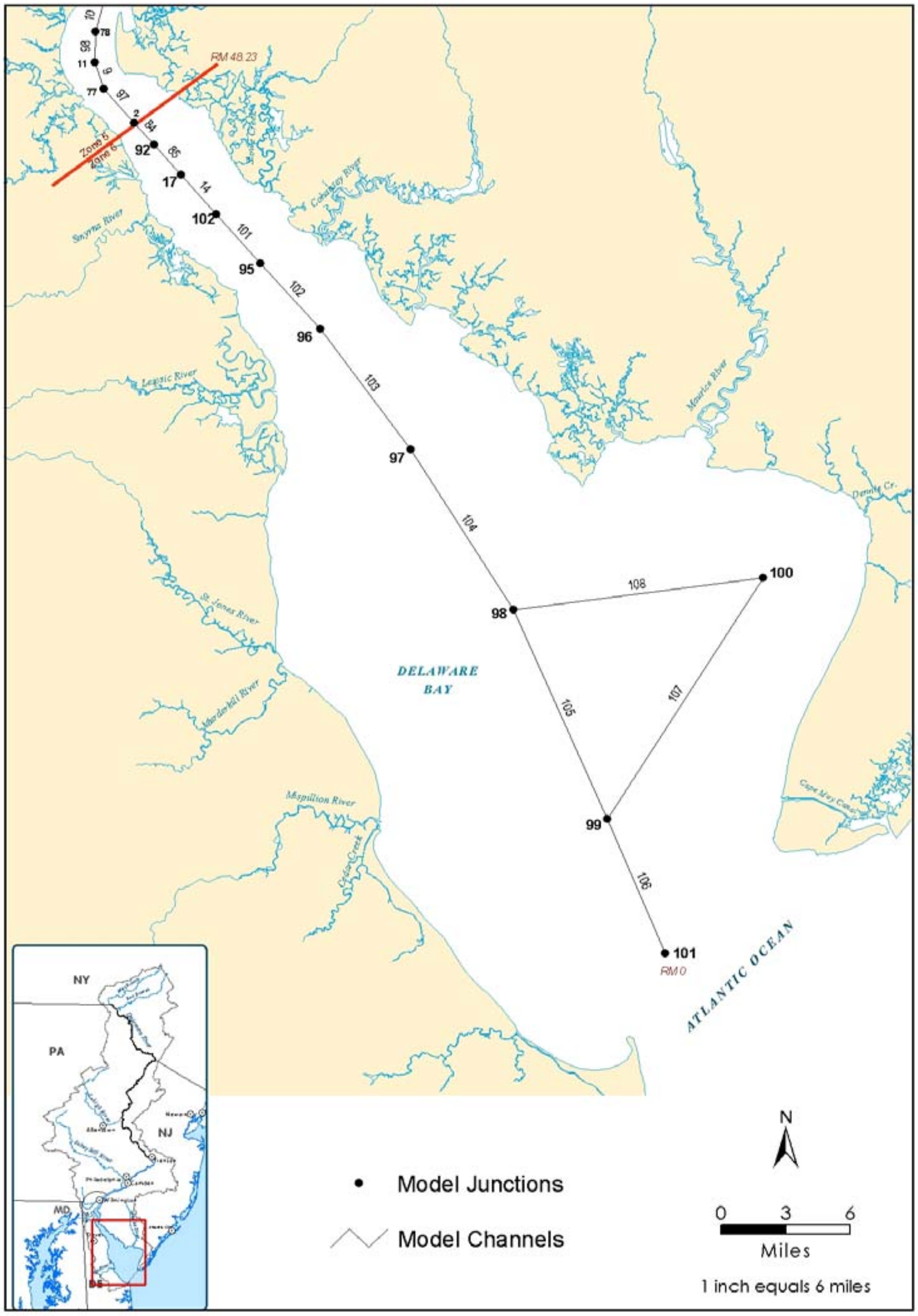


Figure 4-1(e): Schematic diagram of the segmentation for the DYNHYD5 hydrodynamic model (Version 2.0): Zone 6

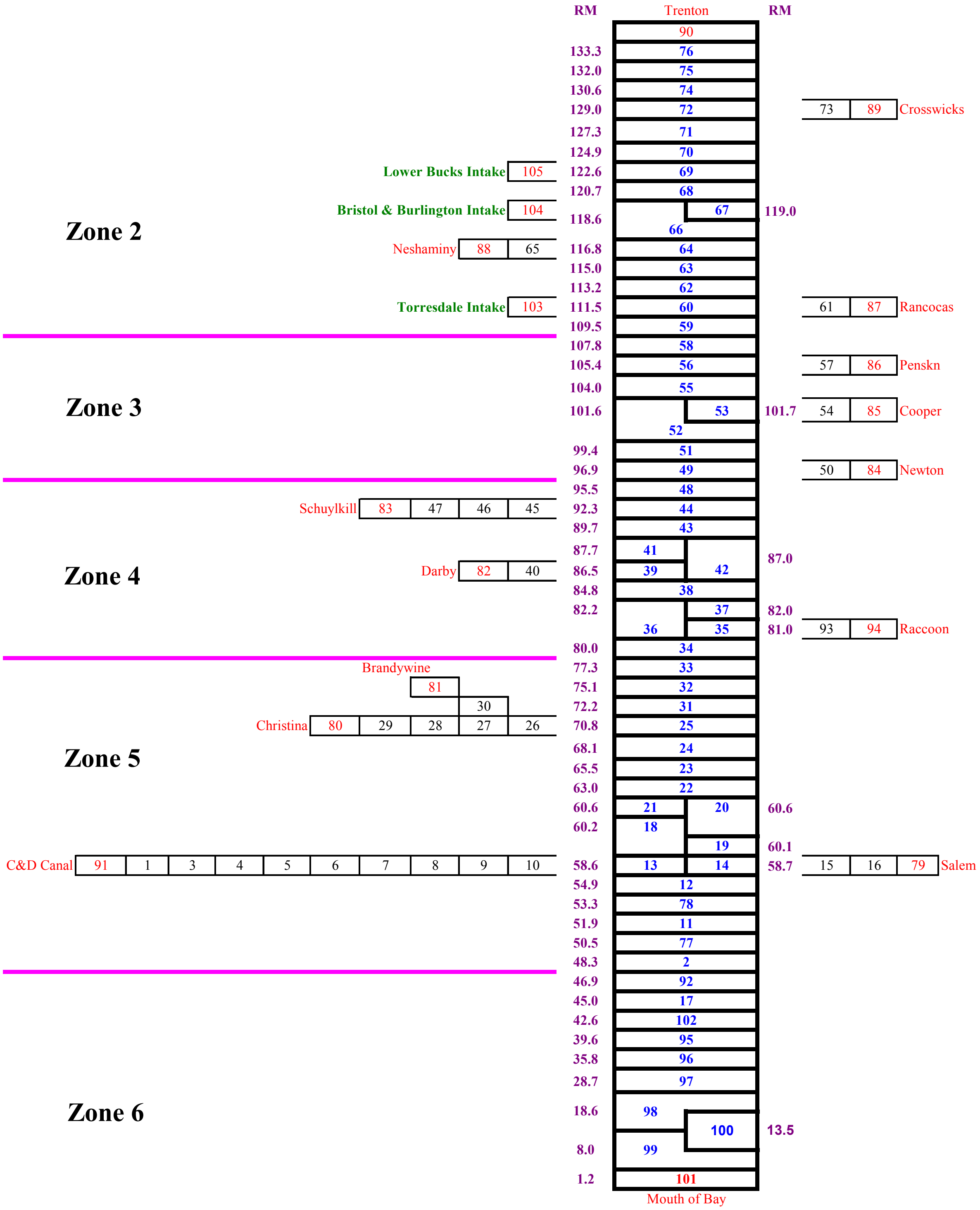


Figure 4-1(f) : Schematic diagram of the segmentation for the DYNHYD5 hydrodynamic model (Version 2.0) for all Zones: Boundaries are marked in red colored letters and drinking water intakes are marked in green colored letters.

Table 4-1: Summary of the junction data.

Node No.	River Mile	Surface Area (m^2)	Bottom Elevation[a] (m)	Node No.	River Mile	Surface Area (m^2)	Bottom Elevation[a] (m)
1	58.6	558800	-8.64	54	101.6	330047.	-1.48
2	48.3	11926900	-5.54	55	104.0	2898224.	-6.41
3	58.6	438900	-8.64	56	105.4	2508300.	-6.93
4	58.6	375980	-8.91	57	105.4	190491.	-1.86
5	58.6	336160	-9.18	58	107.8	2487769.	-7.40
6	58.6	429880	-9.23	59	109.5	2735115.	-7.09
7	58.6	523600	-9.28	60	111.5	2526880.	-6.46
8	58.6	583660.	-9.24	61	111.5	693730.	-3.18
9	58.6	664180.	-9.25	62	113.2	2186401.	-4.89
10	58.6	685410.	-9.23	63	115.0	1672200.	-7.19
11	51.9	9341080.	-5.52	64	116.8	1791112.	-5.70
12	54.9	12758070.	-5.08	65	116.8	255475.	-3.19
13	58.6	8766871.	-6.45	66	118.6	1435770.	-8.05
14	58.7	5064157.	-1.35	67	119.0	417771.	-3.29
15	58.6	2351584.	-2.18	68	120.7	1435770.	-7.76
16	58.6	6374031.	-1.23	69	122.6	1219777.	-7.16
17	45.0	24912800.	-5.07	70	124.9	1575120.	-6.93
18	60.2	5167297.	-3.97	71	127.3	1672200.	-6.74
19	60.1	5177611.	-1.33	72	129.0	1207700.	-5.16
20	60.6	6157438.	-5.61	73	129.0	156351.	-1.29
21	63.0	7034125.	-2.14	74	130.6	969504.	-3.86
22	63.0	10221140.	-5.04	75	132.0	650300.	-4.81
23	65.5	9519791.	-5.59	76	133.3	646500.	-1.67
24	68.1	7735475.	-5.64	77	50.5	9839210.	-5.22
25	70.8	7384800.	-5.99	78	53.3	8672718.	-5.30
26	70.8	660094.	-5.01	79	58.6	7173807.	-1.68
27	70.8	587896.	-2.29	80	70.8	8500.	-1.20

Node No.	River Mile	Surface Area (m^2)	Bottom Elevation[a] (m)	Node No.	River Mile	Surface Area (m^2)	Bottom Elevation[a] (m)
28	70.8	567268.	-1.20	81	70.8	11900.	-3.24
29	70.8	587896.	-1.20	82	86.5	9100.	-2.80
30	70.8	206279.	-3.24	83	92.3	16900.	-5.13
31	72.2	7993324.	-5.30	84	96.9	5100.	-1.87
32	75.1	7065067.	-5.93	85	101.6	9100.	-1.48
33	77.3	6704078.	-5.43	86	105.4	9100.	-1.86
34	80.0	5517972.	-5.83	87	111.5	18300.	-3.18
35	81.0	1897769.	-2.82	88	116.8	10200.	-3.19
36	82.2	3228271.	-8.32	89	129.0	10200.	-1.29
37	82.0	1165478.	-1.07	90	134.0	26300.	-1.67
38	84.8	4352494.	-5.46	91	58.6	655600.	-8.25
39	86.5	1392385.	-2.42	92	46.9	14443000.	-5.01
40	86.5	515698.	-2.80	93	82.2	433547.	-1.87
41	87.7	1443955.	-2.38	94	82.2	495482.	-1.87
42	87.0	2980736.	-6.46	95	39.6	45906200.	-5.51
43	89.7	4548459.	-8.41	96	35.8	86887700.	-5.02
44	92.3	5507658	-7.17	97	28.7	286164000.	-4.24
45	92.3	711663.	-7.43	98	18.6	401974000.	-5.79
46	92.3	825117.	-7.21	99	8.0	462987600.	-8.83
47	92.3	433186.	-5.13	100	13.5	335131600.	-2.64
48	95.5	3733656.	-6.42	101	1.2	92928860.	-12.57
49	96.9	2887910.	-10.67	102	42.6	31825000.	-5.32
50	96.9	268163.	-1.87	103	111.5	10000.	-6.50
51	99.4	2722887.	-8.95	104	118.6	10000.	-6.50
52	101.6	2403154.	-6.70	105	122.6	10000.	-6.50
53	101.7	1340552.	-1.67				

a- The datum for the bottom elevations was NGVD1929.

Table 4-2: Summary of the channel geometry.

