HYDRODYAMIC MODELING AND INITIAL WATER QUALITY EVALUATIONS SUPPORTING THE FEDERAL FEASIBILITY STUDY AND NEPA DOCUMENTATION – PRETTY LAKE

Presented to:

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Executive Summary

Moffatt & Nichol (M&N) has been engaged by the City of Norfolk (City) to perform hydrodynamic modeling and water quality evaluations to support the Federal Coastal Storm Risk Management (CSRM) study. For this purpose, M&N performed hydrodynamic simulations in Pretty Lake and analyzed results to determine CSRM project impacts to salinities, flushing, and freshwater residence time (fresh water age), which can collectively be used to qualitatively assess potential impacts to water quality.

Potential Project impacts to circulation and water quality in Pretty Lake are evaluated with two sets of hydrodynamic simulation scenarios representing typical late-summer conditions and post-storm conditions.

Simulation of late-summer conditions are intended to provide insight of Project impacts on typical tidal flushing times, fresh water age and salinity during late-summer, when water quality is most critical, while simulation of post-storm conditions are intended to reflect potential Project impacts on recovery time to typical water levels, circulation and salinity when the gates of the flood control structure re-open following a storm. A summary of the findings from both analyses is presented below.

Water Quality Analysis for Typical Conditions

- Deviations in the tidally-averaged freshwater age and tidally-averaged salinity between *without Project* and *with Project* scenario are negligible under both existing and future conditions.
- Slightly increased flushing rates (decreasing flushing times) are observed from model results for the *with Project* scenarios, which can be explained by secondary circulation patterns and a mechanism for enhanced mixing introduced by the proposed flood control structure.
- Relative Project impacts are consistent between existing and future conditions simulations.
- Future rise in sea levels results in overall higher flushing rates (decreased flushing times) and tidally-averaged salinities than under present-day water level conditions.

Water Quality Analysis for Post-Storm Recovery Conditions

- Recovery time decreases from upstream to downstream regions in the Bay.
- Following gate re-opening, conservative tracer concentrations are higher for the *with Project* scenarios but decline to *without Project* concentrations within 30 days (or less in downstream regions).

- The time required for the conservative tracer to be almost completely flushed out of the bay is somewhat reduced for all stations for all future conditions scenarios.
- Salinity for *with Project* coincides with salinity for *without Project* after about 25 days (or less in downstream regions) under present-day sea level conditions and about 20 days or less under future sea level conditions.

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1. Introduction

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1.1. Background

The City of Norfolk (City) and the Norfolk District, U.S. Army Corps of Engineers (USACE), are partnering to conduct a Coastal Storm Risk Management (CSRM) Study to determine the Federal interest and feasibility of alternatives to mitigate coastal flood risk in the City. The CSRM Study is in the Feasibility Study (FS) phase in which alternatives are proposed and developed to conceptual/preliminary design level, benefit/cost analyses are conducted, and environmental studies are completed to comply with the National Environmental Policy Act (NEPA). The magnitude of the feasibility study will require an Environmental Impact Statement (EIS).

A component of the FS / EIS is the analysis of expected impacts of certain proposed alternatives on tidal circulation and water quality in three water bodies within the City. These water bodies are shown in Figure 1-1and include Broad Creek, the Lafayette River and Pretty Lake. The purpose of the modeling is to support determination of whether the proposed alternatives will have significant impacts on circulation and water quality, and if so, to what degree and what potential mitigation actions might be applied / required.

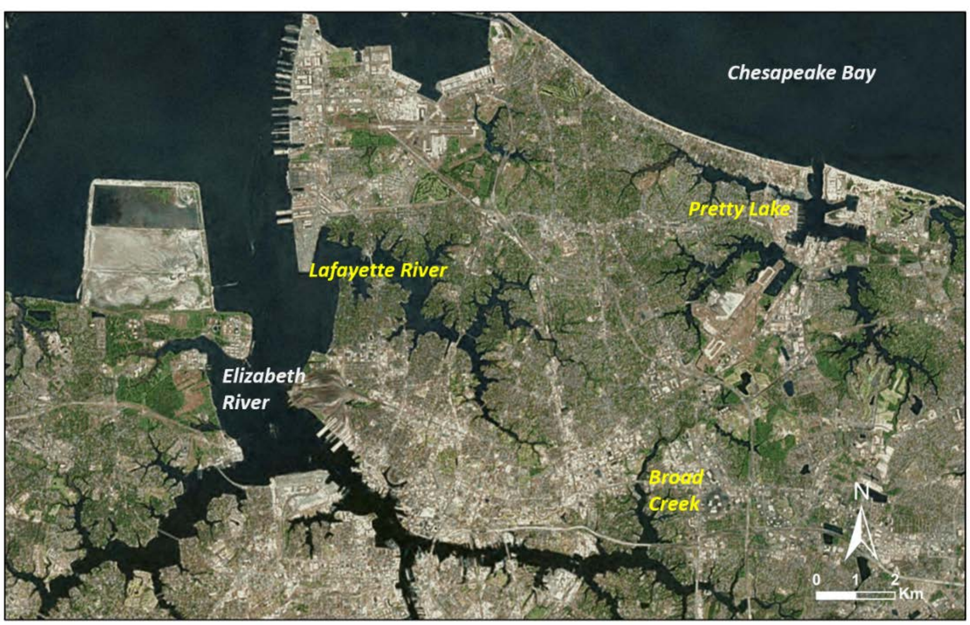


Figure 1-1 Locations of Water Bodies Addressed in the CRSM Study

1.2. Scope of Study

The purpose of this study is to develop and perform hydrodynamic modeling and analysis of circulation, flushing, and transport of constituents to support the formulation and evaluation of alternative(s) – as proposed by USACE – for mitigating coastal flooding impacts in Pretty Lake. To achieve this, the scope of work included the following:

1. **Model development**
   A three-dimensional hydrodynamic model of Pretty Lake was developed using bathymetry data from diverse publicly available sources as well as previously collected data sets. Details on model development can be found in Chapter 2
2. **Data collection and analysis**
   Historical water level, salinity, wind and freshwater flow data from the region was compiled and analyzed to develop model boundary conditions for both calibration and production simulations.
3. **Model calibration**
   Iterative simulations were conducted to achieve calibration of modeled water levels to measurements available at various locations of the model domain. Chapter 3 provides details on calibration simulations.
4. **Hydrodynamic simulations**
   Two hydrodynamic scenarios (and a number of sub-scenarios) representing typical and post-storm recovery conditions were simulated to evaluate potential project impacts on hydrodynamics in Pretty Lake. Simulations included transport of conservative and first order decay constituents for evaluation of water quality. A description of the simulations setup is provided in Chapter 4.
5. **Water quality analysis**
   A post-processing routine for the hydrodynamic simulations results was developed to determine flushing, fresh-water age and salinity in particular areas of interest in Pretty Lake. Evaluation of these metrics allowed for a qualitative assessment of potential project impacts on water quality in Pretty Lake. Detailed results of the derived water quality parameters are presented in Chapter 5 and Chapter 6. Chapter 7 summarizes the findings in this study and provides further study recommendations.

2. Model Development

2.1. Model Description

Delft3D is a numerical modeling software suite that performs simulations of flows, sediment transports, waves, morphological development, water quality and ecology in coastal, rivers and estuarine areas based on fundamental mechanisms and processes describing each phenomenon.

Delft3D-FlOW is the core hydrodynamic module in the model as it provides the unsteady flow and transport information that is used as a basis in other modules. Delft3D-FLOW simulates flow and transport phenomena resulting from tidal and meteorological forcing by solving the unsteady shallow water equations in two (depth averaged) or three dimensions.

The system of equations, derived from the three dimensional Navier-Stokes equations for incompressible free surface flow, consists of the horizontal equations of motion, the continuity equation, and the transport equations for conservative constituents. Numerically, the partial differential equations are solved by finite differences once they are discretized in space with the use of curvilinear or rectangular grid cells.

In the vertical direction, two types of vertical grid with distinctive layer thickness characteristics are supported in Delft3D:

- The σ-grid, with a vertical layer thickness varying with the water depth, and a constant number of active layers (denoted as the σ-model).
- The Z-grid, with a fixed vertical layer thickness and the number of active layers varying with the water depth. The layer thickness at the top is determined by the actual water level and at the bottom by the local topography. The model using this grid is referred to as the Z-model.

2.2. Model Domain

Figure 2-1 presents the computational domain for the Pretty Lake Delft3D model. The grid includes 17,923 elements and the horizontal resolution ranges from 6 m (20 ft.) inside Pretty Lake to 55m (180 ft.) in the Chesapeake Bay outside Little Creek Inlet. The σ-model was applied in the vertical direction, with six equally spaced layers. Grid details near the Little Creek Harbor entrance from the sea, and the proposed alignment of the CSRM flood control structure (Project), near the Shore Drive Bridge, are shown in Figure 2-2.

The jetties at Little Creek Inlet and the permanent wall segments of the flood control structure were implemented in the model grid as *thin dams*, i.e. infinitely thin features which prohibit flow exchange between two adjacent computational cells without reducing the total wet surface and volume of the model (See Section 4.3).

Horizontal coordinates for the model are in meters relative to UTM18 North coordinates, and vertical dimensions are in meters relative to the North American Vertical Datum of 1988 (NAVD88).