Name	Channel No.	Length meter	Width meter	Angle degree	Name	Channel No.	Length meter	Width meter	Angle degree
C&D	1	2093	220	90	Pennsauken	57	1930	427	110
MAIN	2	1889	220	90	MAIN	58	2742	53	150
C&D	3	1528	220	90	MAIN	59	3656	932	60
C&D	4	1528	220	90	MAIN	60	2437	762	45
C&D	5	2380	220	90	Rancocas	61	2949	871	80
C&D	6	2380	220	90	MAIN	62	2745	65	90
C&D	7	2926	220	90	MAIN	63	2949	851	75
C&D	8	3111	220	90	MAIN	64	2949	966	85
C&D	9	2285	4381	330	Neshaminy	65	2949	848	75
C&D	10	2285	3796	15	MAIN	66	2745	181	90
MAIN	11	4570	2347	5	MAIN	67	2745	766	80
MAIN	12	3120	1372	90	MAIN	68	2745	712	85
MAIN	13	5890	518	40	MAIN	69	2898	652	90
MAIN	14	4000	7129	320	MAIN	70	1930	89	300
Salem	15	2742	305	60	MAIN	71	2898	649	90
Salem	16	2742	1320	50	MAIN	72	3356	466	70
MAIN	17	4163	1625	355	Crosswicks	73	2389	296	90
MAIN	18	4164	1158	315	MAIN	74	2389	307	10
MAIN	19	2742	1410	320	MAIN	75	2949	433	40
MAIN	20	4164	1036	320	MAIN	76	3305	415	125
MAIN	21	3250	1871	320	MAIN	77	3660	433	90
MAIN	22	2945	1494	280	MAIN	78	2745	406	70
MAIN	23	3352	2316	30	Salem	79	1830	91	60
MAIN	24	4265	1189	330	Christina	80	2288	430	355
MAIN	25	4164	2747	45	Brandywine	81	2438	363	330
Christina	26	3656	2501	30	Darby	82	2438	239	355
Christina	27	3656	2080	20	Schuylkill	83	2980	220	90
Christina	28	2844	239	315	Newton	84	2714	5664	330
Christina	29	2844	230	255	Cooper	85	3000	6530	325

Name	Channel No.	Length meter	Width meter	Angle degree	Name	Channel No.	Length meter	Width meter	Angle degree
Brandywine	30	2844	169	225	Pennsauken	86	1472	102	255
MAIN	31	2844	102	225	Rancocas	87	1472	179	320
MAIN	32	2844	179	320	Neshaminy	88	1421	98	20
MAIN	33	3656	2086	10	Crosswicks	89	1675	142	45
MAIN	34	3656	2225	30	Trenton	90	1421	37	105
MAIN	35	3656	2107	40	C&D	91	1421	53	150
MAIN	36	4062	2095	45	MAIN	92	1422	65	90
MAIN	37	3656	1236	45	Raccoon	93	1422	181	90
MAIN	38	3250	1185	60	Raccoon	94	1015	89	300
MAIN	39	3656	1320	45	MAIN	95	965	91	60
Darby	40	2234	754	60	MAIN	96	1269	239	355
MAIN	41	2234	1059	25	MAIN	97	2285	4816	330
MAIN	42	1930	792	45	MAIN	98	2285	3795	15
MAIN	43	3656	1506	90	MAIN	99	2438	203	315
MAIN	44	2742	98	20	MAIN	100	9754	102	315
Schuylkill	45	1930	417	90	Mouth of the Bay	101	5000	7794	320
Schuylkill	46	3656	417	90	MAIN	102	6900	8636	320
Schuylkill	47	3656	1248	80	Torresdale Intake	103	10880	15362	322
MAIN	48	4750	1156	60	Bristol Intake	104	14941	22981	336
MAIN	49	3250	195	330	LowBucks Intake	105	16803	25824	330
Newton	50	3250	173	10	MAIN	106	11167	25025	325
MAIN	51	3250	142	45	MAIN	107	24041	14351	29
MAIN	52	3656	1152	90	MAIN	108	21563	13281	253
MAIN	53	3656	912	35	MAIN	109	4563	581	270
Cooper	54	2742	37	105	MAIN	110	4563	581	270
MAIN	55	3656	786	350	MAIN	111	4563	581	270
MAIN	56	3148	1014	10					

4.2 Data Compilation

4.2.1 Tidal Height

Available water surface elevation (tidal height) data were obtained from National Oceanic Atmospheric Administration (NOAA) web-site (http://www.co-ops.nos.noaa.gov/data_res.html) for the period from September 1, 2001 to March 31, 2003, which coincides with the calibration period of the PCBs water quality model. Seven tide gaging stations were available with the verified hourly tidal heights within the model domain (Figure 4-2). Hourly tidal heights were downloaded based on Local Standard Time (LST), units of meters, and Mean Lower Low Water (MLLW) datum. Retrieved water surface elevation data sets were then converted to the NGVD1929 datum. The data for the water surface elevation at Burlington, New Jersey were obtained from the US Geological Survey (USGS) by personal contact (personal contact with Robert Schopp,USGS, NJ District, 2003). A summary of the available water surface elevation data with model node information is contained in Table 4-3.

Figure 4-2: Map of locations of the tide gage stations in the Delaware River Estuary.

Table 4-3: Summary of available water surface elevation data from NOAA and USGS for the Delaware River Estuary.

Station Name	Station ID	River Mile	Available Period	NODE No.	MLLW - NGVD29 meter
Lewes	8557380	1.5	9/1/01 ~ 3/31/03	101	0.6523
Brandywine Shoal	8555889	15	7/1/02 ~ 3/31/03	99	0.6800[a]
Reedy Point	8551910	58	9/1/01 ~ 3/31/03	10	0.7681
Philadelphia	8545240	100	9/1/01 ~ 3/31/03	51	0.7010[b]
Tacony-Palmyra Bridge	8538886	107	6/11/02 ~ 3/31/03	58	0.8400[a]
Burlington	01464598	119	6/20/02 ~ 1/16/03[C] 3/1/03 ~ 3/31/03	66	Reported with NGVD29 datum
Newbold	8548989	127	11/15/01 ~ 3/31/03	71	0.9700[a]

a - Information on the difference between mean lower low water (MLLW) and NGVD1929 was not available. The difference was assumed to correct the NOAA's verified data into the model's datum of NGVD1929.

b - There were two tidal stations for Philadelphia under NOAA's web site. One station (Station ID 8545240) contained tidal height data for the modeling period and the other station (Station ID 8545530) only contained the MLLW to NGVD29 relationship. The station 8545240 had NAVD88 height related to MLLW. A downloadable software (called VERTCON) was used to calculate the relationship between NAVD88 and NGVD29 using the latitude and longitude. Using the location information and the 'VERTCON', the vertical relationship between NAVD88 and NGVD29 was calculated to be 0.332 meters. NAVD88 from MLLW for this station was reported as 1.033 meters. Thus, the calculated relationship between MLLW and NGVD29 became 0.701 meters.

c - The data gap was caused by an ice jam at the gaging station.

4.2.2 Inflows

4.2.2.1 Inflows from Tributaries

Daily flows from twenty-two (22) tributaries, including the Delaware River at Trenton and Schuylkill River, were input into the model. Daily average flows for the Delaware River at Trenton for the entire calibration period are shown in Figure 4-3. The flow at Trenton varied from 69 to 2,237 m^3 /sec (or 2,420 to 79,000 ft^3/sec) during the calibration period. The annual average freshwater inflows from Trenton makeup more than 60% of total freshwater inflows into the Delaware River Estuary. Daily flows for the ungaged tributaries

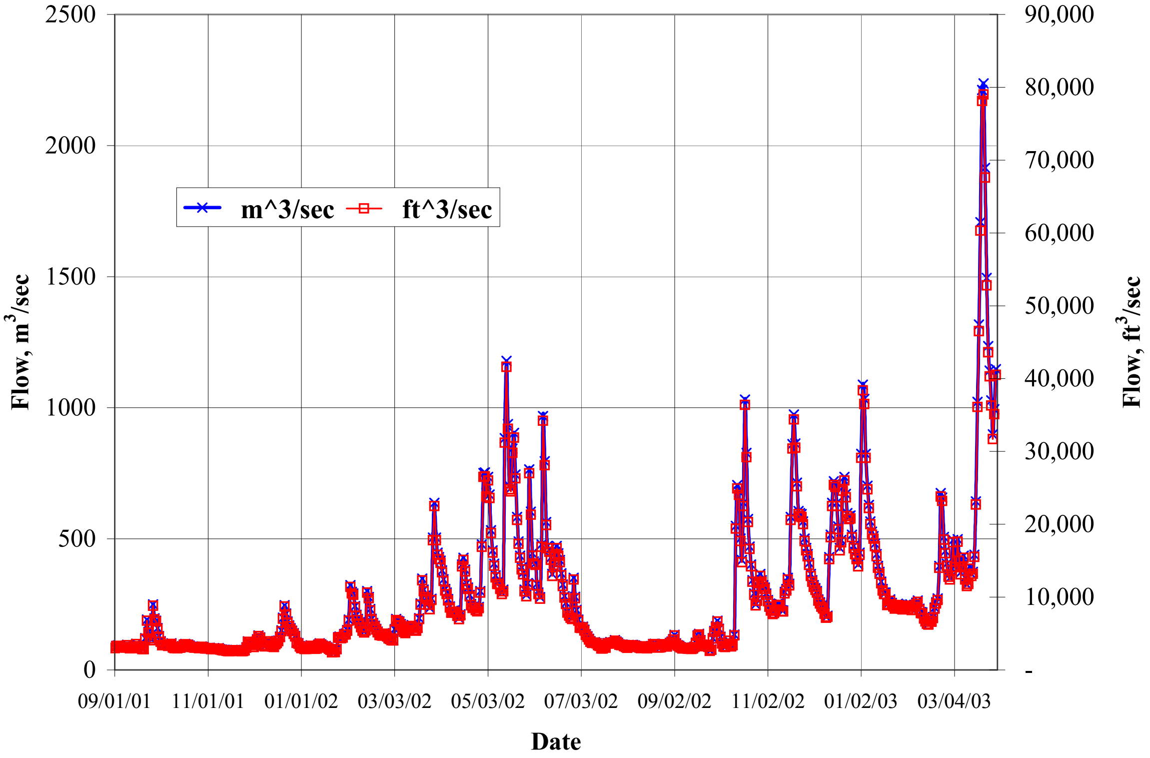


Figure 4-3: Daily average flow for the Delaware River at Trenton during the model calibration period.

were extrapolated from nearby gaging stations with drainage area adjustments. Detailed methods and assumptions on tributary flow calculations are summarized in DRBC (2003b).

4.2.2.2 Inflows from Discharges

Seventeen (17) NPDES permittees with discharges that contribute to the top 90 percent of the cumulative flows among 144 discharges were requested to submit the daily average effluent flows. These daily average inflows (577 data points per discharge) were used in the model for the calibration period. For the rest of the discharges, a mean flow value per discharge for the entire calibration period was calculated using the Permit Compliance System (PCS) data, and used in the model. More detailed description can be found in the model calibration report (DRBC, 2003b). Four water intake withdrawals were also incorporated into the model. Those four intakes were: the City of Philadelphia, Torresdale; City of Burlington; Bristol Borough; and Lower Bucks County JMUA. Daily average intake flow data were obtained from the City of Philadelphia for the Torresdale intake and incorporated into the model. The other, three intakes were assigned their average intake flow rate value.

4.2.3 Current Velocity

Limited current velocity data were available during the model calibration period. The Acoustic Doppler Current Profiler (ADCP) was deployed in the mid section of the Estuary to measure the current velocity profiles in a number of transects by the University of Delaware. The data were obtained through the personal contact and used to confirm the performance of the model. (Personal communication with Dr. Christopher Sommerfield).

4.3 Calibration of the DYNHYD5 Hydrodynamic Model

4.3.1 Code Modification

The original DYNHYD5 source codes had been modified to reduce the simulation time in the earlier version of DYNHYD5 model for the Delaware River Estuary. Most of the modifications were performed to comment out the linkage with the graphic output processing subroutines. In this version, additional modifications were required to incorporate the larger number of junctions and channels, larger number of variable inflows, and longer time series inputs. The dimensions of the corresponding variables in 'Dynhyd.CMN' file were therefore updated.

4.3.2 Assignment of Open Boundaries With Forcing Tides and the Computational Time Step

Two downstream boundaries were assigned with the forcing tidal heights. One was located at the Mouth of the Bay (Lewes, DE) and the other was at the Western end of C & D canal (Chesapeake City, MD). A combination of the measured high and low tidal heights and hourly observed tidal heights were input into the model along with the corresponding times for the mainstem downstream boundary at Lewes, DE. The derived hourly tidal heights from the hourly observed data at the Reedy Island gaging station were assigned as forcing tides at the C&D Canal boundary. The relationship for tidal heights at Chesapeake City from Reedy Island station was obtained from the NOAA (International Marine, 2001). The average phase lag was about 55 minutes (high and low tides at Chesapeake City were 55 minutes ahead of Reedy Is. Station's) and amplitude correction factor was 0.5 (multiply 0.5 to the Reedy Is. Station's tidal heights). The forcing tidal heights at both boundaries were adjusted to NGVD1929 datum before incorporated into the model.

The computational time step for the DYNHYD5 hydrodynamic model was set to 30 seconds to maintain the stability of the model.

4.3.3 Determination of Manning's Coefficients

The Manning's coefficient (n) plays an important role on water movement in the DYNHYD5 hydrodynamic model. Manning's coefficient was the key factor in calibrating the advective movement of the water mass.

The basic sensitivity of the model's responses to the assigned Manning's coefficients revealed that assigning a larger Manning's coefficient slowed down the tidal propagation and decreased the tidal amplitude. Smaller Manning's coefficients resulted in faster tidal propagation and increased tidal amplitude, as expected. Assignment of too large or too small of Manning's coefficients could cause the instability of the model.

To have a better fit in the regression between the simulated and the observed tidal heights, numerous combinations of Manning's coefficients sets were tested. From these, acceptable values were assigned for the sections of the model's domain. The assigned Manning's coefficients are summarized graphically in Figure 4-4.

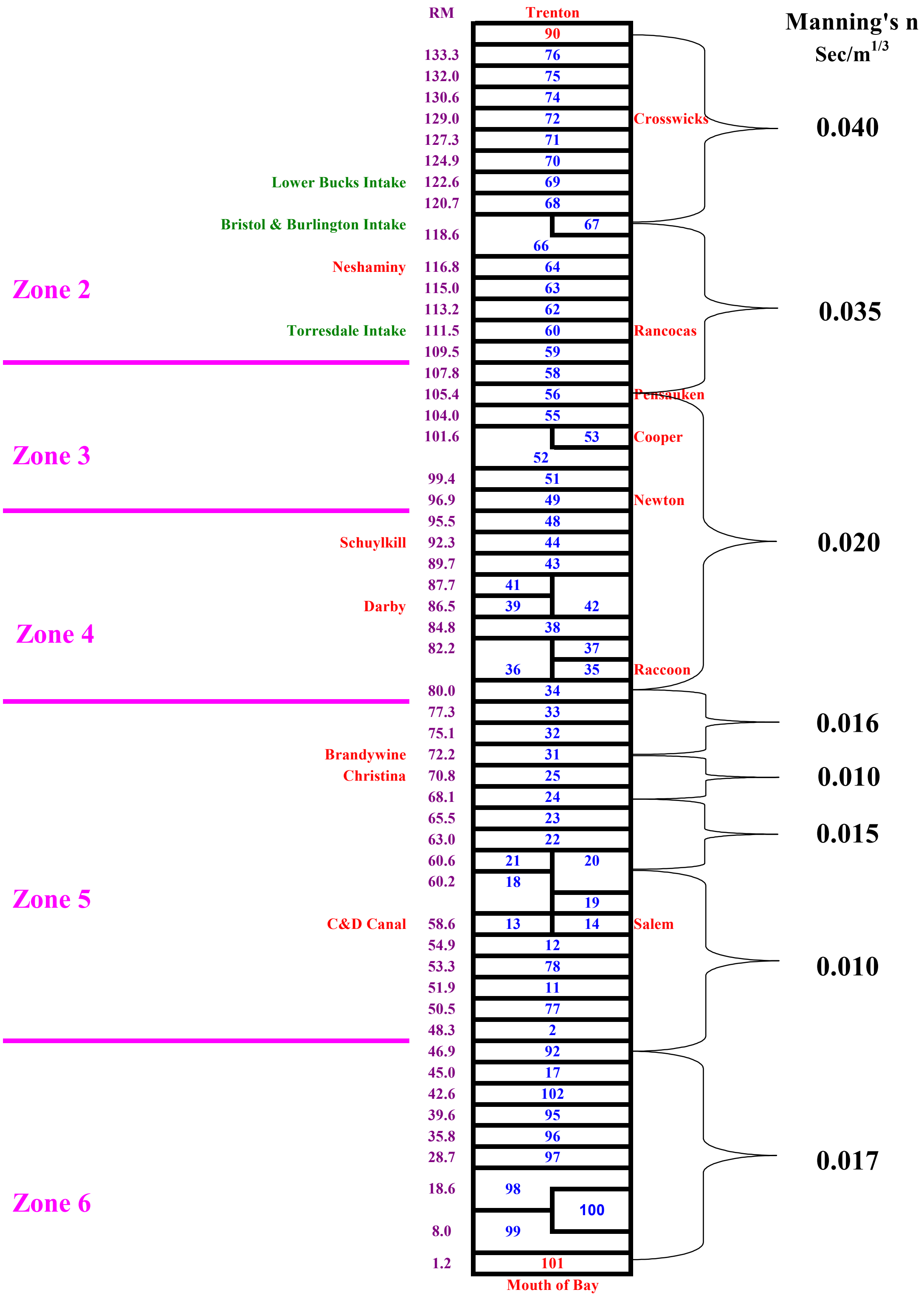


Figure 4-4: Assigned Manning's coefficients for the main channel of the model segments. Only the main stem of the Delaware Estuary is shown.

4.3.4 Influence of the C&D Canal

While calibrating the hydrodynamic model, it was found that the C&D Canal played a very important role in chloride concentration profiles in the lower part of the Delaware Estuary. The direction and the magnitude of the net flow between the Chesapeake and Delaware Estuary made a significant impact on the chemical transport in the Delaware Estuary. The Manning's coefficient for the channels within the C&D Canal was assigned with a value of 0.030, which was comparable with the earlier study result (n=0.026) performed by Gardner and Pritchard (1974). In addition, the predicted amplitude of the tidal velocity was maintained at about 1.0 m/sec within the C&D Canal and this was confirmed by Dr. Kuo-Chuin Wong of the University of Delaware and Dr. William Boicourt of the University of Maryland (personal communications).

4.3.4.1 Issue Statement

Direction of net flow and magnitude

During the early stage of the calibration process, the direction of the net flow within the C&D Canal was predicted to be westward (from the Delaware into the Chesapeake Estuary) with an average flow rate of about 300 m^3/sec by the model. These results were contradictory to the number of earlier study results (Gardner and Pritchard, 1974; Pritchard and Gardner, 1974; Thatcher and Najarian, 1981; Johnson et. al., 1999). All of the previous field and modeling study results revealed that the long-term net flow within C&D Canal had eastward flow direction with net flow rates ranging from 30 to 259 m^3/sec in their studies.

Chloride Gradient in the Delaware Estuary

The water quality model was run with the hydrodynamic model output which contained the westward C&D net flow condition. Dispersion coefficients in the water quality model were set to zero for the whole estuary in this run. The chloride concentration for the downstream boundary at Lewes, DE was set at 16,000 mg/L. Note that the simulation period was from August 2001 to November 2002 for these calibration runs (See the Section 2.2 of the concept of the rolling calibration regarding the differences in the simulation period).

The temporal variations of the simulated chloride concentrations at River Mile (RM) 54 were plotted along with the daily freshwater inflows at Trenton, NJ (Figure 4-5). As shown in Figure 4-5, the chloride concentrations in the Delaware Estuary were greatly influenced by the upstream freshwater inflows. During the low freshwater inflow period, a significant ocean water intrusion was simulated. The chloride concentrations were dropped significantly during the high freshwater inflow conditions, as expected. The simulated chloride concentrations were compared with the observed data at River Mile 54 (Figure 4-6). The model over-predicted the chloride concentrations, especially during the low freshwater inflow period. One of the main reasons was that the C&D Canal withdrew water from the Delaware Estuary, causing water from the ocean moving up during the low freshwater inflow period. Because the model was already set with zero dispersion coefficients, there was no other mechanisms to depress the chloride intrusion from the ocean.

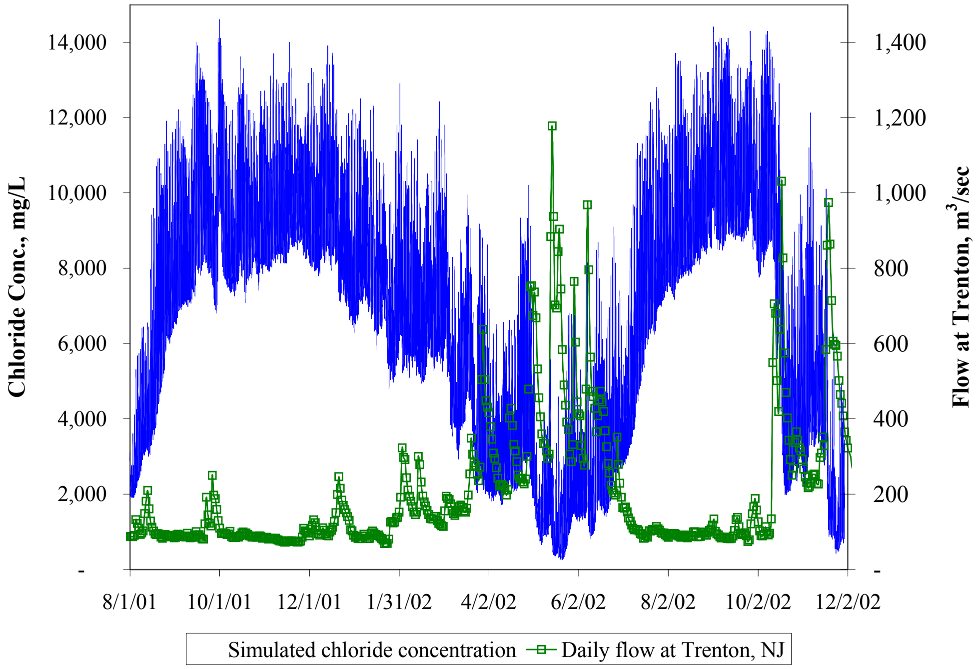


Figure 4-5: Temporal variations of the simulated chloride at RM 54 related to the inflows at Trenton.

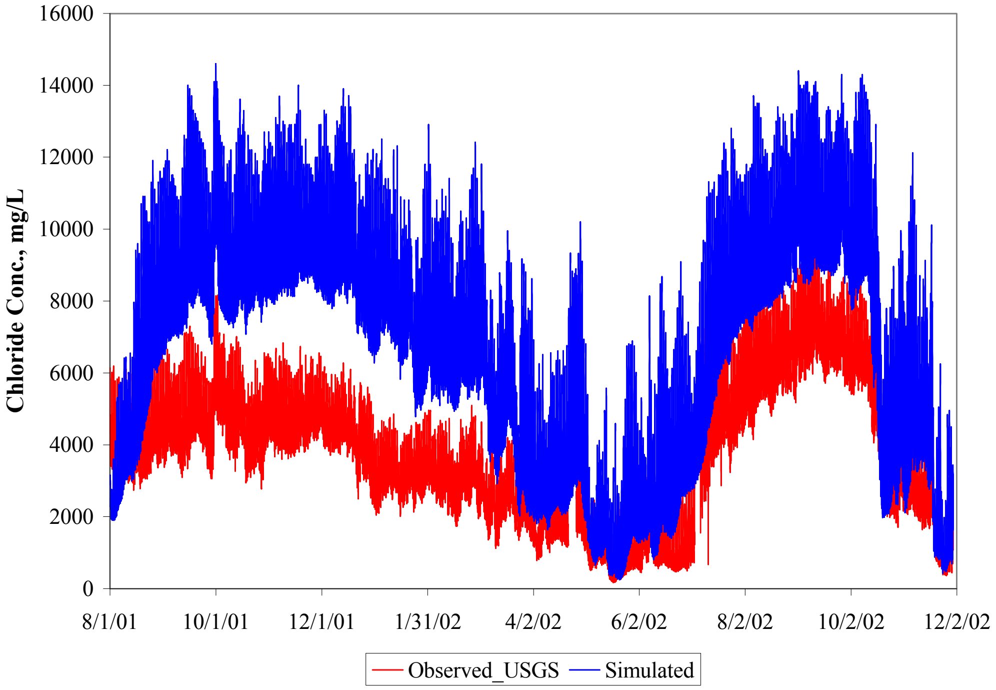


Figure 4-6: Temporal variations of the simulated and the observed chloride concentration at RM 54.

4.3.4.2 Approach and Modification to the Tidal Datum at Chesapeake City, MD

Because the manipulation of dispersion coefficients could not resolve the intrusion of chloride, an advective movement correction was performed within the C&D Canal. A certain level of adjustment was required to correctly simulate the direction and magnitude of the net flow through the C&D Canal. The major components that determined the direction and the magnitude of the flows within the C&D Canal were the tidal heights at both ends of the Canal, Chesapeake City and Reedy Point, in this model. It was decided that adjustments on the tidal heights at the Chesapeake City would be made and not to make any adjustment on tidal heights at Reedy Point Station, because the tidal heights at Reedy Point were actually observed. On the other hand, the tidal heights at the Chesapeake City were derived from the Reedy Point station's observed data. To force the net flow direction eastward (from Chesapeake to Delaware Estuary), the tidal heights at the west end (Chesapeake City) were raised. The tidal datum at Chesapeake City was shifted up at different levels and compared to the results of the sensitivity simulations on chloride concentrations (Figure 4-7). Ten (10) centimeters up-shift of the tidal datum at the Chesapeake City was chosen based upon the simulated chloride concentration profiles.

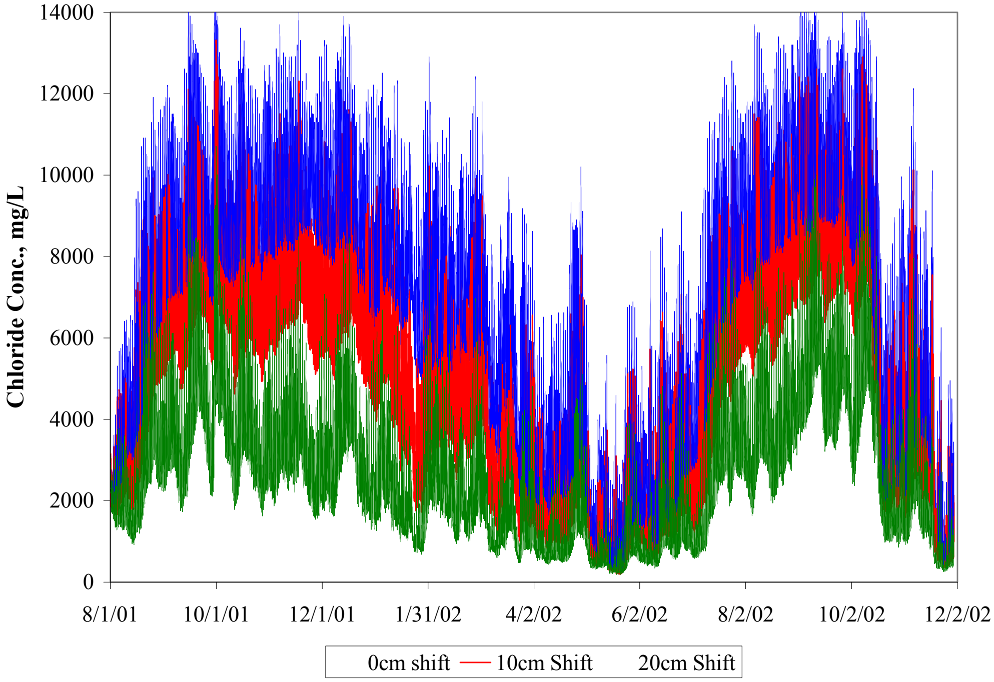


Figure 4-7: Sensitivity simulation results: Impact on chloride concentrations by the datum shift at the Chesapeake City.