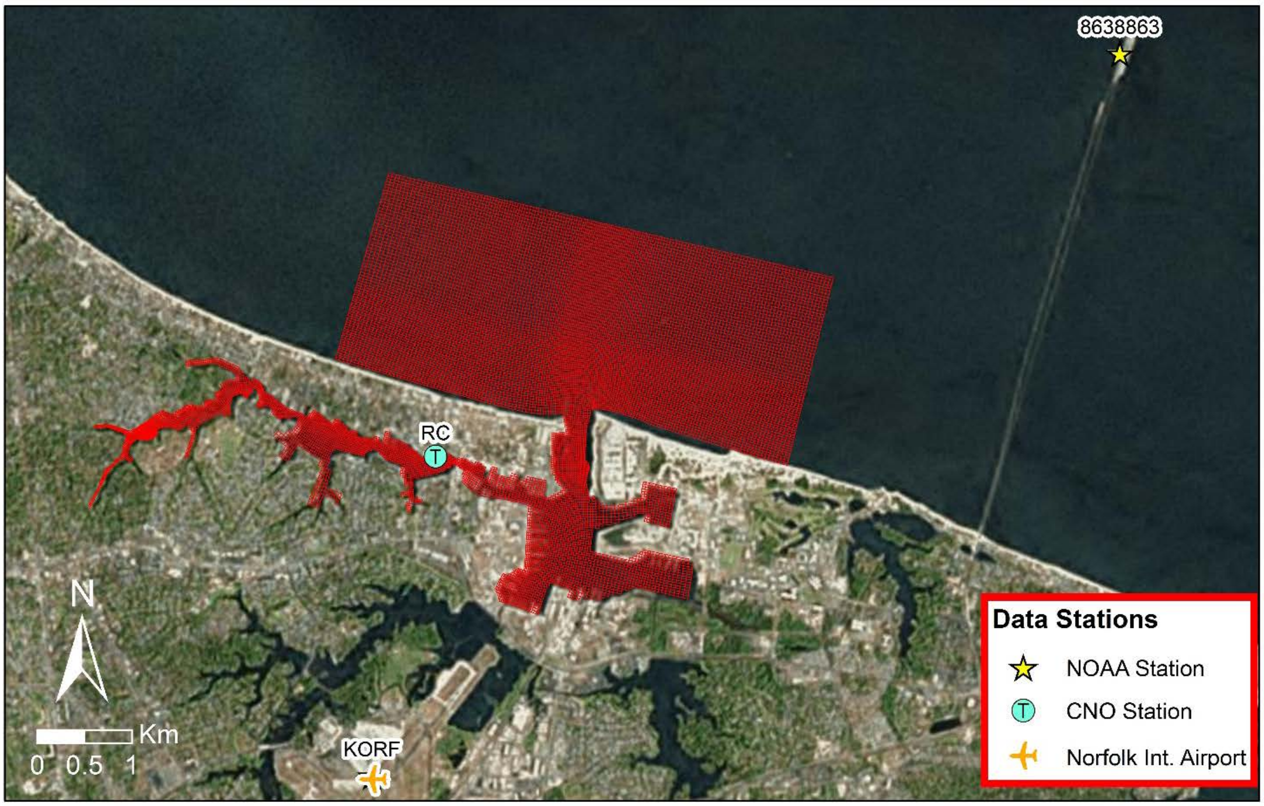


Figure 2-1 Computational Domain and Data Stations for the Pretty Lake Model

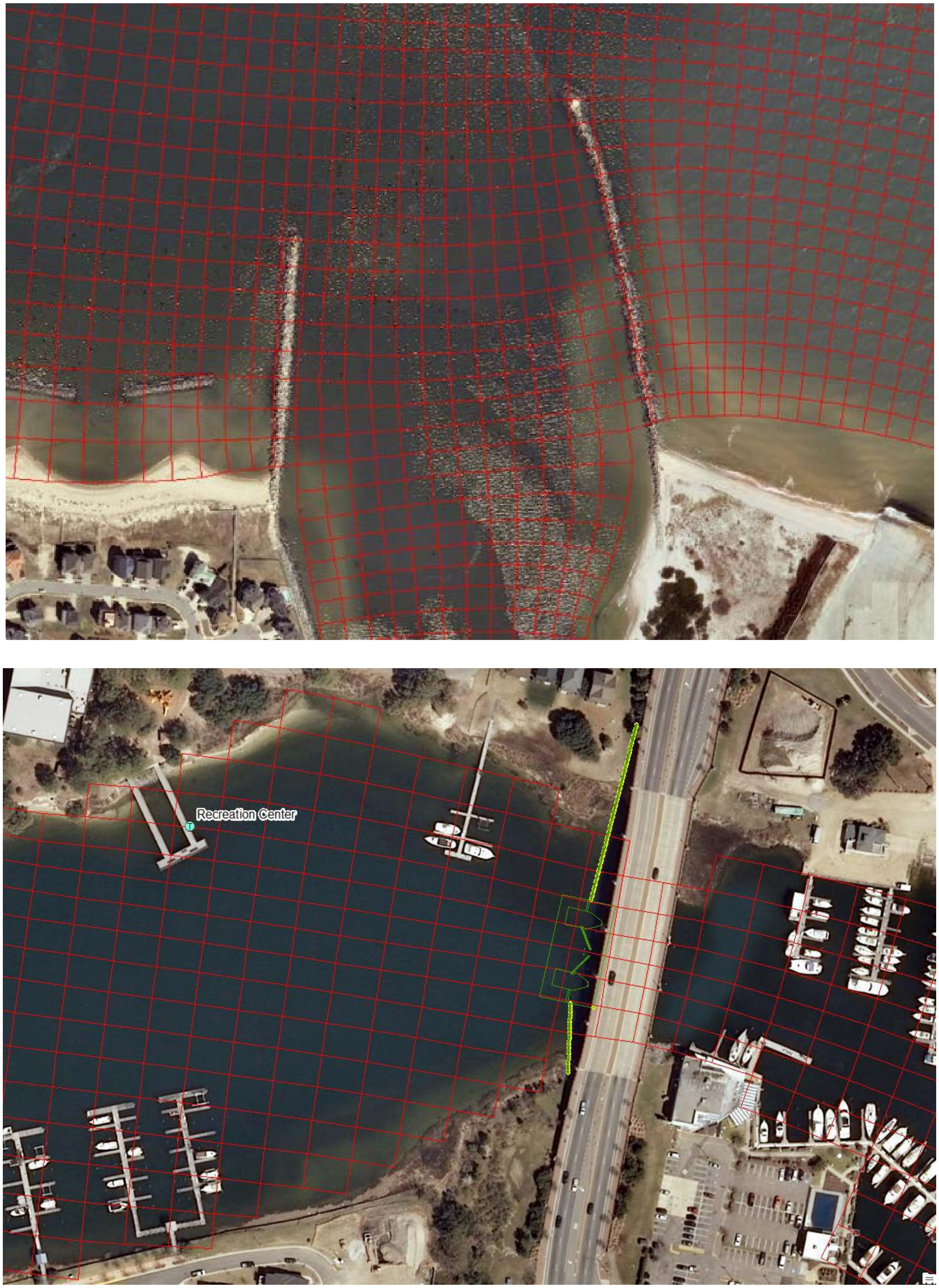


Figure 2-2 Computational Grid Details: Jetties Near Harbor Entrance (Top), and Proposed Structure Alignment (Bottom).

2.3. Model Bathymetry

Bathymetric data from different sources was compiled and processed to cover the entire computational domain with adequate resolution. All bathymetric data sets were adjusted to the NAVD88 vertical datum. Table 2-1provides a list of the data sets and sources included in the Pretty Lake model bathymetry. The model bathymetry is depicted in Figure 2-3.

Table 2-1 Bathymetry Data Sources for the Pretty Lake Model

Data Set	Source
Little River Survey	USACE, 2016
Pretty Lake Secondary Channel Survey	City of Norfolk, 2017
NOAA Navigation Charts 12254 & 12255	NOAA,2017
USGS CoNED Topobathymetric Chesapeake Bay DEM	NOAA,2016
Virginia Beach, Virginia Coastal Digital Elevation Model (DEM)	NOAA,2016
Norfolk, VA LiDAR	USGS, 2014

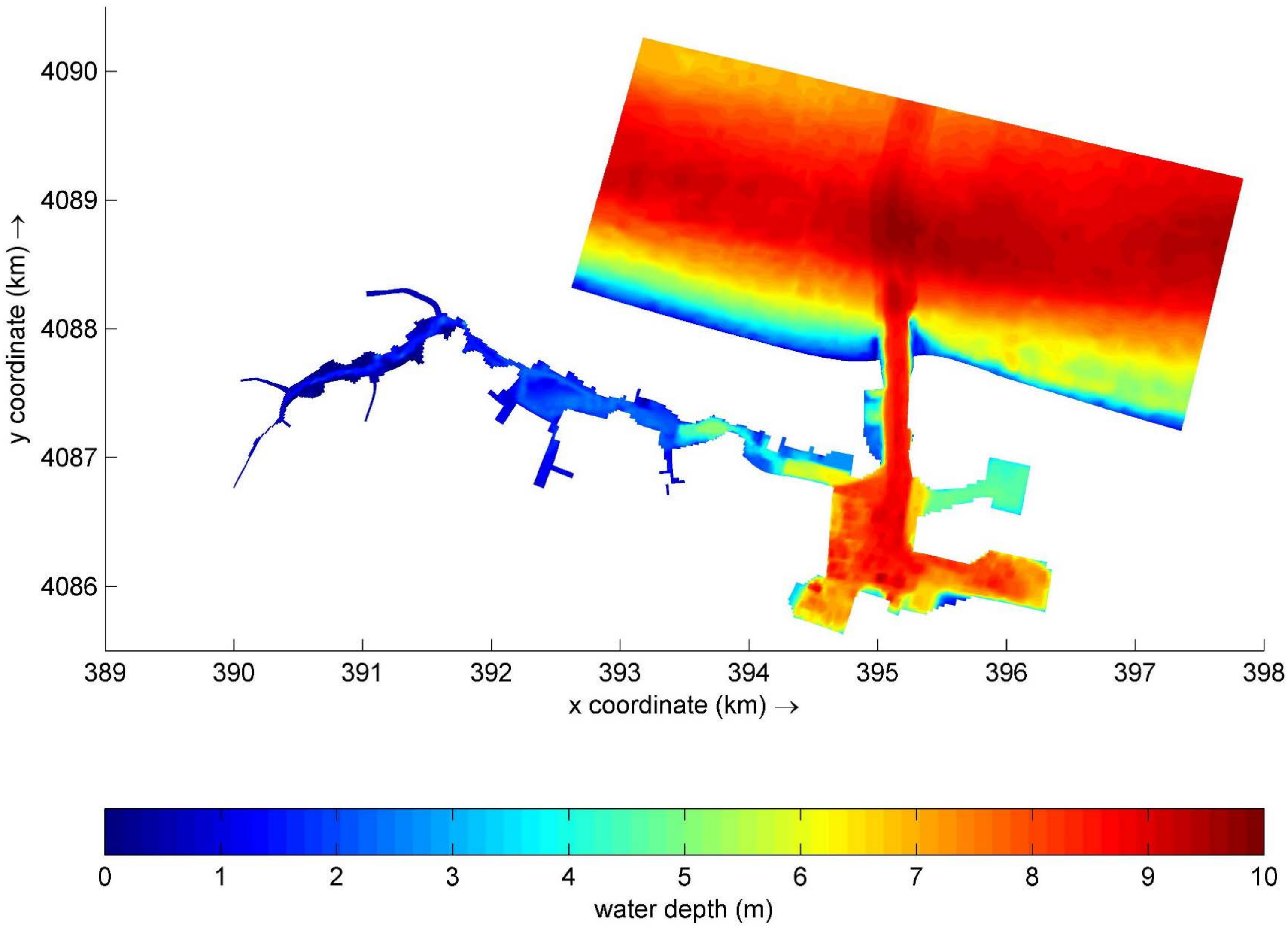


Figure 2-3 Model Bathymetry (m, NAVD88)

3. Model Calibration

3.1. Introduction

The Pretty Lake hydrodynamic model was calibrated for water levels only, as no salinity measurement are available within the Pretty Lake model domain. Hourly water level measurements inside the model domain are available from a City-operated tide gage at the East Ocean View Community Center (RC, see Figure 2-1).

Based on the availability of data, a ten-month simulation period for the calibration runs was set from June 18, 2011 to April 5, 2012. The calibration procedure consisted of a series of iterative runs where calibration parameters for water levels were adjusted systematically until the modeled data was found to be in good agreement with measured data.

3.2. Calibration Setup

A list of the data sets and sources that were input to the Pretty Lake model is given in Table 3-1, and explained in the following sections.

Table 3-1 Data Sets and Sources for Calibration Simulations

No.	Longitude	Latitude	Station Name	Measurement type	Source
1	-76.113°	36.960°	Chesapeake Bay Bridge Tunnel (8638863)	Water Level	NOAA-COOPS
2	-76.201°	36.895°	Norfolk International Airport (KORF)	Wind	Weather Underground
3	Various	Various	N/A (Model Offshore Boundary)	Salinity	VIMS
4	Various	Various	N/A	Fresh Water inflows	VADEQ via VIMS

3.2.1. Water Level Boundary

The hydrodynamic model was forced with measured water levels from NOAA-COOPS Chesapeake Bay Bridge Tunnel tide gage (86386963, see Figure 2-1) located about 6 km Northeast of the model offshore boundary.

The measured water levels are depicted in Figure 3-1. For the calibration period, the water level record includes non-astronomical components, resulting in positive or negative storm surge. The effects of hurricane Irene in 2011, are captured in the data set with a positive surge (i.e. measured water level above predicted water level) of up to 1.2 m on August 27, 2011.

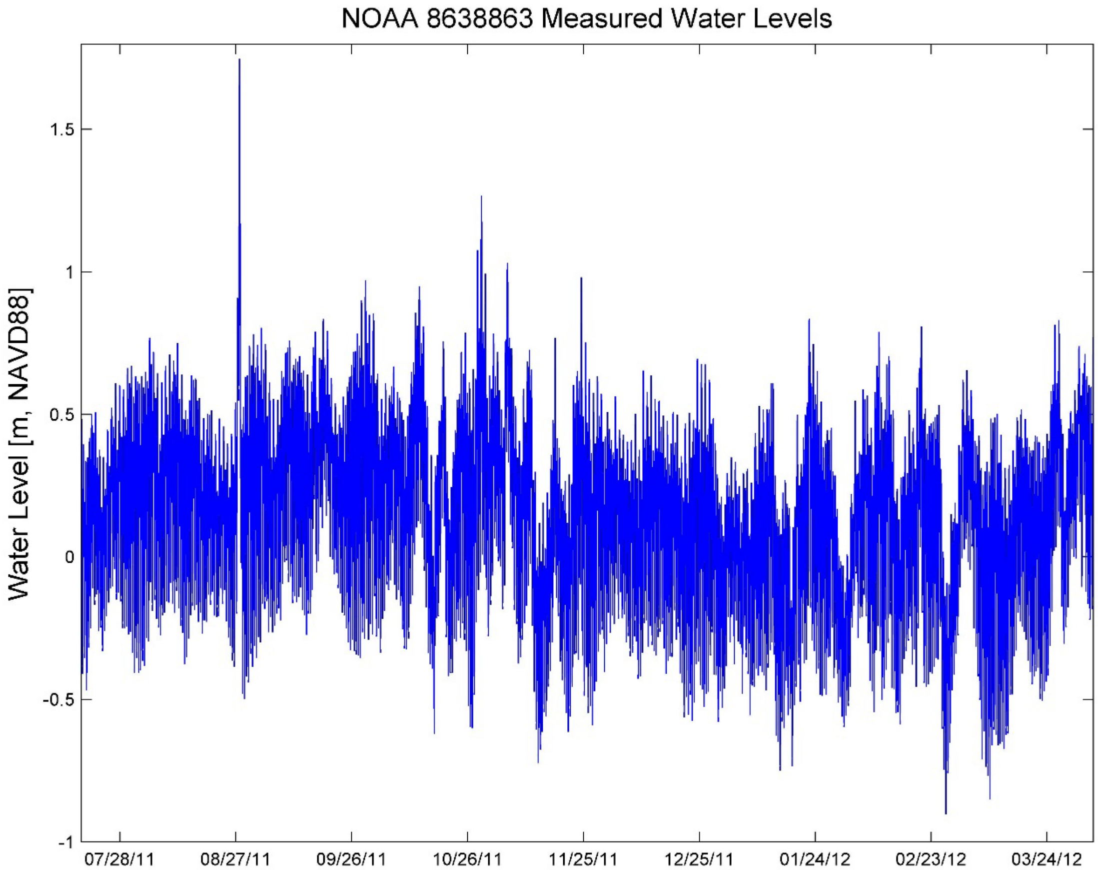


Figure 3-1 Water Level Boundary Condition for Model Calibration

3.2.2. Salinity

The salinity boundary condition for the model consisted of an hourly time series of simulated 3D salinity at the model offshore boundary. The simulated data was provided by the Virginia Institute of Marine Science (VIMS) from their regional HEM3D model (Du and Shen, 2016) of Chesapeake Bay. Figure 3-2 depicts the salinity boundary conditions (averaged along the model boundary) for the surface and bottom layers, clearly showing significant vertical salinity gradients during certain periods.

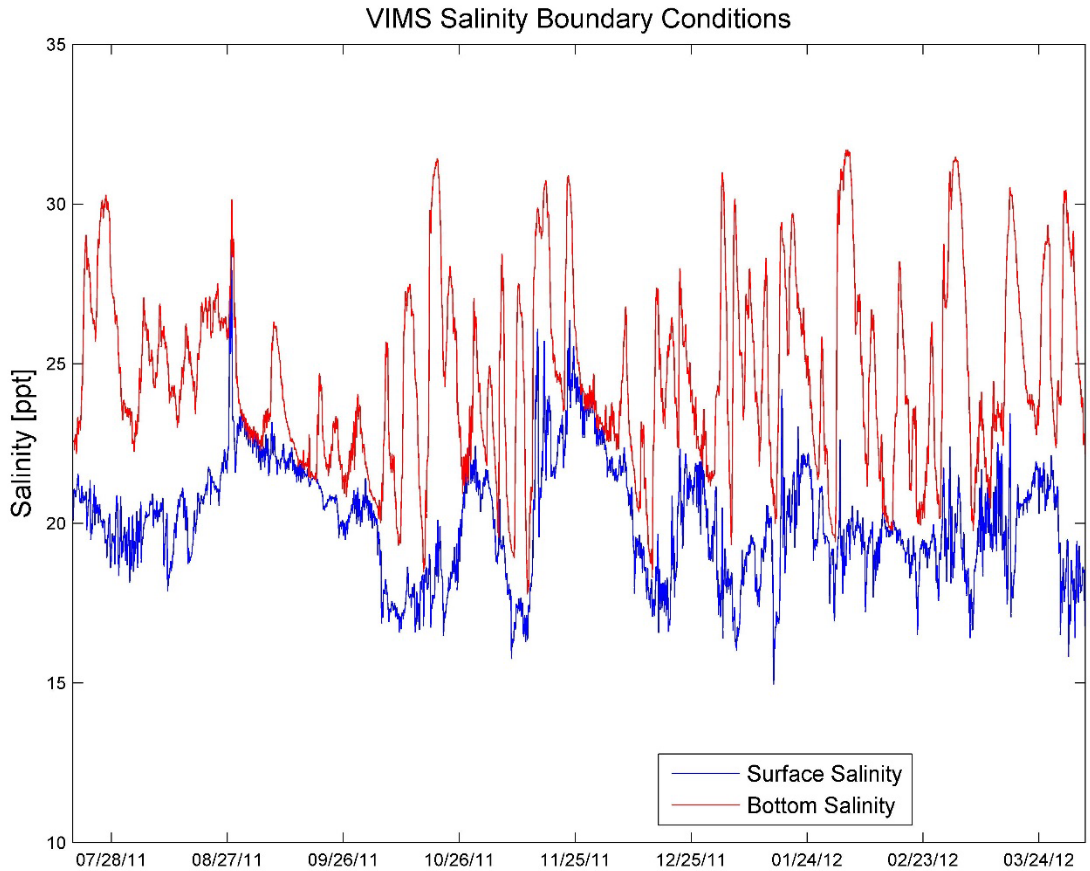


Figure 3-2 Salinity Boundary Condition for Model Calibration

3.2.3. Fresh Water Inflows

Daily freshwater inflows from rainfall-runoff were developed from selected output from the Virginia Department of Environmental Quality (VADEQ) statewide watershed model hindcast. From previous regional modeling work, VIMS was already in possession of daily runoff time series for all watersheds draining to the Elizabeth and James Rivers. The Pretty Lake watershed was not included in the VADEQ dataset obtained from VIMS, but the Broad Creek watershed was in that data set. Because of the similarities in soil types, percent impervious cover, and other watershed characteristics affecting runoff, discharge from the Broad Creek area watershed was scaled based on relative watershed areas and applied to the Pretty Lake model. M&N delineated 11 sub-watersheds within the Pretty Lake watershed, based on previous work modeling extreme storm runoff into Pretty Lake performed by M&N (Fugro, 2012), and located 11 corresponding sources within the Delft3D model domain where the runoff would be added to the surface layer of the model.

Figure 3-3 shows the sub-watersheds and their discharge locations into the model. The runoff was distributed to each sub-watershed based on the following process:

1. Divide Broad Creek watershed runoff by watershed area to get a time series of runoff per unit watershed area.

2. For each Pretty Lake sub-watershed, multiply the Broad Creek runoff per unit area by the sub-watershed area.

3. Route the computed runoff time series through the sub-watershed's corresponding discharge source.

All runoff inflow sources were assumed to be completely fresh with salinities of 0 ppt and were set to discharge into the surface vertical layer.

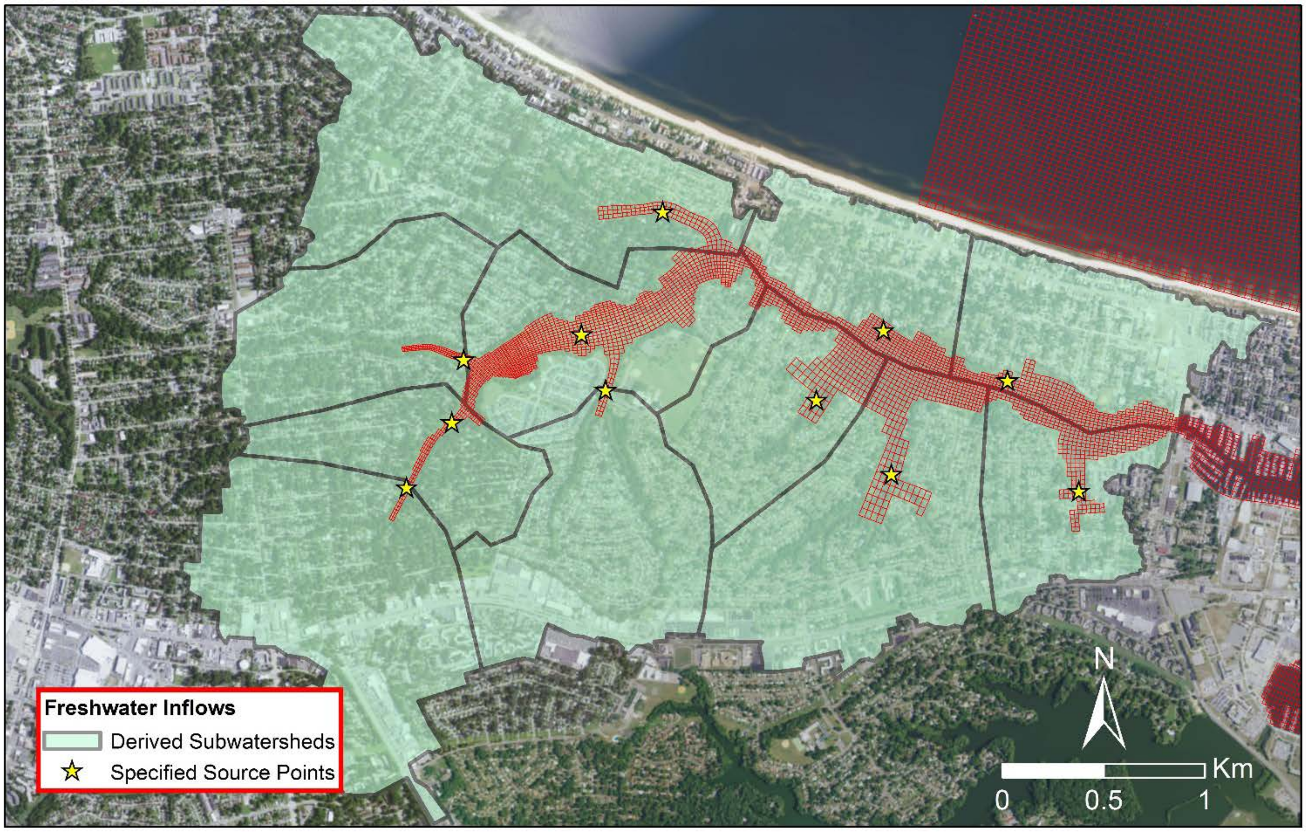


Figure 3-3 Sub-watersheds and Rainfall Runoff Discharge Locations for the Pretty Lake Model

3.2.4. Wind

An hourly time series of wind speed and wind direction from the Norfolk International Airport (KORF, see Figure 2-1) was input to the model as a spatially invariant wind field. Figure 3-4 depicts the wind data set.