4.3.4.3 Confirmation of the Datum Adjustment

Even though the monitoring of the long-term flow, or the actual tidal heights at Chesapeake City with a survey of the station's datum would be the only way to clearly justify this adjustment, a number of previous studies and the modeling results reenforced the approach we took in this modeling work.

With 10 centimeter of up-shift of the datum at Chesapeake City, the model simulated the net flow direction of eastward. This result agreed with the earlier studies described in the Section 4.3.4.1. In addition, Thatcher and Najarian (1981) applied same approach to force the net flow direction to east in their previous modeling work. Lastly, a crucial justification may be observed in the setup in the recently developed Chesapeake Bay Model (Wang and Johnson, 2002). In their model, the C&D Canal was treated as a river boundary and a constant flow rate of 21.24 m^3/sec was assigned. The direction of flow was from the Chesapeake toward the Delaware Bay. The sensitivity simulation results on datum shift for the entire calibration period (577 days) are summarized in Table 4-4. The direction of the long-term net flow changes at a point between 5 and 10 centimeters datum shift. With 10 centimeter shift, the net flow amount for the entire calibration period was simulated to be 20.6 m^3/sec, which was almost exact amount of flow rate assigned in Chesapeake Bay Model.

Table 4-4: The direction and magnitude of the simulated, long-term net flow in C&D Canal with various amount of datum shift.

Scenario	Direction of net flow	Magnitude of the net flow (m^3/sec)	
Datum Up-shift amount cm		Calibration period (577 days)	Feb 2002 to Jan 2003 (365 days)
0	West	246	257
5	West	114	126
10	East	20.6	19.1
15	East	158	148
20	East	298	297

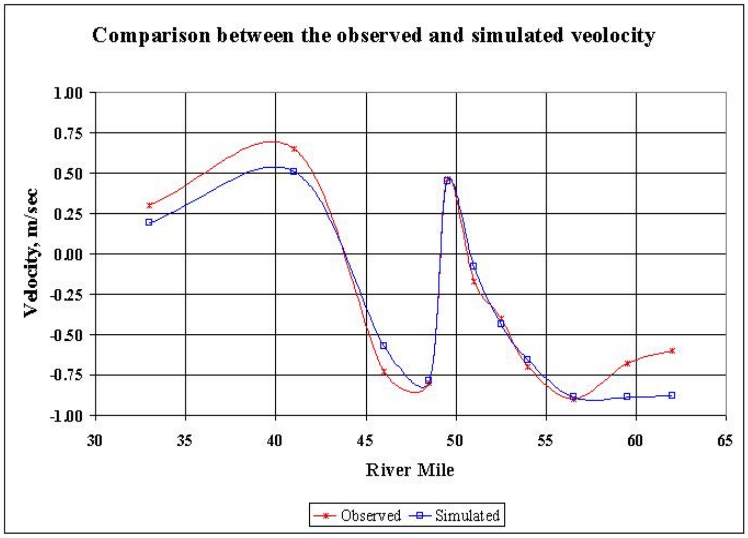
4.4 Calibration Results

The input file for DYNHYD5 hydrodynamic model for the calibration period is provided in Appendix A. Because of the file size, portions of the daily inflows and forcing tide input sections were shortened.

4.4.1 Comparisons with Current Velocity

ADCP results from eleven transects were selected to compare with the hydrodynamic model outputs. The current velocity profile data for those 11 transects were post-processed to obtain the average velocity and then the results were compared with the simulated current velocity. Review of the plots and results of regression

(a)



(b)

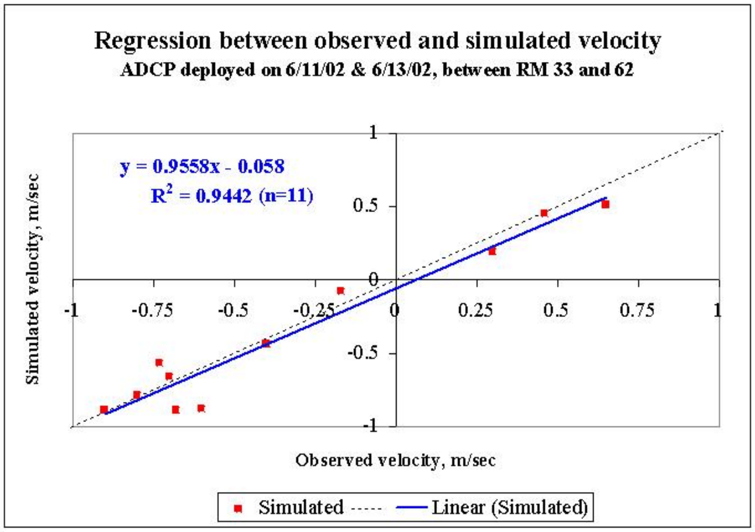


Figure 4-8: Comparison between the observed and the simulated current velocity: (a) Spatial plot; (b) Linear regression results.

analyses confirms that the model reproduces the current velocity relatively well both spatially and temporally (Figures 4-8 (a) and (b)).

4.4.2 Calibration Results of the Tidal Heights

The simulated tidal heights are compared with the observed tidal heights at six tide gaging stations. The observed data and the simulated tidal heights are presented in four types of plots per station. The four plots are: (a) temporal plot for the entire calibration period; (b) temporal plot for the last 3 weeks of the calibration period; (c) linear regression plot; (d) cumulative frequency distribution plot. Figures 4-9 a, b, c and d represent the comparison plots at the Reedy Point Station as an example. The tidal height comparison plots for the rest of the stations are presented in the Appendix C. The temporal comparison plots showed good agreement between the observed data and the simulated results for both the amplitudes and the phases of the tidal heights. The results of the linear regression between the observed data and the simulated tidal heights are summarized in Table 4-5. If simulated and observed data are equal, then the slope would be one and intercept would be zero. The slopes were ranged from 0.945 to 1.027 and the intercepts were ranged from -0.087 to 0.035. The square of the correlation coefficients (R^2) were varied from 0.930 to 0.994. The cumulative frequency distribution plots show a good agreement between the simulated and the observed tidal heights throughout the ranges of the tidal heights.

Table 4-5: The summary of the regression results between the observed data and the simulated tidal heights.

Station Name	**River Mile**	**Slope**	**Intercept**	**R^2**
Brandywine Shoal	8.0	0.973	0.005	0.994
Reedy Point	58.6	0.961	0.035	0.937
Philadelphia	99.4	1.027	-0.087	0.941
Tacony-Palmyra	107.8	1.026	0.012	0.934
Burlington	118.6	0.979	-0.075	0.942
Newbold	127.3	0.945	0.010	0.930

The calibrated DYNHYD5 hydrodynamic model successfully reproduced the tidal heights. The model generated the tidal heights reasonably well on both the amplitudes and the phases of the tidal heights. Along with the current velocity confirmation results and tidal height comparison results, the calibrated DYNHYD5 hydrodynamic model for the Delaware River Estuary correctly generates the advective movement of the water mass.

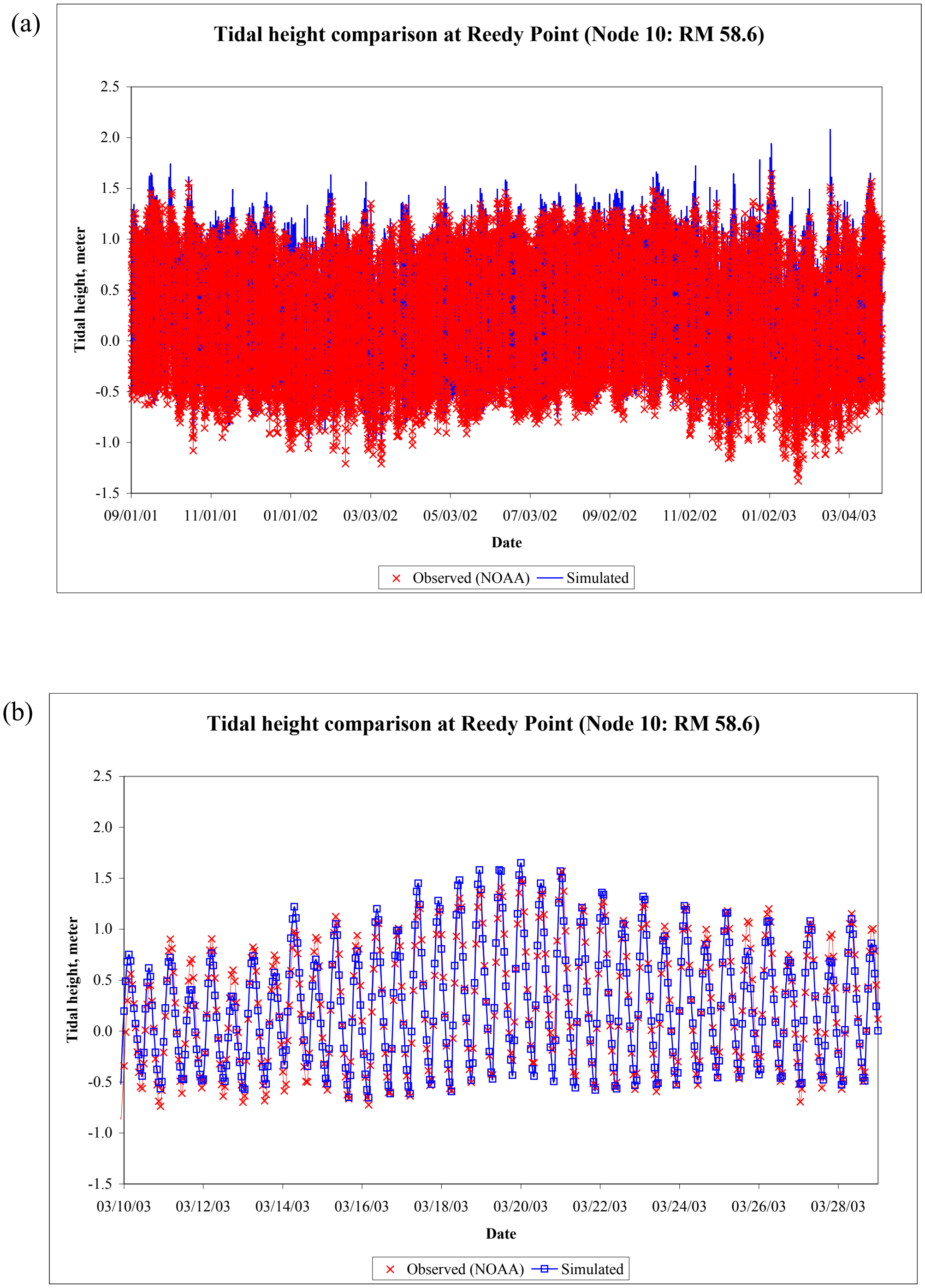


Figure 4-9: The observed and the simulated tidal heights at Reedy Point (River Mile 58.6): (a) for the entire calibration period; (b) from the period March 10, 2003 to March 31, 2003.