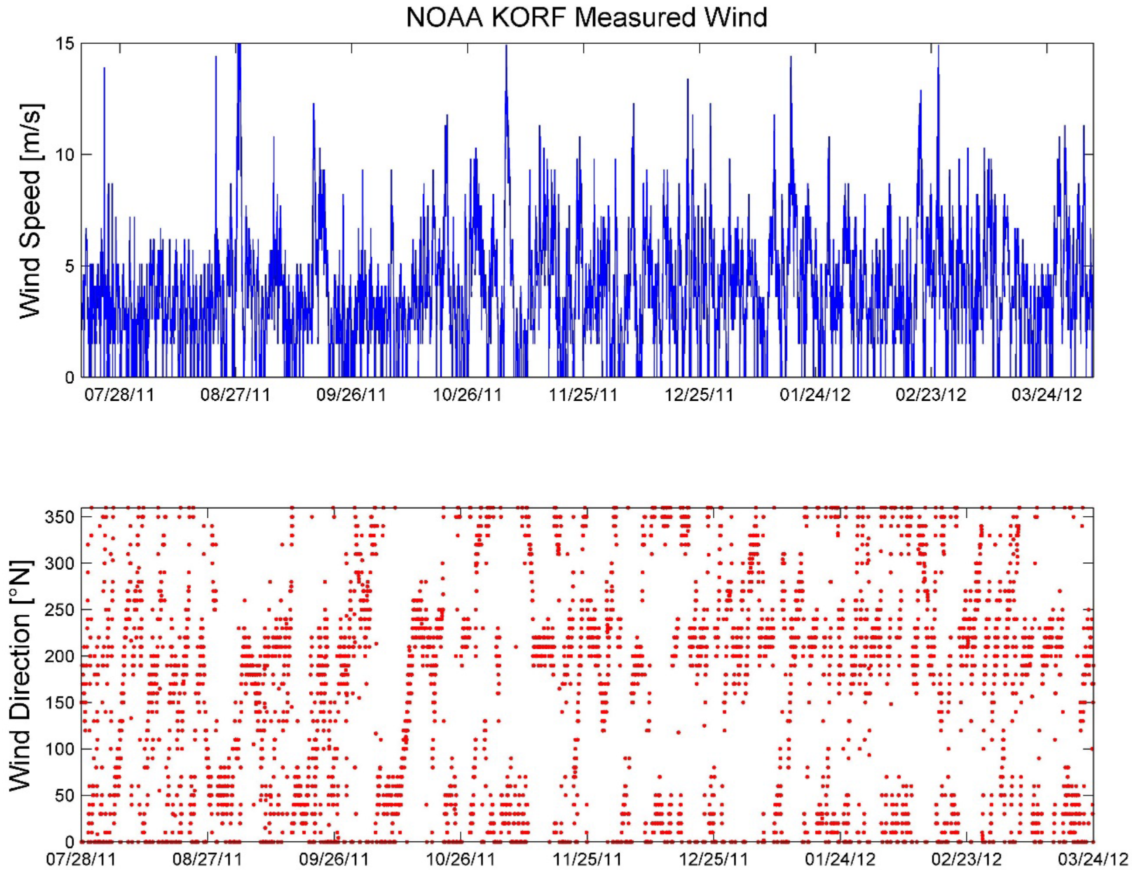


Figure 3-4 Wind Conditions for Model Calibration

3.3. Water Level Calibration

Water level calibration for the Pretty Lake model was achieved by adjusting the values for bed roughness coefficient. Bottom roughness was specified using the Chezy formulation, with a constant coefficient of 0.65 $m^{1/2}/s$. A comparison between measured and modeled water levels at the Recreation Center tide gage is depicted in Figure 3-5. The results showed excellent agreement between the measurements and the model predictions with the exception of several short periods when the model under-predicted the measured water levels.

In order to quantify the agreement between measured and modeled data, the following statistical parameters were determined:

- Root Mean Squared Error (RMSE,) $\varepsilon_{RMS} = \sqrt{\overline{(x-y)^2}}$
- Mean Absolute Error (MAE, m) $MAE = \overline{|x-y|}$
- Correlation Coefficient (R) $R = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2}\sqrt{\sum(y-\bar{y})^2}}$

- Model Prediction Capability Index (d) $d = 1 - \frac{\overline{(x-y)^2}}{\overline{\left(|x-\bar{x}| - |y-\bar{x}|\right)^2}}$

where, *x* and *y* represent the measured and modeled water level data; respectively. Results are provided in Table 3-2. A Correlation coefficient (R) of 0.98 and a prediction capability index of 0.99 confirm the accuracy of the modeled water levels.

Table 3-2 Statistical Parameters for Comparison between Measured and Modeled Water Levels

RMSE [m]	MAE [m]	R	d
0.06	0.03	0.98	0.99

A comparison between the measured and modeled amplitude and phase of tidal constituents (i.e. the astronomical components of the tide) at the Recreation Center gage was also made. Figure 3-6 shows the tidal constituent comparisons. The model results again show excellent agreement with the measured data, over-predicting the major tidal constituent M2 by less than 5%.

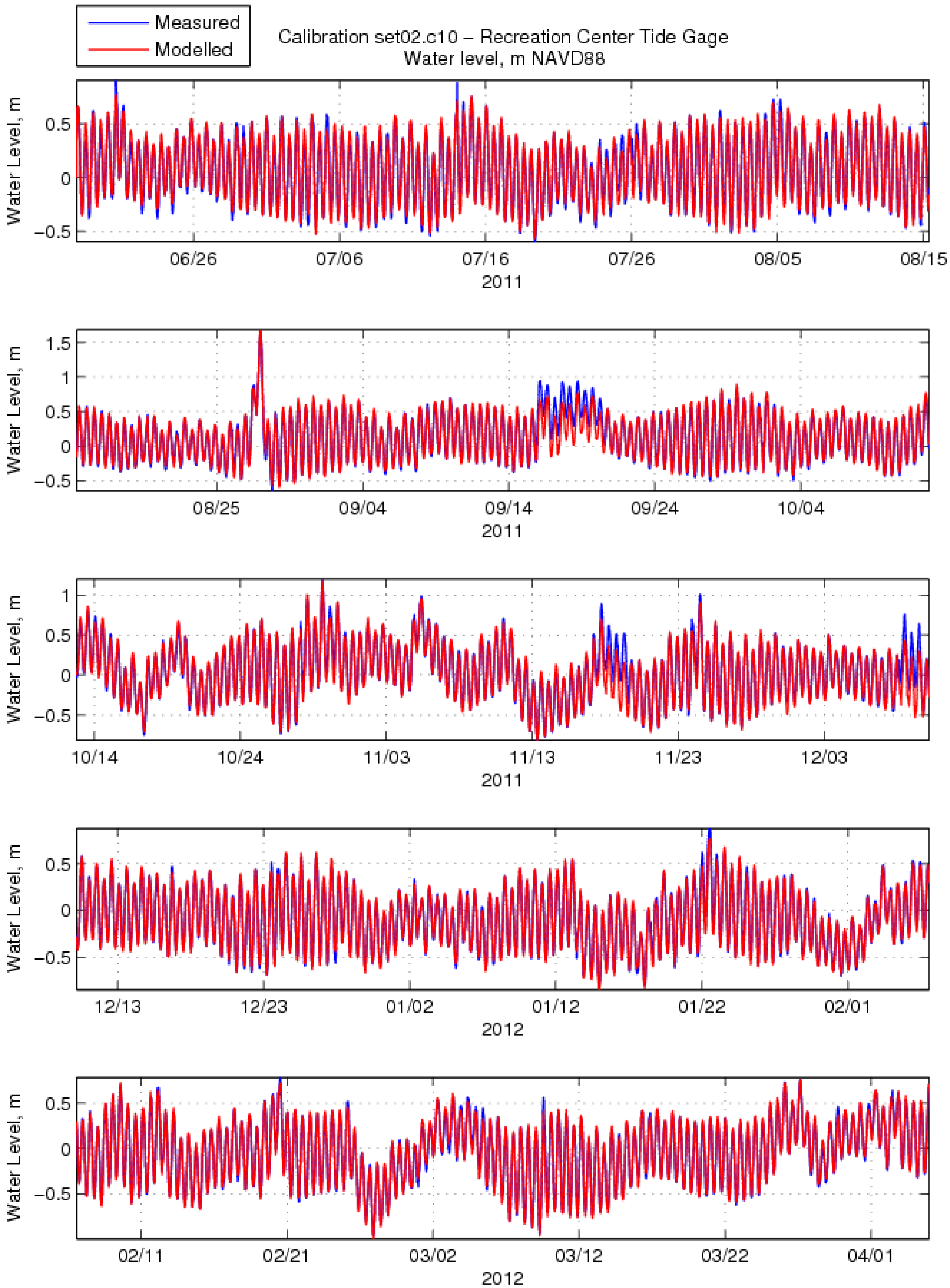


Figure 3-5 Measured VS Modeled Water Levels at the Recreation Center Tide Gage

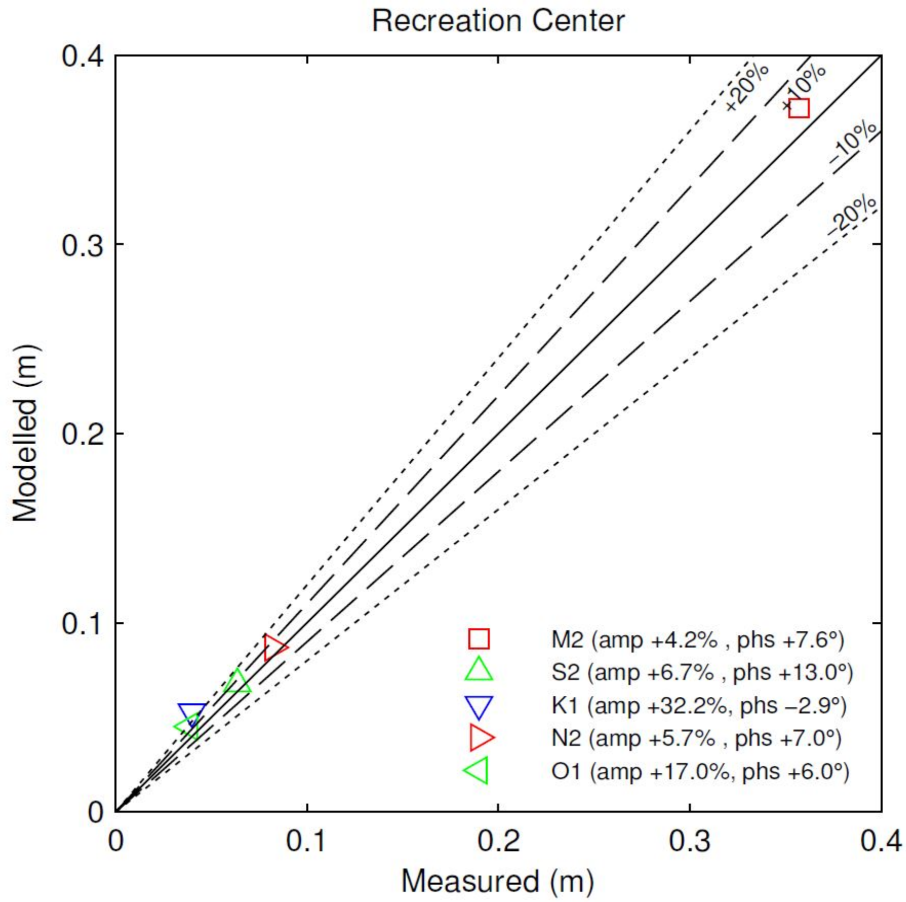


Figure 3-6 Measured VS Modeled Tidal Constituents at the Recreation Center Tide Gage

3.4. Modeled Salinities

Modeled Salinities were not calibrated due to lack of measurements within the Pretty Lake model computational domain. However, salinity calibration was performed for the Elizabeth River/Broad Creek model by adjusting eddy viscosity and diffusivity coefficients.

Table 3-3 provides the calibration parameter settings which resulted in the best agreement between measured and modeled salinity data for the Elizabeth River/Broad Creek Model. These settings were used in the Pretty Lake model for subsequent water quality evaluation simulations.

Table 3-3 Salinity Calibration Parameter for the Elizabeth River/Broad Creek Model

Horizontal		Vertical		Turbulence Closure Model
Background Eddy Viscosity (m^2/s)	Background Eddy Diffusivity (m^2/s)	Background Eddy Viscosity (m^2/s)	Background Eddy Diffusivity (m^2/s)	
0.01	0.1	0.001	0	K-Epsilon

Figure 3-7 shows daily averaged surface and bottom salinitiy at the location of the Recreation Center tide gage as modeled with the viscosity parameters provided in Table 3-3. A well mixed water column is predominant over the calibration period with salinity gradients equal or lower than 1 ppt.

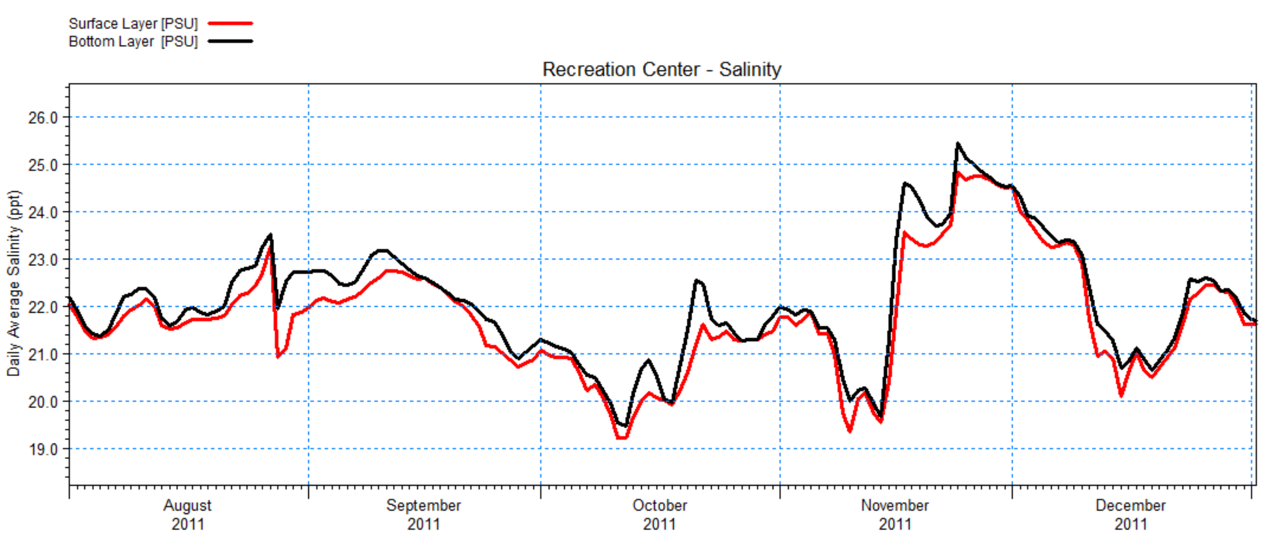


Figure 3-7 Modeled Daily Averaged Salinity at the Location of the Recreation Center Tide Gage

3.5. Summary

The main findings regarding calibration of the Pretty Lake hydrodynamic model are summarized below.

- Water level calibration was achieved by adjusting the value for bottom roughness.
- A Chezy roughness scheme with constant coefficient of 0.65 enabled the desired level of calibration for water levels.
- Excellent agreement between modeled and measured water level data was achieved, with a correlation coefficient of R=0.98 and RMS error RMSE=0.06 m.
- Salinity calibration was not performed due to lack of measured data, thus modeled salinities and the level of stratification inside the Pretty Lake area could not be verified.
- Eddy viscosity and diffusivity (salinity calibration parameters) were set according to those in the Elizabeth River/Broad Creek model for subsequent water quality evaluation simulations.

4. Water Quality Analysis Setup

4.1. Introduction

Potential Project impacts to circulation and water quality in Pretty Lake are evaluated with two sets of hydrodynamic simulation scenarios representing typical late-summer conditions and post-storm conditions.

Simulation of late-summer conditions are intended to provide insight of Project impacts on typical tidal flushing times, fresh water age and salinity during late-summer, when water quality is most critical. Simulation of post-storm conditions are intended to reflect potential Project impacts on recovery time to typical water levels, circulation and salinity when the gates of the flood control structure re-open following a storm.

4.2. Methodology

4.2.1. Typical Average Late-Summer Conditions

M&N assessed potential project impacts to water quality for the long-term average condition without explicitly modeling water quality constituents and processes. Instead, a modeling and post-processing framework was developed that uses conservative and decaying tracer concentrations to derive the flushing times and the tidally-averaged freshwater age, as well as tidally-averaged salinities for particular areas of interest in Pretty Lake. Model boundary conditions were set up such that the hydrodynamics, and salinity reached a dynamic steady-state prior to tracer simulation. In this context, dynamic steady-state means that a parameter value varies over the tidal cycle but remains relatively constant at a given spatial location and for a particular phase of the tidal cycle.

The methodology for computing specific water-quality proxy quantities from model results are described below:

- **Bay flushing time**: The term *bay* is used to represent the interior domain on the protected side of the flood control structures. An initial conservative tracer concentration was set to a constant value throughout the bay and zero outside of the bay and at all boundaries. The model was run long enough to flush out most of the tracer. Tracer concentrations over time were used in post-processing to compute flushing time. Tracer concentration decreases exponentially with time at a rate that is equivalent to the inverse of the flushing time. Thus, by plotting the natural log of the tracer concentration versus time, flushing time was computed as the inverse of the slope of the curve. Ideally the curve is a straight line, but in practice it often isn't. Thus, a linear best fit was used to determine the slope and thus the flushing time.

  Tracer concentrations were averaged over space at specific output times for the entire bay and for various regions of the bay, such as the upper bay. The time series of these spatially-averaged concentrations were used to determine the flushing time for the bay regions. Flushing times were compared among scenarios. The flushing time is actually the first flushing period, referred to as the *e-folding time*, where approximately 63 % of the initial water in the bay region of interest has been flushed out.

- **Salinity**: Salinity reached a dynamic steady-state, which means varied over the tidal cycle, but values were close to the same at a given spatial location and phase of the tidal cycle. Output salinity was averaged for each computational cell over a lunar month (tidally-averaged) after reaching dynamic steady-state. Tidally-averaged salinity for the computational cells was averaged spatially over specific regions (e.g., entire bay, upper bay, etc.) and compared among scenarios.

- **Fresh water residence time**: Tracer studies were performed to determine the residence time of the freshwater inflows. After dynamic steady-state spin-up, the model was run with initial conditions of zero tracer concentrations. Tracer concentrations at the most upstream freshwater source were set to a constant value, and tidal boundary tracer concentrations were set to zero. The model was allowed to run until dynamic steady-state conditions for tracer concentrations throughout the bay were reached. A tracer pair, one conservative and one decaying, was introduced in the freshwater source and their concentrations were used to obtain dynamic, steady-state water age, or residence time, for the freshwater source using a procedure that is including in the Delt3d model. The decay rate was set to the reciprocal of the bay flushing time. Similar to salinity, freshwater age was tidally-averaged over the lunar month producing tidally-averaged fresh water age (residence time) for every computational cell.

4.2.2. Post Storm Recovery

A major rainfall event was imposed on the system with sea levels, tides, and wind conditions that are typically coincident with a major storm, such as a hurricane. The sea level and tides had storm surge characteristics that would cause flooding in the bay, necessitating closure of the barrier's gates. The model was started with the dynamic, steady-state, typical conditions described above and run long enough to capture not only the storm runoff and surge event, but the weeks following the event to allow enough time to restore the system to pre-storm conditions in terms of water levels and salinity, plus enough time to determine flushing time characteristics. In the *with Project* condition, the gates of the proposed structure were closed at the beginning of the storm event, remained closed during the storm and were re-opened once the water levels had receded to typical tidal conditions. The *with* and *without Project* scenarios were time referenced for comparing the two conditions. The time reference, or time zero, was established as the beginning of the rainfall-runoff hydrograph.

- **Freshwater tracers:** Two types of tracers were introduced in the freshwater inflows, a conservative and decaying tracer. These are two separate tracer variables and are not related to tracer pairs used for modeling water age in the typical average simulations (above section 4.2.1). The decay rate used for the non-conservative tracer was 0.5 per day. Initial concentrations for the tracers were specified to zero throughout the model domain, and were set to a constant value at all freshwater sources within the bay throughout the runoff hydrograph imposed during the storm. Tracer concentrations were tracked over time at various locations, such as an upstream location and at the structure exit in the main channel.

Tracer concentrations versus time were compared for *with* and *without Project* conditions. The model was run long enough to flush out most of the tracers.

Freshwater tracers did not reach a dynamic steady-state, since inflow to the bay was not constant through time; therefore, freshwater age could not be derived. Instead, tracer concentrations were tracked over time at relevant locations.

- **Salinity**: Time series of output salinity were compared among scenarios for point locations. Salinity was monitored to gain insight on the recovery time for the system, i.e. the time required for restoration of pre-storm conditions.

4.3. Model Scenarios

For each of the hydrodynamic scenarios described above, the following sub-scenario simulations were conducted:

- ***Without Project***: Simulations without the proposed flood control structure were carried out to establish the base condition for the evaluation of Project impacts.

- ***With Project***: These simulations evaluate permanent Project impacts by incorporating the proposed flood control structure to the computational grid. The structure's single operable gate is open during the late-summer conditions and is operated as necessary during the post-storm recovery simulations.

Flood control structures were incorporated into the computational domain by specifying thin dams (Figure 4-1), i.e. infinitely thin features which prohibit flow exchange between two adjacent computational cells without reducing the total wet surface and volume of the model. A sill elevation of -8 feet (2.4 m) NAVD88 was set throughout the structure's footprint.

Simulations *with* and w*ithout Project* described above are also conducted for existing and future conditions as described below:

- **Existing conditions:** These simulations involve present-day water levels and bathymetry in the Elizabeth River. Essentially, tidal and discharge boundary conditions were input to the model as available in different publicly available data sources.
- **Future conditions**: These simulations are intended to incorporate effects of future water levels.

As directed by USACE, an expected sea level rise of 1.6 feet (0.48 m) is assumed for the end-of-plan year 2076. Imposed water levels at the open boundary of the model are adjusted accordingly. It is assumed that the bathymetry of Pretty Lake and adjacent waters in the model domain will be identical between the Existing and Future conditions.