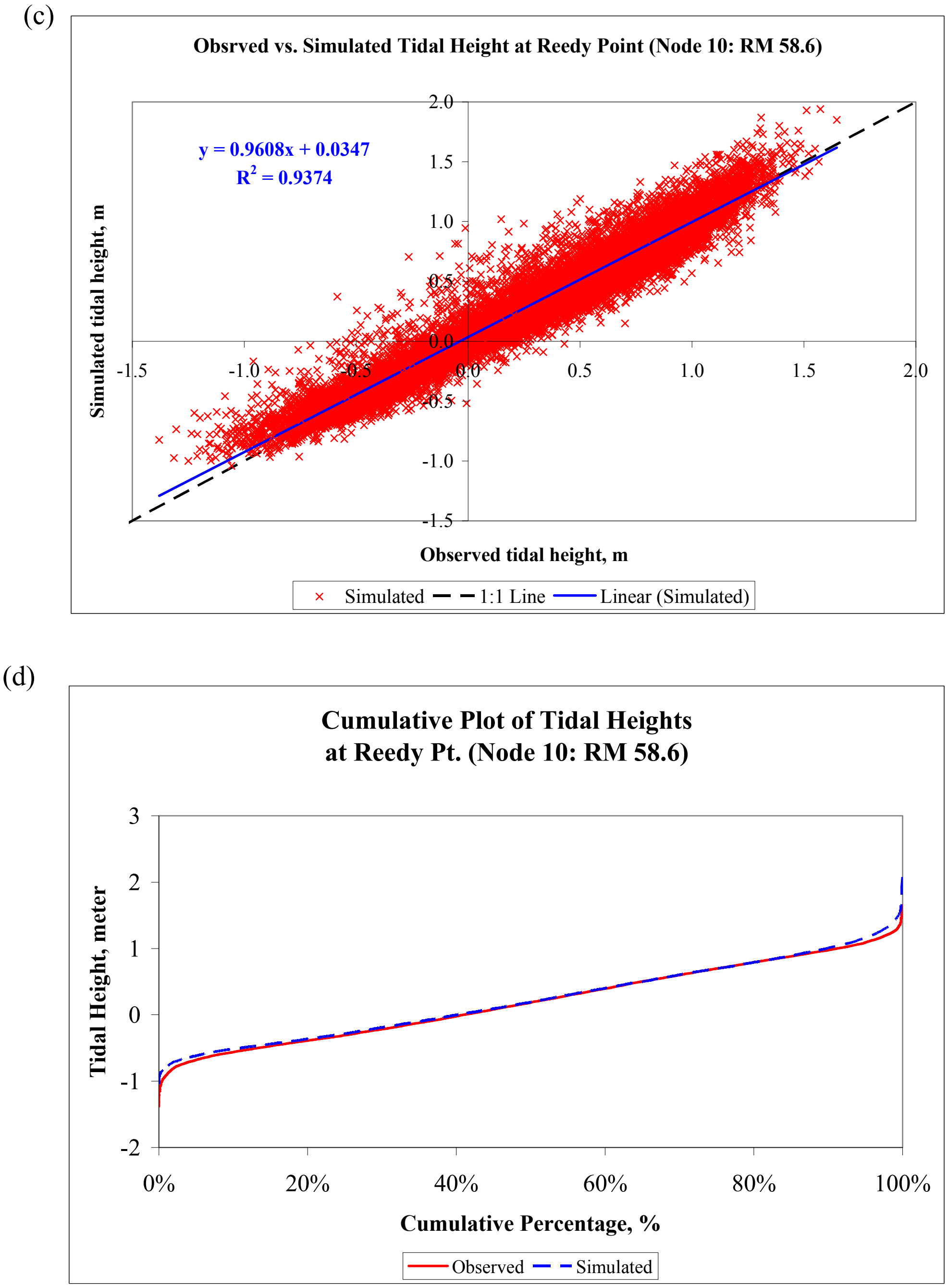


Figure 4-9: The observed and the simulated tidal heights at Reedy Point (River Mile 58.6): (c) Linear regression results (n=13,777); (d) cumulative frequency distribution curve.

5 CALIBRATION OF WATER QUALITY (CHLORIDE) MODEL

As a part of the hydrodynamic model calibration, the original TOXI5 model was linked with the outputs from the calibrated DYNHYD5 model. Fifteen (15) minutes of the computational time step was used for the water quality model. TOXI5 model was then calibrated against the chloride concentrations to determined the dispersive mixing within the Estuary. Chloride concentrations were traced throughout the model domain and compared with the observed data with various sets of assigned dispersion coefficients. The main objective in this calibration process was to determine a set of advection factor and dispersion coefficients for the water quality model.

5.1 Water Quality Model Segmentation

The segmentation of the water quality model was established through one to one mapping with the segmentation of the DYNHYD5 hydrodynamic model. Because the water quality model (TOXI5) required boundary flows from outside its network, one junction above each of the TOXI5 boundary segments was not mapped. Thus, the total number of segments for the water quality model became 87. The schematic diagram of the water quality model segmentation is depicted in Figure 5.1.

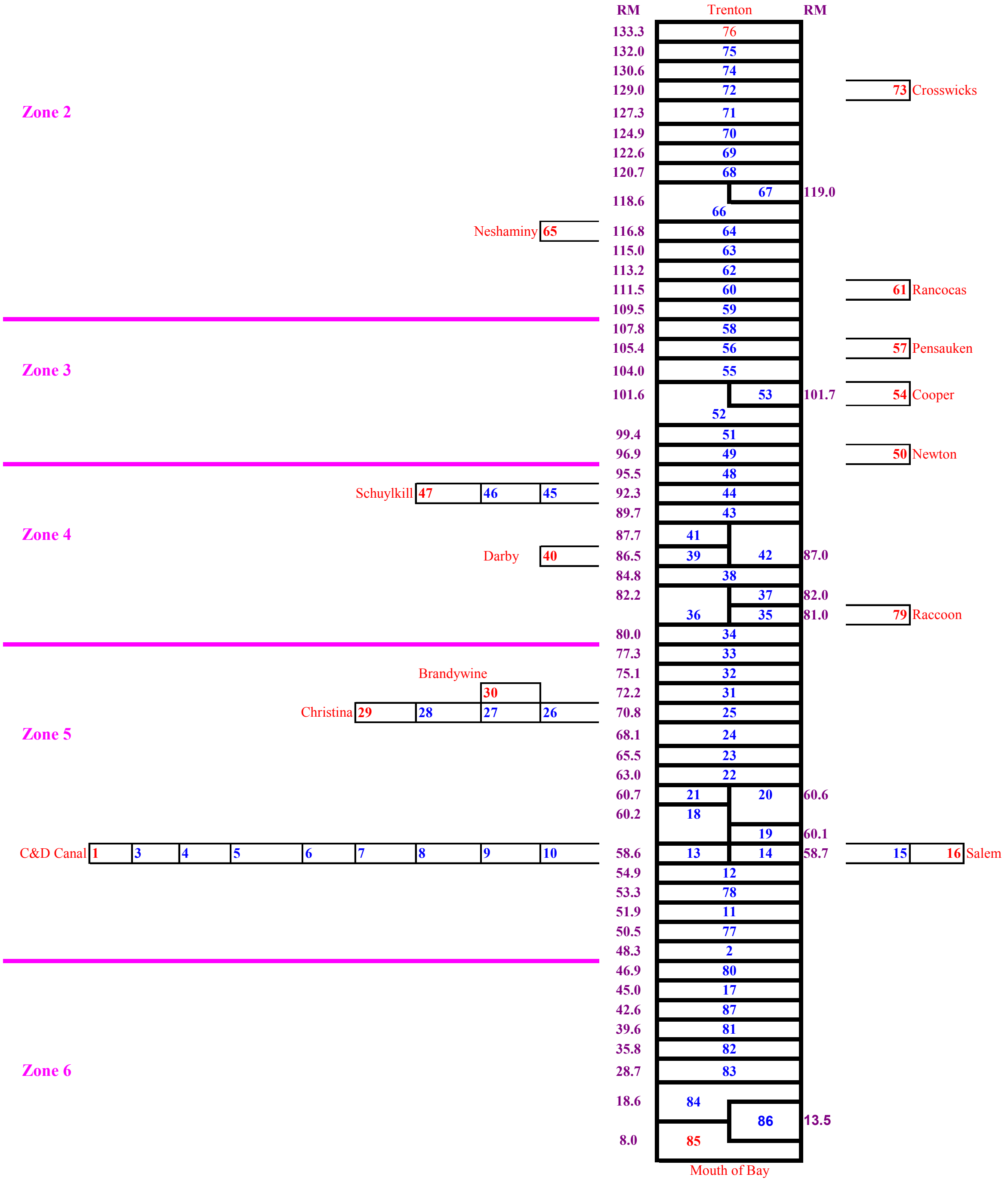


Figure 5-1: Schematic diagram of the segmentation for the water quality model.

5.2 Data Compilation and Processes

One of the biggest merits in calibrating a hydrodynamic model in an estuarine system is the existence of the natural conservative chemical. Salt content is usually used as a part of the hydrodynamic model calibration process in an estuarine system. Because of our rolling calibration approach (i.e., longer time period), using the salt content as a calibration parameter seemed to be a logical choice rather than performing a dye study. The salt content can be expressed in a number of ways. The direct expression of the salt content, salinity, was usually in units of parts per thousand (ppt). The chloride concentration in milligrams per liter is another way of expressing the salt content. The chloride concentration is typically obtained by laboratory testing. On the other hand, the specific conductance (or conductivity) is another way to express salinity. The specific conductance is basically a measurement of the electrical transmisivity (in a unit of micro Siemens per centimeter), which can be affected by other minerals in ambient water. However, in highly saline water environment, the impact from other mineral content is much smaller than that from the chloride content. The limitation of using the specific conductance as a surrogate measurement for salinity is not clearly defined. All three types of available salt content data were compiled for the Delaware Estuary from late 90s to March 2003. The chloride concentration was chosen to be the form of salt content in this model calibration, thus all the compiled data were converted into chloride concentration before use.

5.2.1 DRBC (BoatRun) Monitoring Data

Boatrun data, which is the water quality monitoring program run by DRBC throughout the Estuary, were used in the chloride calibration. Water samples were collected at a depth of three feet below the water surface and were targeted for the slack tide conditions. Because of slack tide sampling, it could be assumed that the collected data represented the full range of chloride concentrations for the monitoring station. A total of twenty-two (22) stations were monitored and the sampling frequency was either 12 or 7 times per year, depending on the location of the station. The benefit of these data sets was that chloride concentration was actually measured in the laboratory. Therefore, any conversion process was not required. The observed chloride data sets were used as calibration targets and also used to assign the mainstem upstream and downstream boundary conditions.

5.2.2 USGS Continuous Monitoring Stations

Water temperature and specific conductance were measured using automatic monitors hourly at four locations along the Estuary by USGS. Those four stations are: (1) Reedy Is. Station (RM 54); (2) Chester Station (RM 82); (3) Fort Mifflin Station (RM 92); and (4) Ben Franklin Station (RM 100). No data were collected during the winter season with exception of the Reedy Island Station. Hourly specific conductance and water temperature data were downloaded from the USGS Automated Data Processing System (ADAPS). The hourly observed specific conductance were then converted into chloride concentration for use with the hydrodynamic model calibration.

5.2.3 Other Sources of Data

1. Chloride data collected in Schuylkill River by Academy of the Natural Science: Measured chloride data for the Schuylkill River were available for the time period of 1999 and 2000. These data sets were used to assign the boundary conditions at the Schuylkill River.

2. The chloride concentration data within the C&D Canal were provided by DNREC (Richard Greene, DNREC, personal communication), and these data sets were used in assigning the C&D Canal boundary.

5.2.4 Data Process

DRBC's (BoatRun) chloride concentration data were directly compared with the model outputs without any data manipulation. However, the continuous monitored data collected by USGS required conversions. Using time series specific conductivity and water temperature data, the salinity was calculated using a relationship provided by DNREC (Greene, 1998). This specific conductance to salinity relationship was claimed to be valid over a wide range of the salinity (0 to 40 ppt). The calculated salinity values were then converted into chloride concentration by applying the simple relationship (APHA, 1995).

$$\text{Chloride concentration (mg/L)} = \text{Salinity (ppt)} \times 1000 / 1.80655$$

These converted time series chloride data at four USGS stations were then compared with the observed BoatRun chloride concentration data to validate the conversion relationship. The comparison results are provided in the Figures 5-2 through 5-5. Note that the y-axis scales are different in all four figures. The derived and observed chloride concentrations show a good agreement for the data collected at the Reedy Island station. Because the locations did not coincide between the DRBC and the USGS stations, the observed data from two DRBC monitoring stations were used to bound the derived data for both Chester (Figure 5-3) and Fort Mifflin (Figure 5-4) USGS stations. During the high flow period (March to June 2002), both the observed and derived chloride concentrations were below 200 mg/L except at the Reedy Island station. The conversion relationship between chloride concentration and salinity appeared to breakdown where the chloride concentrations are less than 200 mg/L. The derived chloride concentrations were systematically higher than the concentrations observed by DRBC monitoring program (Figures 5-3, 5-4 and 5-5). For this reason, a caution is needed in interpreting the model performance when the converted chloride data are used to compare with the model outputs. Both the derived and observed chloride concentrations were below 200 mg/L at all time for the Ben Franklin Bridge Station. Figure 5-5 shows a clear discrepancy between the derived and the observed chloride concentrations collected at Ben Franklin Bridge station. With this observation, the derived chloride concentration data at the Ben Franklin Bridge station were not used in this model calibration.

Further development of a relationship is required between salinity and chloride concentration in low regime of chloride concentrations in order to utilize all the data collected at the four USGS stations in the Delaware Estuary.

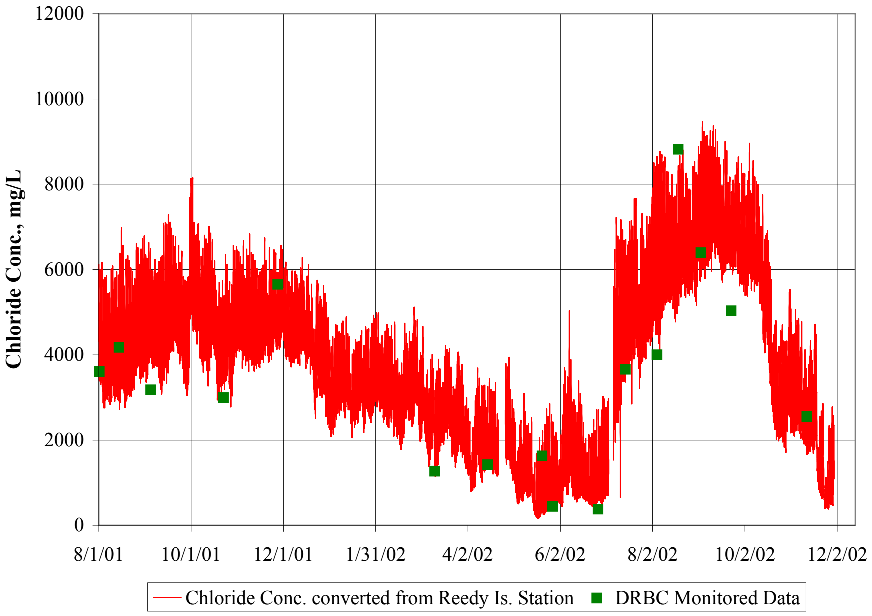


Figure 5-2: Temporal comparison of chloride concentrations derived from the USGS monitored specific conductance data and the monitored chloride data at the Reedy Island station.