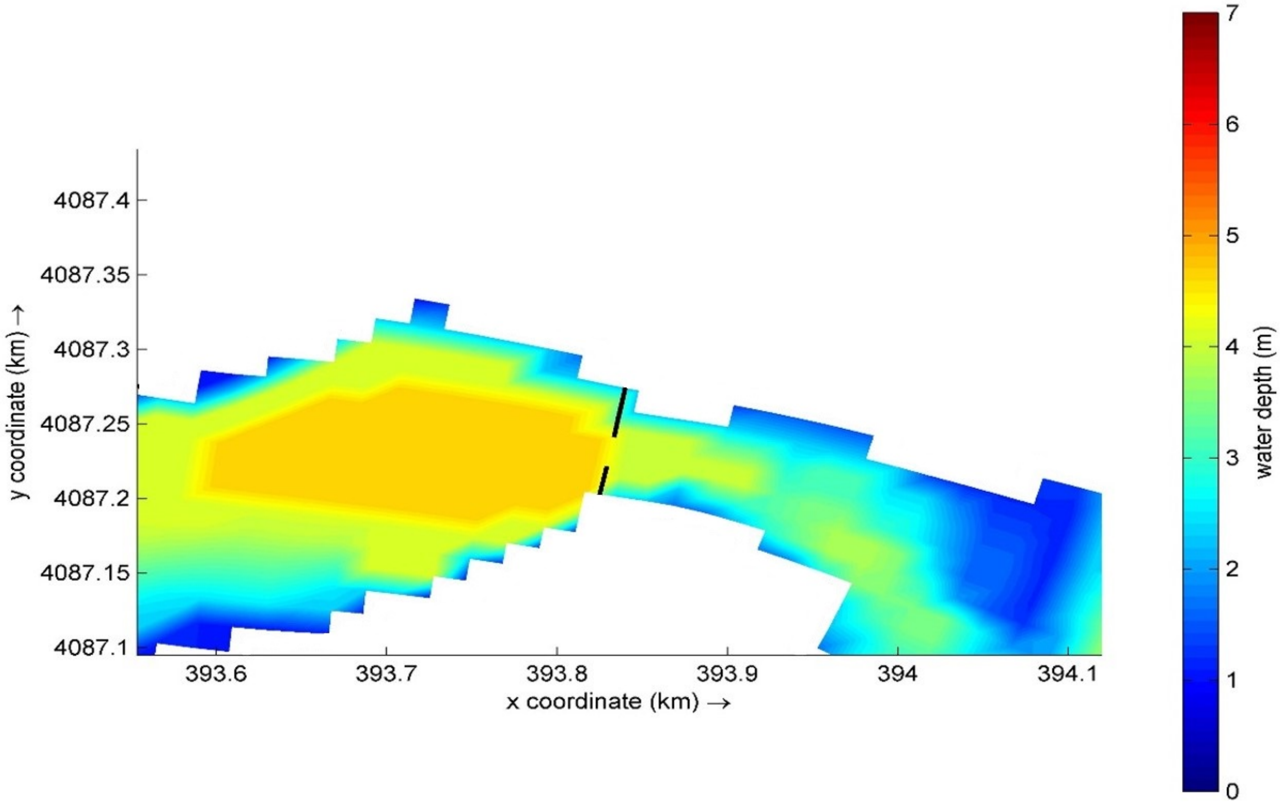


Figure 4-1 Thin Dams for the With Project Simulations

4.4. Typical Late-Summer Conditions Simulations Setup

To determine the potential long-term Project impacts on water quality, M&N relied on calculating *with* vs. *without Project* values for flushing time, salinity, and fresh water age under dynamic steady-state conditions. For the hydrodynamics to reach a dynamic steady-state condition, the model needs to be forced with boundary conditions that do not vary significantly at frequencies lower than that of the tidal cycle. The boundary conditions were derived to represent typical conditions during late summer (approximately July 15th through September 15th), when water quality is most critical; and the effects of any short-term events such as storms that could interrupt the dynamic steady state conditions were excluded.

The simulation period was set to six months, and the boundary conditions to force the model were imposed as follows.

4.4.1. Water Level Boundary

The amplitude and phase of 26 harmonic constituents, as derived by NOAA-CO-OPS for Chesapeake Bay Bridge Tunnel (86386863, see Figure 2-1), were specified to create a purely astronomical tidal boundary condition. The generated water level time series at the model offshore boundary, encompassing the summer months, is depicted in Figure 4-2.

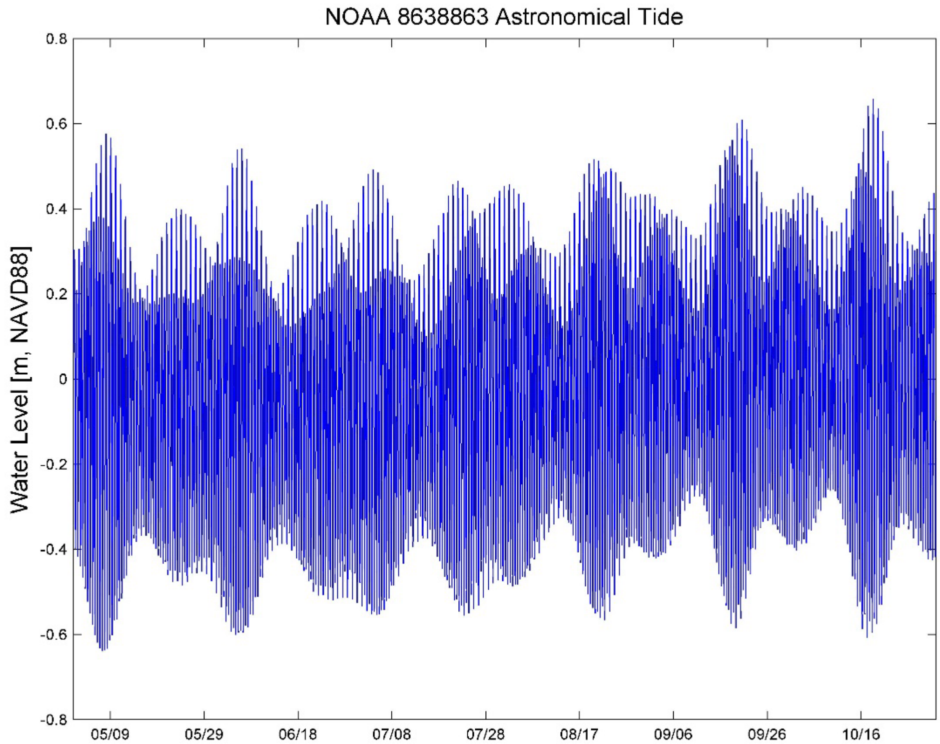


Figure 4-2 Astronomical Water Level Boundary Condition

4.4.2. Salinity

Late-summer salinity boundary conditions were derived from VIMS' simulated 3D salinity data (see section 3.2.2). The data set, comprising the period between January 2010 and December 2013, was analyzed to determine the typical late-summer salinity conditions. Because no year can be described as "typical" (depth-averaged salinities as well as vertical salinity gradients during late summer, vary considerably among years) the following approach was taken: daily salinity values were averaged over the four late-summer periods (i.e. mid-July to mid-September) included in the simulated salinity data set to obtain a one-month 3D salinity time series. This condition was consecutively repeated over the simulation period. A linear vertical salinity profile was adopted. Figure 4-3 shows the salinity boundary condition (averaged along the model offshore boundary) for the surface and bottom layers.

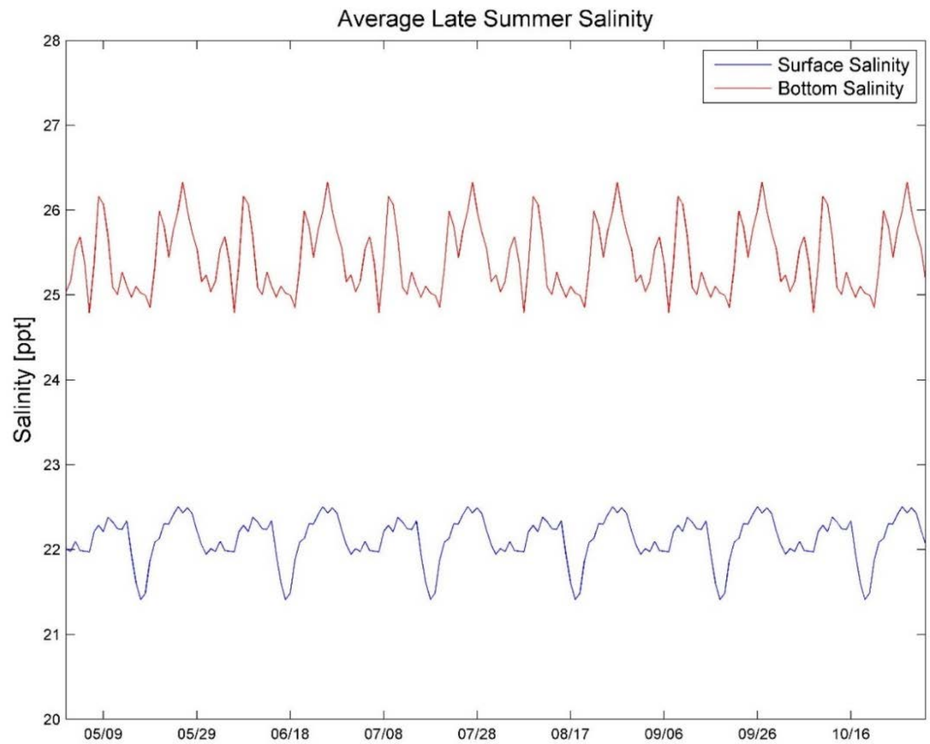


Figure 4-3 Late-Summer Salinity Boundary Condition

4.4.3. Fresh Water Inflows

Approximately 15 years (1990 – 2015) of rainfall-runoff outputs from the VADEQ statewide watershed model hindcast were analyzed to determine representative late summer runoff conditions. Discharge data from July 15th through September 15th of each year were averaged excluding the runoff from major storms, where daily precipitation was greater than 2 inches. The averaged values were imposed as constant freshwater discharges for the six-month simulation to represent steady state runoff conditions. Figure 4-4 indicates the imposed freshwater discharges in cubic meters per day.