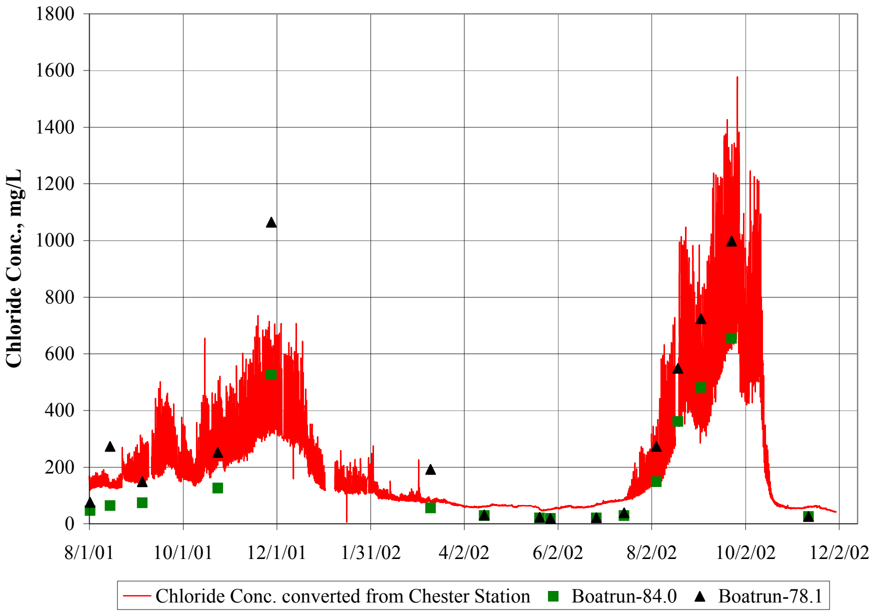


Figure 5-3: Temporal comparison of chloride concentrations derived from the USGS monitored specific conductance data and the monitored chloride data at the Chester station.

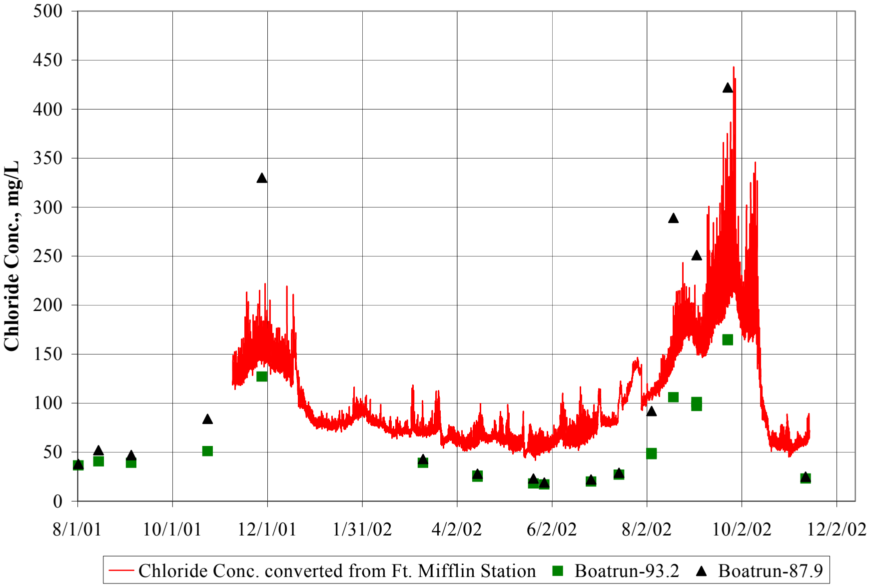


Figure 5-4: Temporal comparison of chloride concentrations derived from the USGS monitored specific conductance data and the monitored chloride data at the Fort Mifflin station.

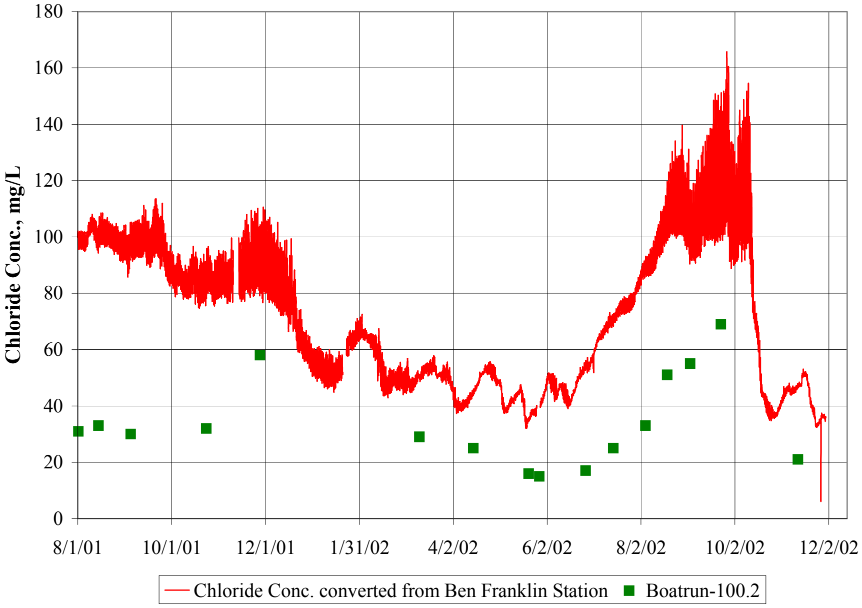


Figure 5-5: Temporal comparison of chloride concentrations derived from the USGS monitored specific conductance data and the monitored chloride data at the Ben Franklin station.

5.3 Calibration of the Chloride Water Quality Model

5.3.1 Assignment of the Boundary Conditions

Because of the lack of observed time series chloride concentration data, constant values were assigned at the boundaries throughout the calibration period. Detailed descriptions of determining the boundary conditions are listed below.

1. The segment for the downstream boundary of the main stem Delaware Estuary occupied from River Mile 3 to 12.6, which is a relatively large size. The observed chloride concentration temporally varied from 9,000 to 18,000 mg/L within the downstream boundary segment according to the DRBC's four years of monitoring data. With the lack of the time series data points at the boundary, the median value of 15,000 mg/L of chloride concentration was assigned.

2. The boundary condition for the C&D Canal was set at 550 mg/L after reviewing the available data and the previous modeling work.

3. The observed chloride data at the most upstream sampling station of the DRBC's monitoring program (BoatRun) were used to determined the upstream boundary condition. The data was tightly bounded with median chloride concentration of 21 mg/L. For the mainstem upstream boundary, the Delaware River at Trenton, the boundary chloride concentration was assigned with 21 mg/L.

4. The chloride concentration at Fairmount Dam, the upstream boundary for the Schuylkill River, varied from 20 to 59 mg/L with a median value of 34 mg/L. The upstream boundary chloride concentration for the Schuylkill River was assigned with 34 mg/L.

5. The rest of the minor tributaries were assigned with the chloride concentrations ranging from 7 to 24 mg/L after reviewing the previous modeling works (DRBC, 1998; HydroQual, Inc., 1998).

5.3.2 Determination of the Advection Factor (ADF) and Dispersion Coefficients

Two parameters were adjusted during the calibration process, the advection factor and longitudinal dispersion coefficients. The advection factor (0 to 0.5) is used by TOXI5 model to modify the finite difference approximation of the advection term in the mass balance differential equation. A non-zero ADF reduces the numerical dispersion produced by a particular velocity, channel length, and time step combination. However, assignment of non-zero ADF could cause instability of the model. ADF of 0.3 was assigned in the Version 1.0 model, while 0.37 was assigned for this version of the model to reduce the numerical dispersion. The increase of the ADF was necessary to reduce the numerical dispersion in the Bay (Zone 6) segments with large segment sizes. The computational time step was determined to be 15 minutes.

Along with the advection factor adjustment, sets of the dispersion coefficients were tested. The assigned dispersion coefficients for the TOXI5 model are graphically summarized in Figure 5-6. Because of the large segment sizes, zero dispersion coefficient was assigned for the segments in the lower portion of the Bay.

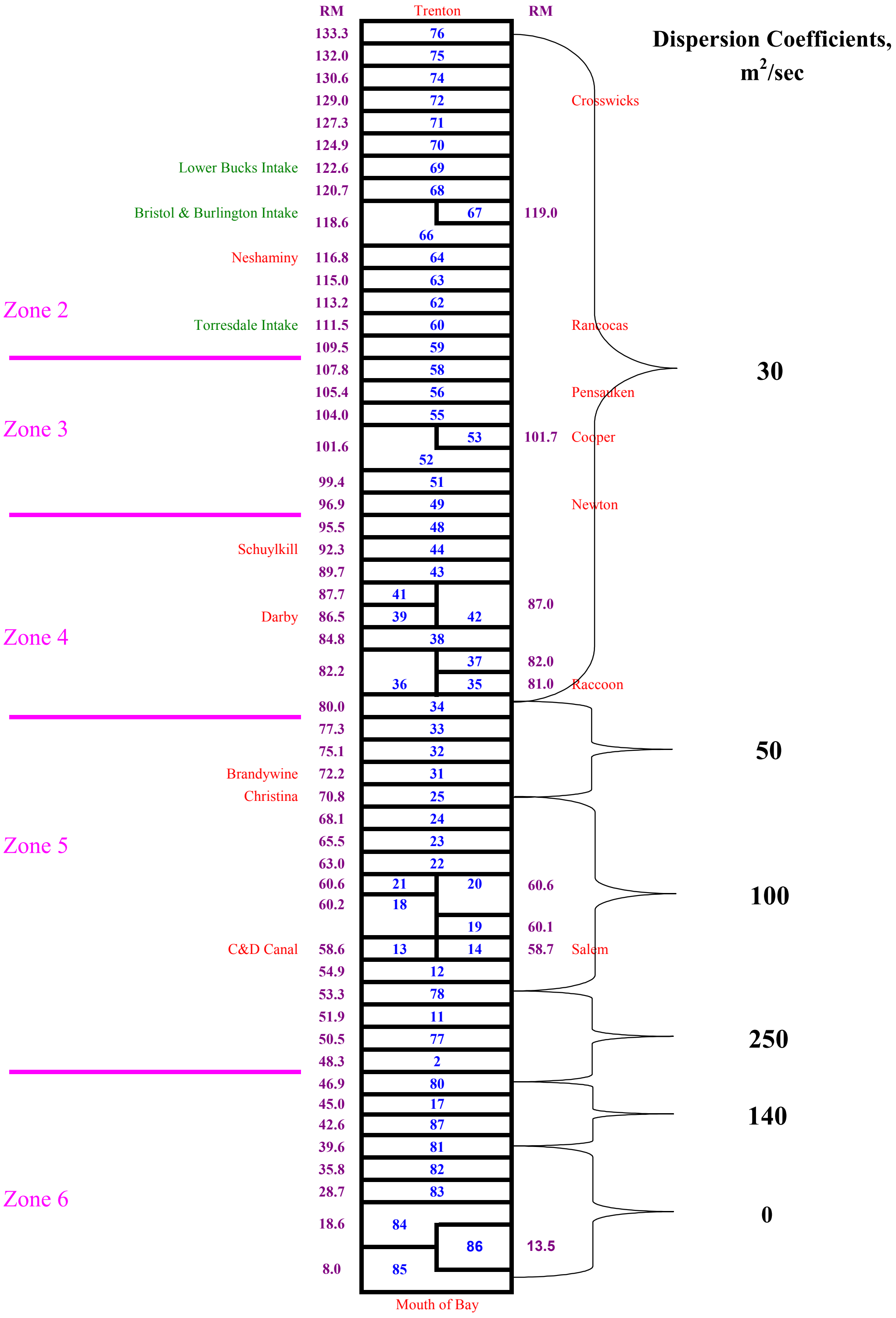


Figure 5-6: Assigned dispersion coefficients for the water quality model. The main stem of Delaware Estuary is only shown in the schematic.

5.4 Calibration Results of Chloride Concentrations

5.4.1 Comparison with the DRBC Data

The model input file for the chloride calibration is provided in Appendix B. The simulated chloride concentrations at 19 segments were compared with the observed DRBC Boatrun data . The temporal chloride comparisons are presented in the Appendix D. Figures D-3 and D-4 show that the model tends to over-predict the chloride concentrations in a lower portion of the Bay (River Miles between 20 and 36). This over-prediction might be associated with the coarse grid segmentation in the lower portion of the Bay. Numerical dispersion is believed to be the main cause for this over-prediction. However, the main objective in the development of Version 2.0 of the hydrodynamic model were (1) to generate an acceptable temporal chemical trend at the Zone 5 / Zone 6 interface; (2) to simulate proper advective and dispersive transport of chemical mass within the Estuary. The simulated chloride results at the Liston Point (River Mile 48.2; boundary between Zones 5 and 6) show a strong positive relationship with the observed chloride data (Figure D-5). Cumulative frequency distributions for the observed and the simulated chloride concentrations were calculated for the segments around the Zones 5 and 6 interface. The three segments used in calculations were node 17 (RM 45), node 2 (RM 48), and node 12 (RM 55) and their corresponding observed data from Smyrna R., Liston Pt., and Reedy Is. monitoring stations. The calculated results were then plotted in Figure 5-7. Figure 5-7 clearly shows that the model reproduces the observed chloride concentrations around the Zones 5 and 6 interface correctly. As shown in the Figures D-6 through D-19 from the Appendix D, there was a good agreement between the simulated chloride concentrations and the observed data at the individual

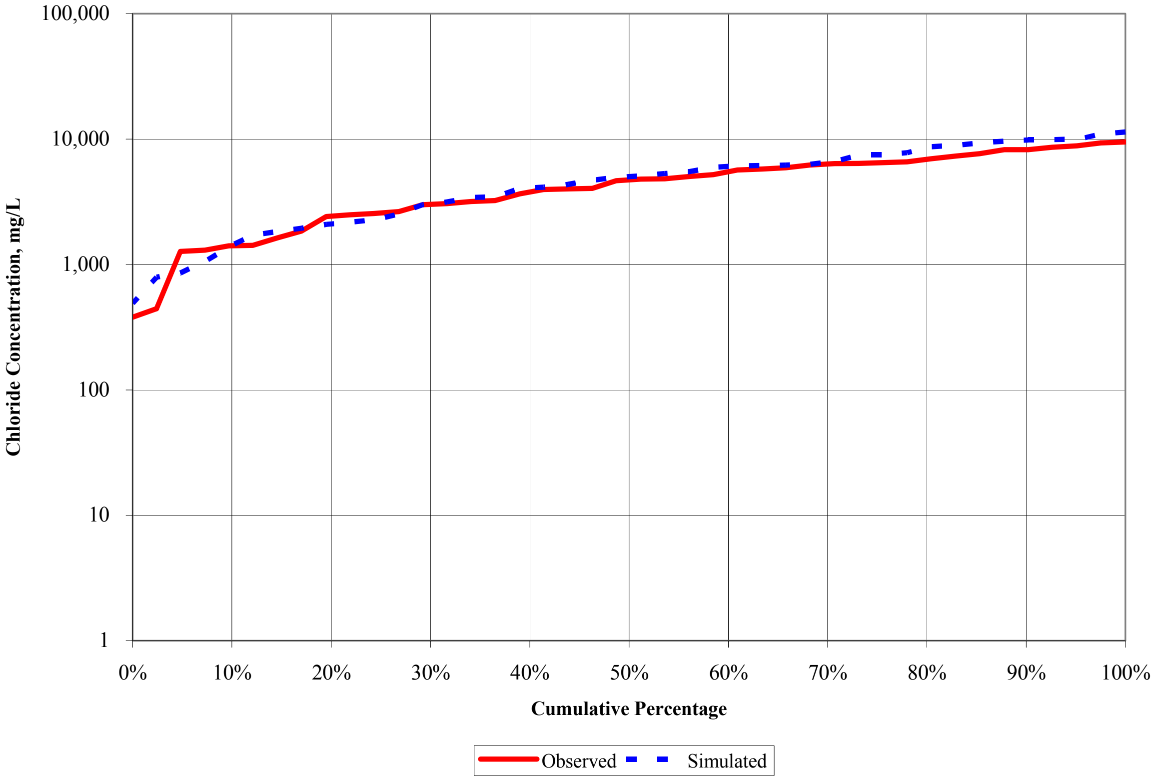


Figure 5-7: Cumulative frequency distributions of the observed and the simulated chloride concentrations: Data from three segments (Node 2, 12 and 17) were combined.

monitoring stations throughout the Estuary. The observed and the simulated chloride concentration data were re-organized to check the model performance on the spatial scale. The monitoring data and the minimum, maximum and median values of the model outputs for the main channel segments of the Estuary are compared in Figure 5-8. River Mile (RM) zero indicates the Mouth of the Delaware Bay at Lewes, DE., and RM 133 is the location of head of the tide at Trenton, NJ. The observed chloride data were well bounded by the minimum and maximum values of the model outputs, and the median values of model outputs generally split the observed data.

All of the comparison plots between the observed and the simulated chloride concentrations indicated that the model was able to reproduce the temporal and spatial trends, and the magnitude of the chloride concentrations within a reasonable range throughout the tidal portion of the Delaware River. The calibrated model therefore properly simulates the advective and dispersive movement of the chloride for the entire Estuary.

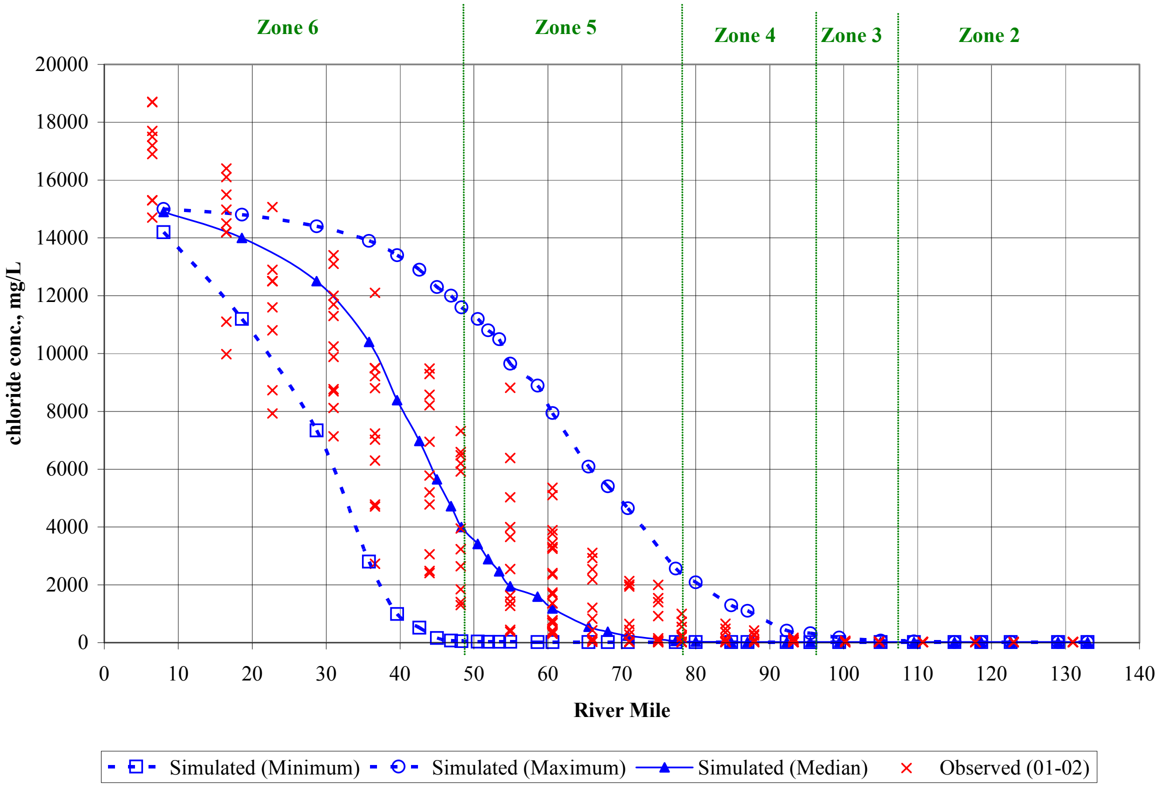


Figure 5-8: Spatial comparison between the observed data (DRBC_BoatRun) and the simulated chloride concentrations throughout the Estuary.

5.4.2 Comparison with USGS Data

Simulated chloride concentrations were compared with chloride concentrations which were derived from the hourly observed specific conductance data measured by USGS. Because the data obtained from USGS stations are long-term continuous (hourly interval) measurements, the comparison with model outputs provides the performance check on the phase of the chloride movement in the estuary. The derived chloride concentration data from Ben Franklin Bridge station were not used in this comparison because of the low chloride concentration and the conversion issues described in the section 5.2.4. For the same reason, only the graphical comparison was performed for two stations: Fort Mifflin (River Mile 91.8) and Chester (River Mile 82.4). The comparisons of the simulated and the derived chloride concentrations over time are presented on Figure 5-9 for Fort Mifflin station and Figure 5-10 for Chester Station. The model successfully reproduces the temporal trend of the chloride concentrations in both locations. Again, the model tends to over-predict above 200 mg/L of chloride concentration regime and under-predict when the chloride concentrations were below 200 mg/L. A further investigation is required on the conversion issue to assess the model output results in a lower regime of chloride concentrations. Still, the model generally matches the peaks, as shown on Figures 5-9(b) and 5-10(b).

The derived and the simulated chloride concentrations were presented in four types of comparisons for the Reedy Island station. The four plots were: (a) temporal plot for the entire calibration period; (b) temporal plot for the first week of September, 2002; (c) linear regression plot; (d) cumulative frequency distribution plot. Figures 5-11, 5-12, 5-13, and 5-14 represent the comparison plots at the Reedy Island station which is located at River Mile 54.2. Figures 5-11 and 5-12 are the comparison plots to check the performance of the model on temporal variations of chloride concentrations. As shown on Figure 5-11, the model predicted the general trend of the temporal variation properly. In addition, Figure 5-12 shows a reasonable prediction on the magnitude and the phase of the chloride variation. The linear regression result is shown on Figure 5-13 with slope of 1.036, intercept of -130 mg/L and R^2 of 0.87. Compared to the wide range of chloride concentrations (60 to 9,500 mg/L) during the calibration period, an intercept of -130 mg/L is a negligible bias. The cumulative frequency distribution plot shows a good agreement between the observed and the predicted results (Figure 5-14). The model slightly under-predicted in the low chloride range and over-predicted in high chloride concentration range. The median value for the USGS station at Reedy Is. was 3,000 mg/L while the model predicted 2,840 mg/L for the calibration period. This result yields -5.3 percent of relative error in the median chloride concentration prediction at the Reedy Is. station.

Overall, the calibrated model successfully reproduces the temporal trend of the chloride concentration at three USGS continuous monitoring stations.

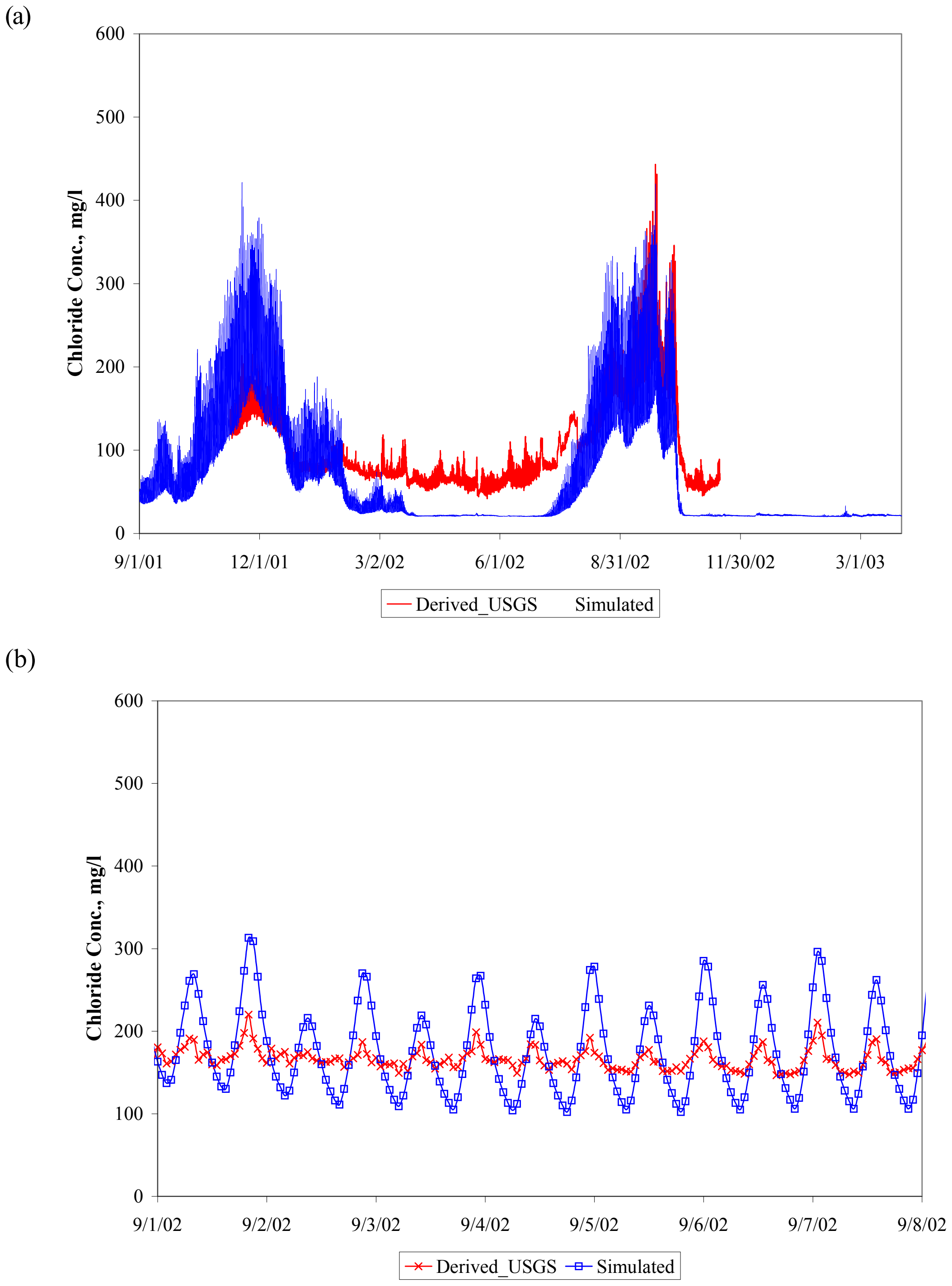


Figure 5-9: Temporal comparison between the observed data (derived from specific conductance from USGS Fort Mifflin Station) and the simulated chloride concentrations for (a) entire simulation period; (b) first week of September 2002.