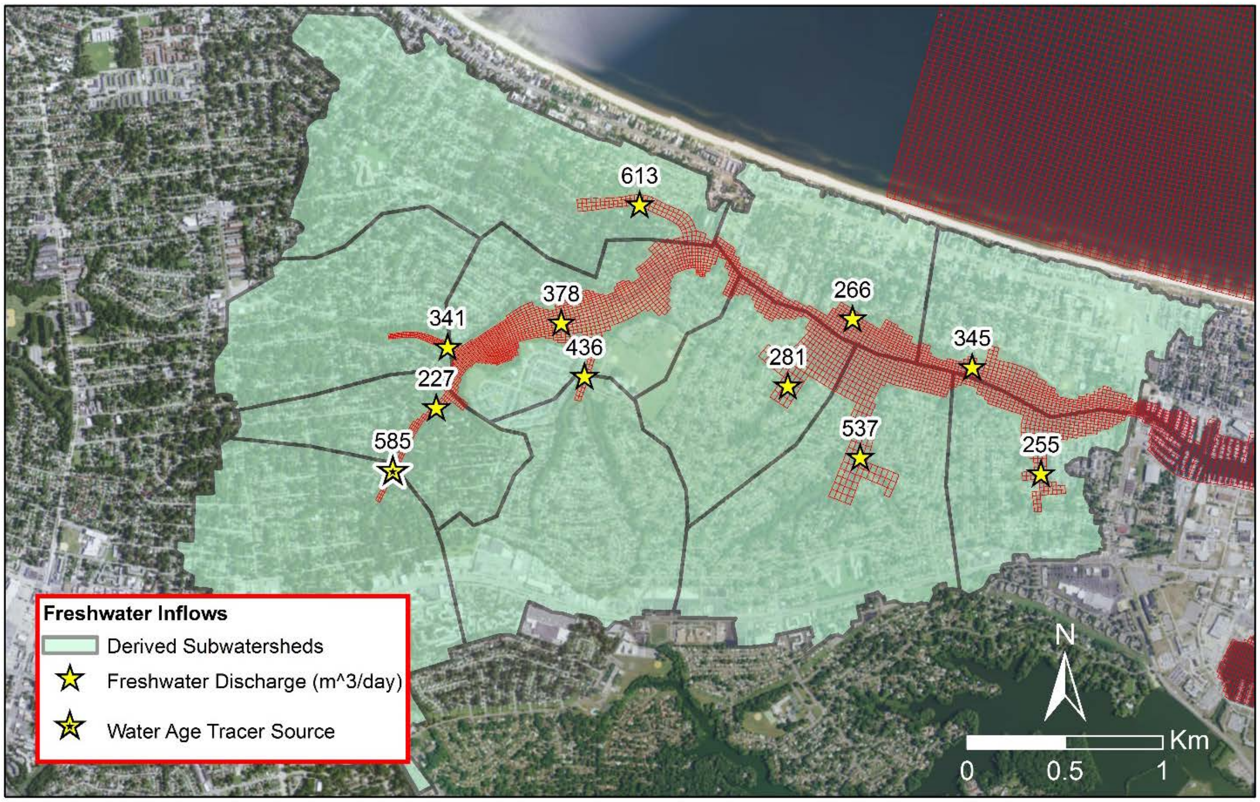
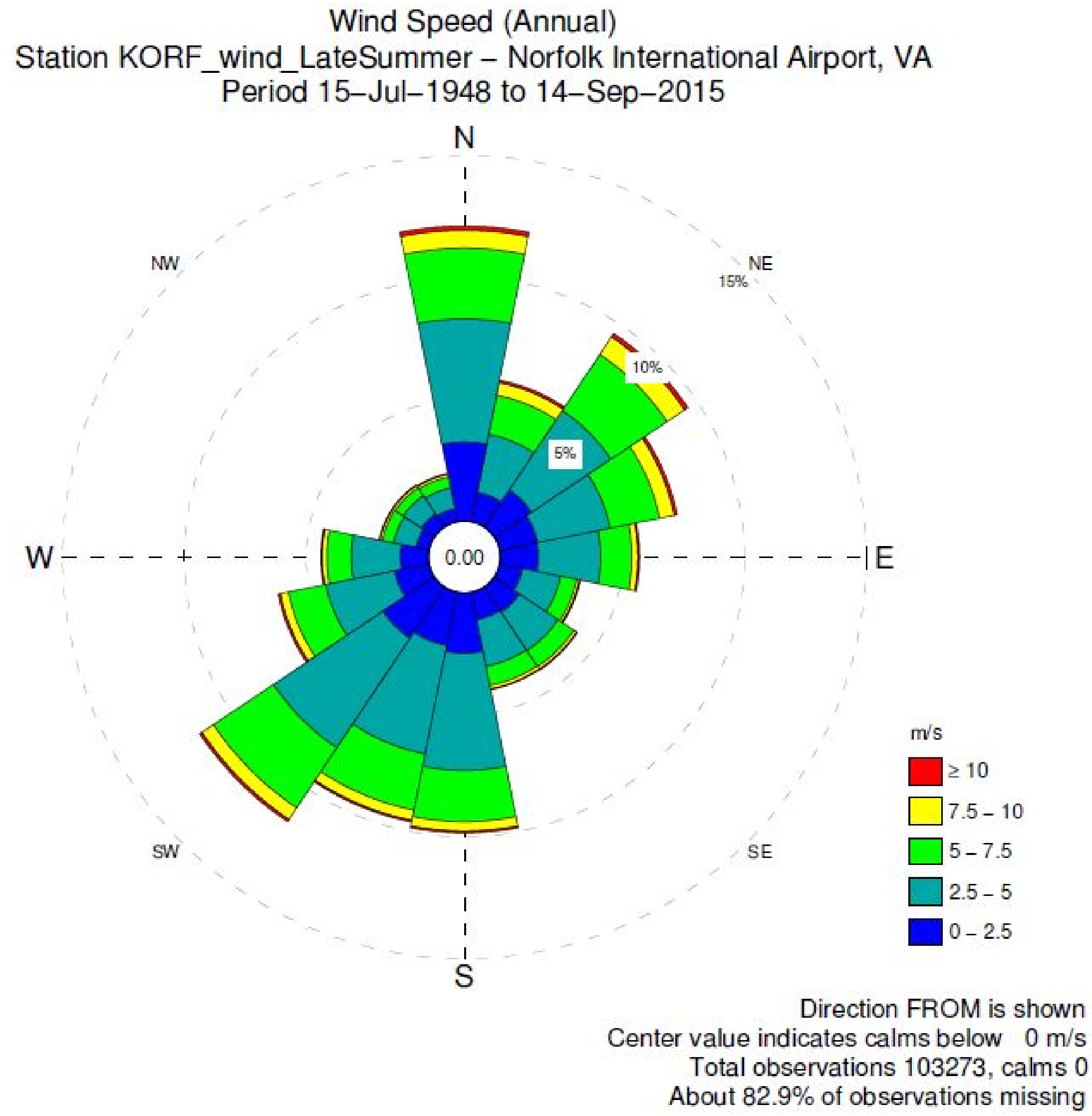


Figure 4-4 Late-summer Freshwater Inflows

4.4.4. Wind

As with the freshwater inflows, the imposed wind, constant in space and time, reflected typical late summer values. Wind measurements from the Norfolk International Airport (KORF, Figure 2-1) were analyzed to derive the late-summer scalar average wind speed and dominant wind direction (i.e. 3.9 m/s, Southwest). This condition was applied for the full simulation period. Figure 4-5 shows the late-summer wind rose for Norfolk International Airport.



Percentage of Occurrence

Wind Speed, m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Total	12.11	5.91	9.54	7.41	5.70	3.36	4.08	4.05	9.84	9.60	11.57	6.30	4.40	2.06	2.06	2.00	100.00
≥ 10	0.18	0.10	0.16	0.12							0.10						1.18
7.5 – 10	0.74	0.52	0.87	0.61	0.25	0.11	0.14	0.15	0.38	0.43	0.57	0.34	0.19	0.10	0.12	0.12	5.64
5 – 7.5	2.90	1.64	2.78	2.07	1.28	0.67	0.78	0.80	2.11	2.35	2.97	1.57	1.00	0.47	0.39	0.45	24.24
2.5 – 5	5.06	2.43	3.93	3.04	2.56	1.59	1.91	1.95	4.81	4.54	5.41	2.87	2.02	0.93	0.90	0.87	44.82
0 – 2.5	3.23	1.22	1.82	1.57	1.54	0.94	1.22	1.13	2.46	2.22	2.52	1.43	1.14	0.54	0.63	0.53	24.13

Figure 4-5 Late-summer Wind Rose for Norfolk International Airport

4.4.5. Flushing Tracers

For the flushing time analysis, initial concentrations of conservative tracers were specified for two regions of interest in Pretty Lake as depicted in Figure 4-6. Tracer concentrations at the offshore boundary and freshwater sources were set to zero.

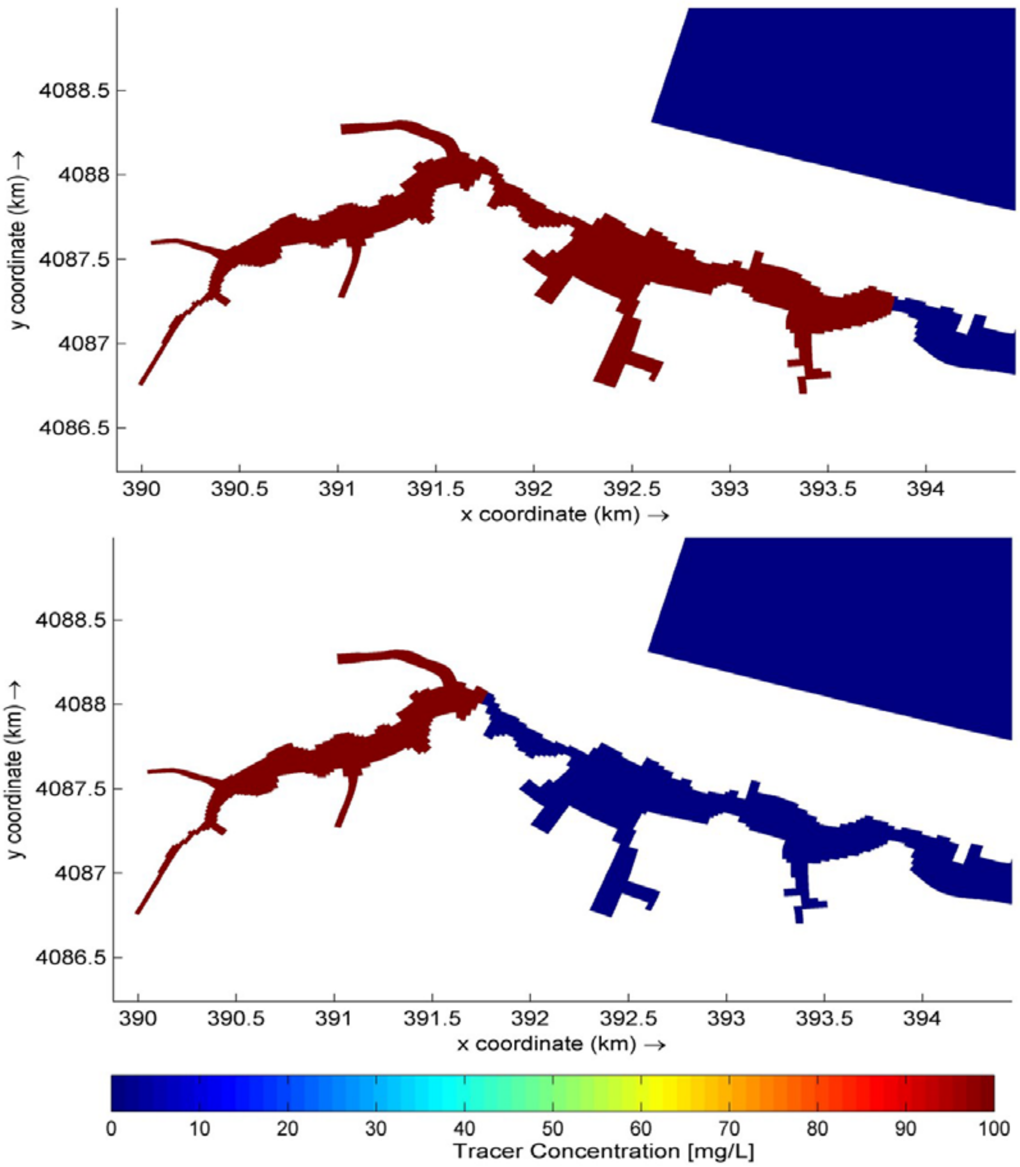


Figure 4-6 Initial Concentrations for Flushing Time Tracers: Whole Bay (Top) and Upper Bay (Bottom)

4.4.6. Water Age Tracers

Water age tracer concentrations were set to a constant value (i.e. 100 mg/L) throughout the simulation period, at the most upstream freshwater source within the Bay (see Figure 4-4) and are set to zero for the rest of the freshwater sources, model offshore boundary, and model domain.

4.5. Post-Storm Recovery Simulations Setup

For the post-storm recovery investigation, simulations were *hot-started* (i.e. initialized with hydrodynamic and salinity steady state conditions) from the late-summer simulations described above.