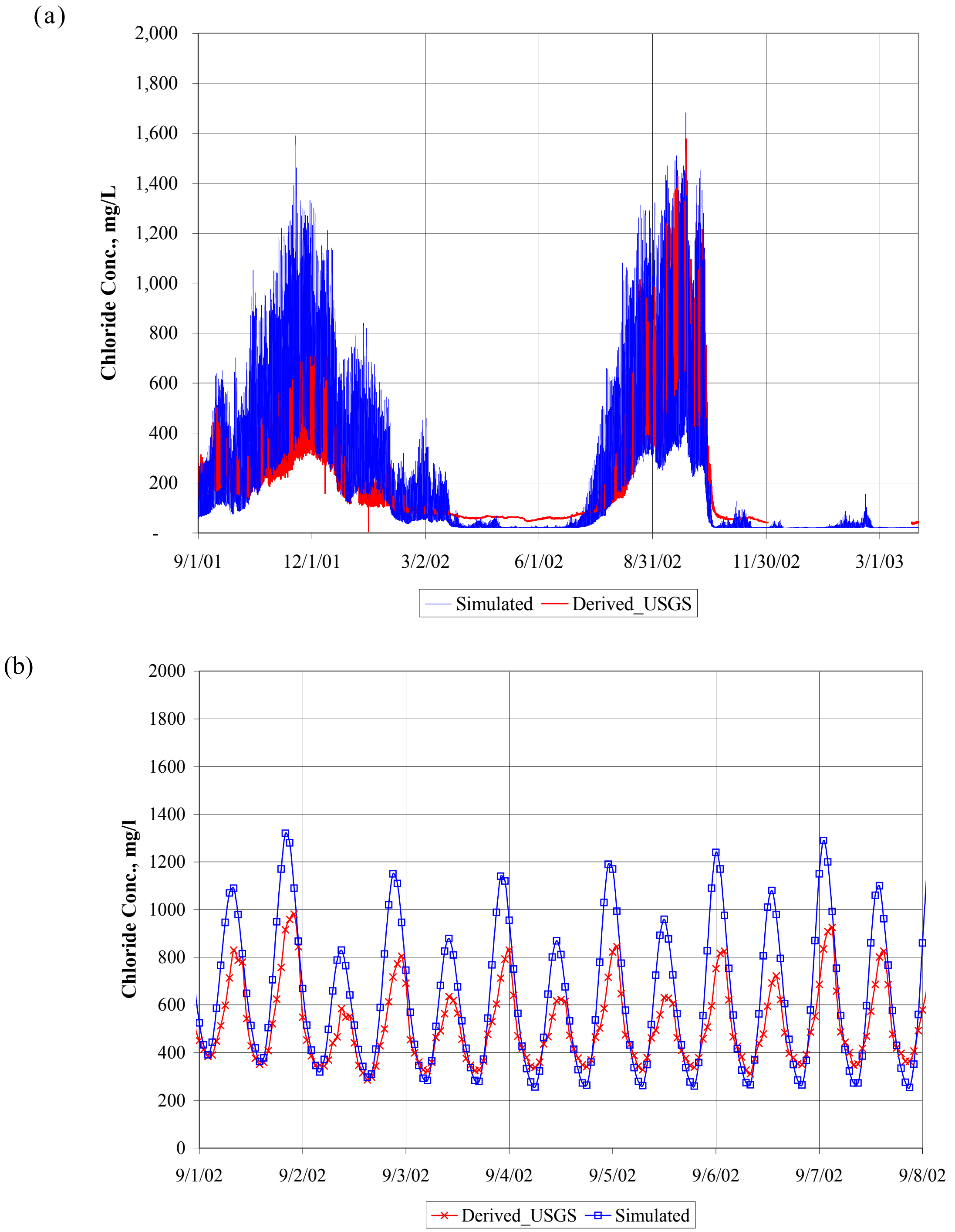


Figure 5-10: Temporal comparison between the observed data (derived from specific conductance from USGS Chester Station) and the simulated chloride concentrations for (a) entire simulation period; (b) first week of September 2002.

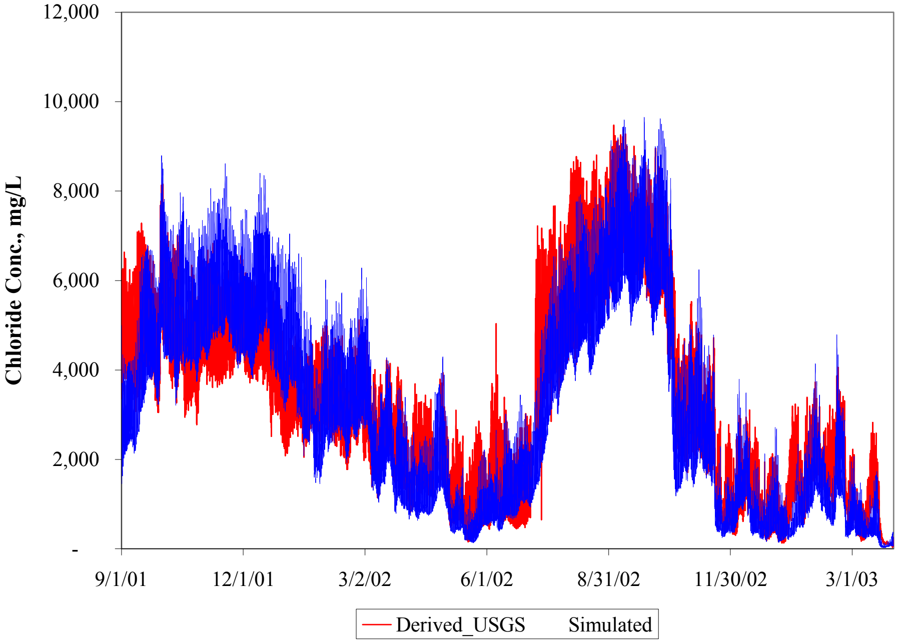


Figure 5-11: Temporal comparison between the observed data (derived from specific conductance from USGS Reedy Is. Station) and the simulated chloride concentrations for the calibration period.

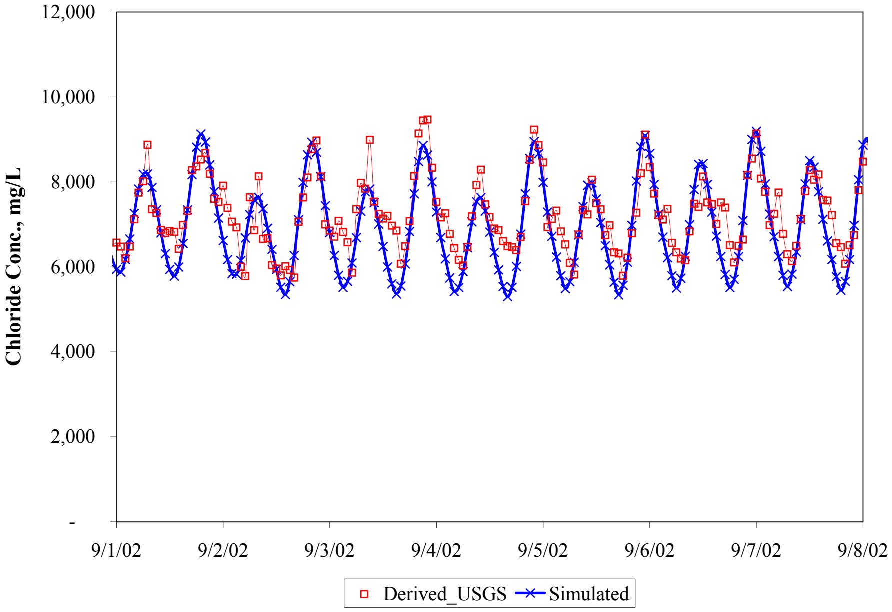


Figure 5-12: Temporal comparison between the observed data (derived from specific conductance from USGS Reedy Is. Station) and the simulated chloride concentrations for the first week of September, 2002.

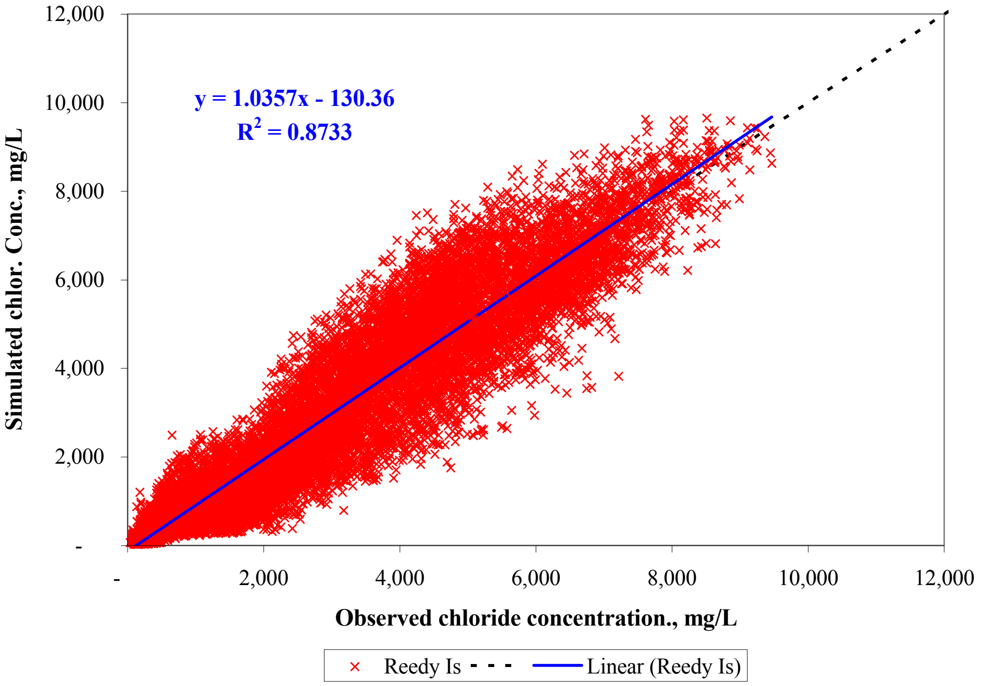


Figure 5-13: Linear regression results between derived and simulated chloride concentrations at Reedy Is. USGS station (n=13,660). Both data sets were hourly time interval throughout the calibration period.

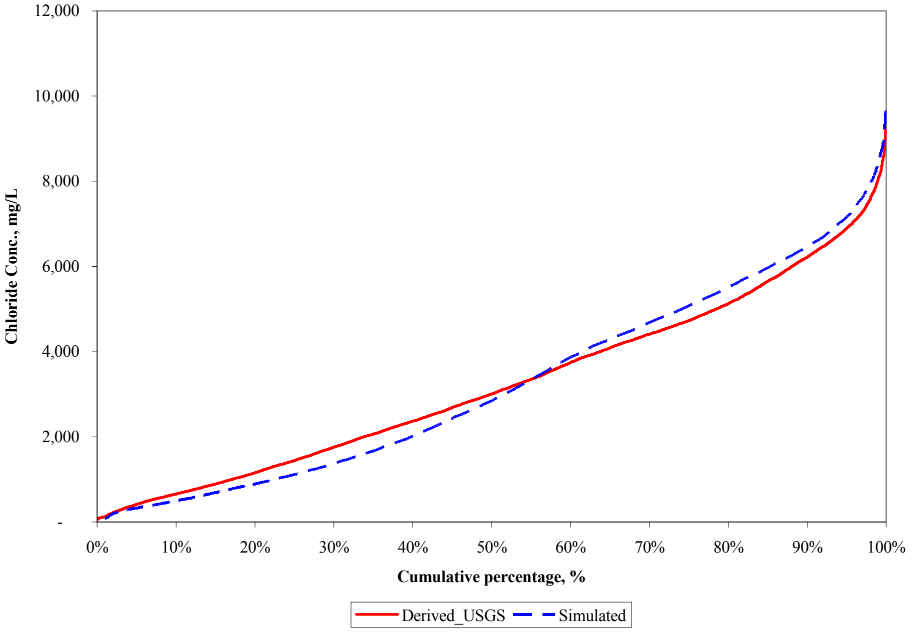


Figure 5-14: Cumulative frequency distributions of the observed and the simulated chloride concentrations for the Reedy Island station.

6. FUTURE REFINEMENTS

The performance of the Version 2.0 DYNHYD5 hydrodynamic model will be increased by incorporating following future works:

1. Refinement of the segmentation in Zone 6. Use of smaller segmentation in zone 6 to reduce the numerical dispersion and increase the resolution of the concentration gradients.

2. Use of the observed tidal heights at the C&D Canal boundary for forcing tides.

3. Measurements of the long-term flow in C&D Canal to identify the direction and magnitude of exchanges between Chesapeake and Delaware Estuary.

4. More frequent time series data collection of chloride concentrations at the major boundaries.

5. Development of the relationship between the chloride and salinity to cover the low regime of salinity information derived from specific conductance data.

6. Measurements of current velocities and incorporating into the calibration process.

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APPENDIX

A. Input File of the Calibrated DYNHYD5 Hydrodynamic Model (Version 2.0)

B. Input File of the Calibrated Water Quality (chloride) Model

C. Calibration Results of the DYNHYD5 Hydrodynamic Model for the Delaware River Estuary

D. Calibration Results of the Water Quality (chloride) Model for the Delaware River Estuary