USACE advised M&N to use historical Hurricane Isabel in 2003 as the design storm. Simulations were started at low tide, one day prior to the storm arrival, which was approximately 12:00 pm on September 17th. A gradual storm surge was imposed at the model offshore boundary, and the rainfall discharge hydrograph associated with such surge event was routed into the Bay through the freshwater sources.

For the *with Project* simulations, the gates of the proposed structure were closed at the beginning of the simulation, and were re-opened after a 4-day (96 hour) simulation period, once the tides and the discharge hydrograph had receded to typical conditions. After gate re-opening, the imposed model boundary conditions reverted to the typical late-summer conditions described above.

Model inputs for the storm period only are described below. The inputs during the post storm recovery periods are described in previous sections and are not repeated here.

4.5.1. Water Level Boundary

Water level boundary conditions were developed from measurements at the Chesapeake Bay Bridge Tunnel tide gage (NOAA-COOPS 8638963). Because the storm simulations were hot-started from the typical summer conditions simulation results, recorded water levels during Isabel were not used directly in this study. Instead, the storm surge component (green curve in Figure 4-7) was first extracted from the record by subtracting the predicted tide levels from the observed water levels; and then superimposed to the typical summer condition tide levels (red curve in Figure 4-7) to form the water level boundary condition for the storm period, depicted by the blue curve in Figure 4-7.

The peak surge at Chesapeake Bay Bridge Tunnel occurred on September 18- and was approximately 1.4 m (4.6 ft.). This peak surge coincides with the high astronomical water levels and results in total water levels of up to 1.9 m at the model open boundary, as depicted in Figure 4-7.

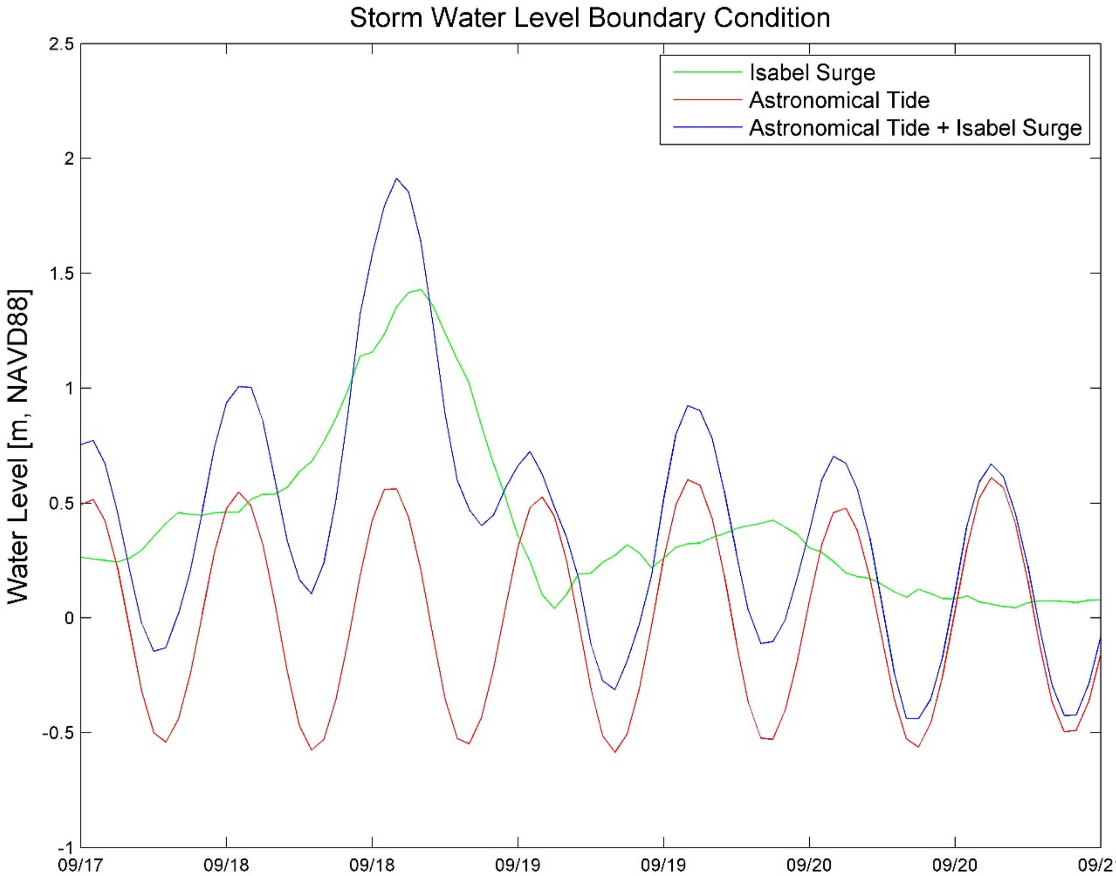


Figure 4-7 Storm Water Level Boundary Condition

4.5.2. Salinity

Surface salinity data for the Isabel storm period was derived from surface water temperature and conductivity data available from the Chesapeake Bay Bridge Tunnel station. A linear vertical salinity profile was assumed, with a constant gradient of 3.3 ppt, equivalent to the average salinity gradient imposed in the late-summer boundary condition derived from VIMS model results (see section 4.4.2).

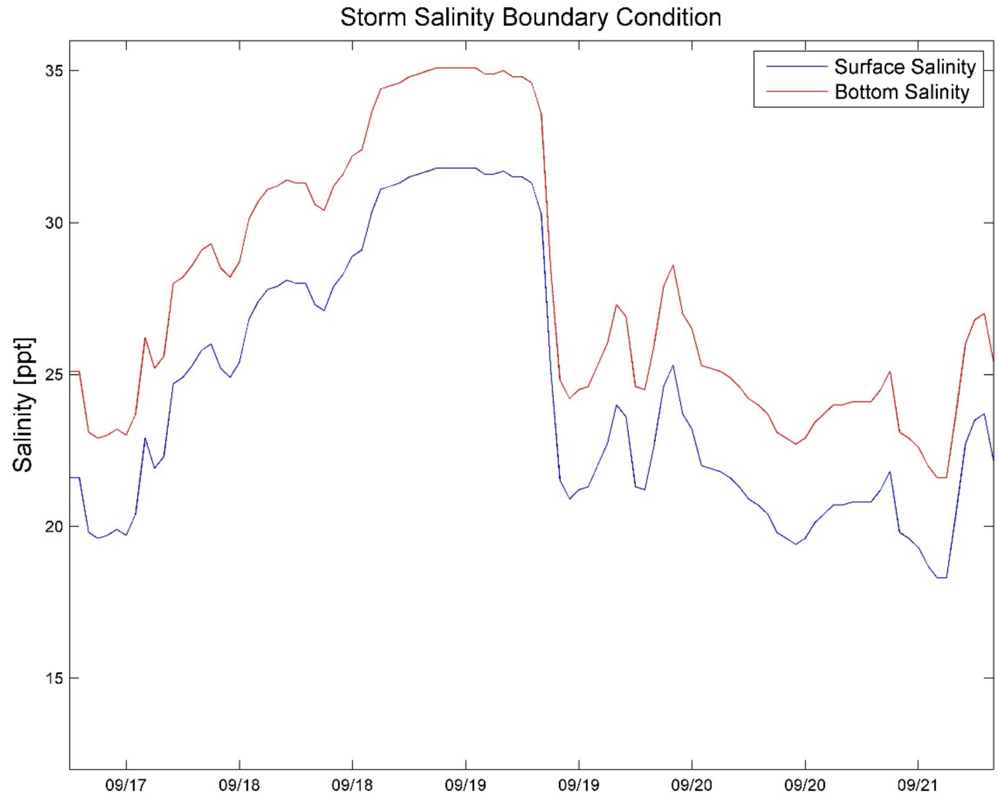


Figure 4-8 Storm Salinity Boundary Condition

4.5.3. Fresh Water Inflows

The daily rainfall-runoff caused by Hurricane Isabel was available for the project area from the VADEQ statewide watershed model hindcast. Based on the VADEQ model, total rainfall depths during the storm ranged from 3.2” to 5.4” over the region, which correspond to 2-yr to 10-yr return period recurrence intervals for a 24-hour storm (Bonnin et. al., 2006).

4.5.4. Wind

Wind records for the full Isabel storm period are available from the Chesapeake Bay Bridge Tunnel station. The data set was smoothed by a 3-hour moving average in order to avoid instabilities related to sudden significant changes in wind speeds and/or wind direction. The smoothed data set is depicted in Figure 4-9. Wind data from the Norfolk International Airport have gaps during Isabel, and were therefore not used for the storm simulation in this study.

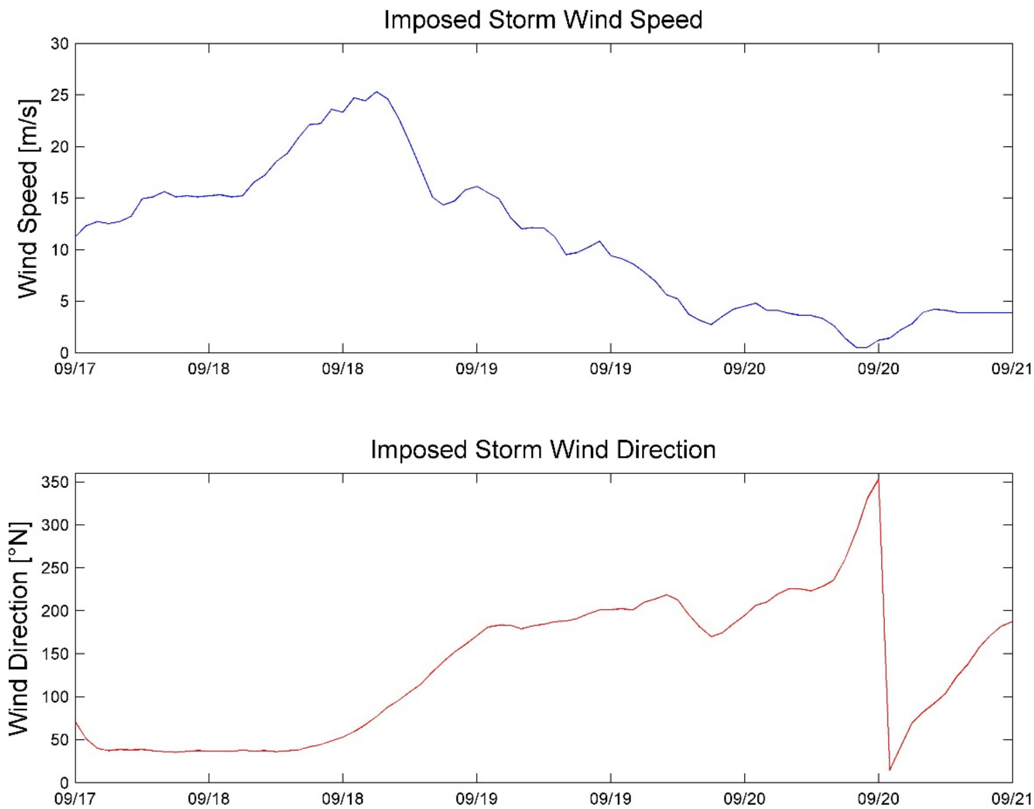


Figure 4-9 Imposed Storm Wind Condition

4.5.5. Freshwater Tracers

Freshwater tracer concentrations were set to a constant value (i.e., 100 mg/L) at all freshwater sources within the bay (and set to zero for all other discharge points) during the storm simulation period. Following the gates re-opening, tracer inflow concentrations are set to zero.

5. Typical Late-Summer Conditions Results

Flushing time, tidally-averaged salinity, and tidally-averaged freshwater age were computed for the full Pretty Lake (Whole Bay) area and Upper Bay region as defined in Figure 5-1.

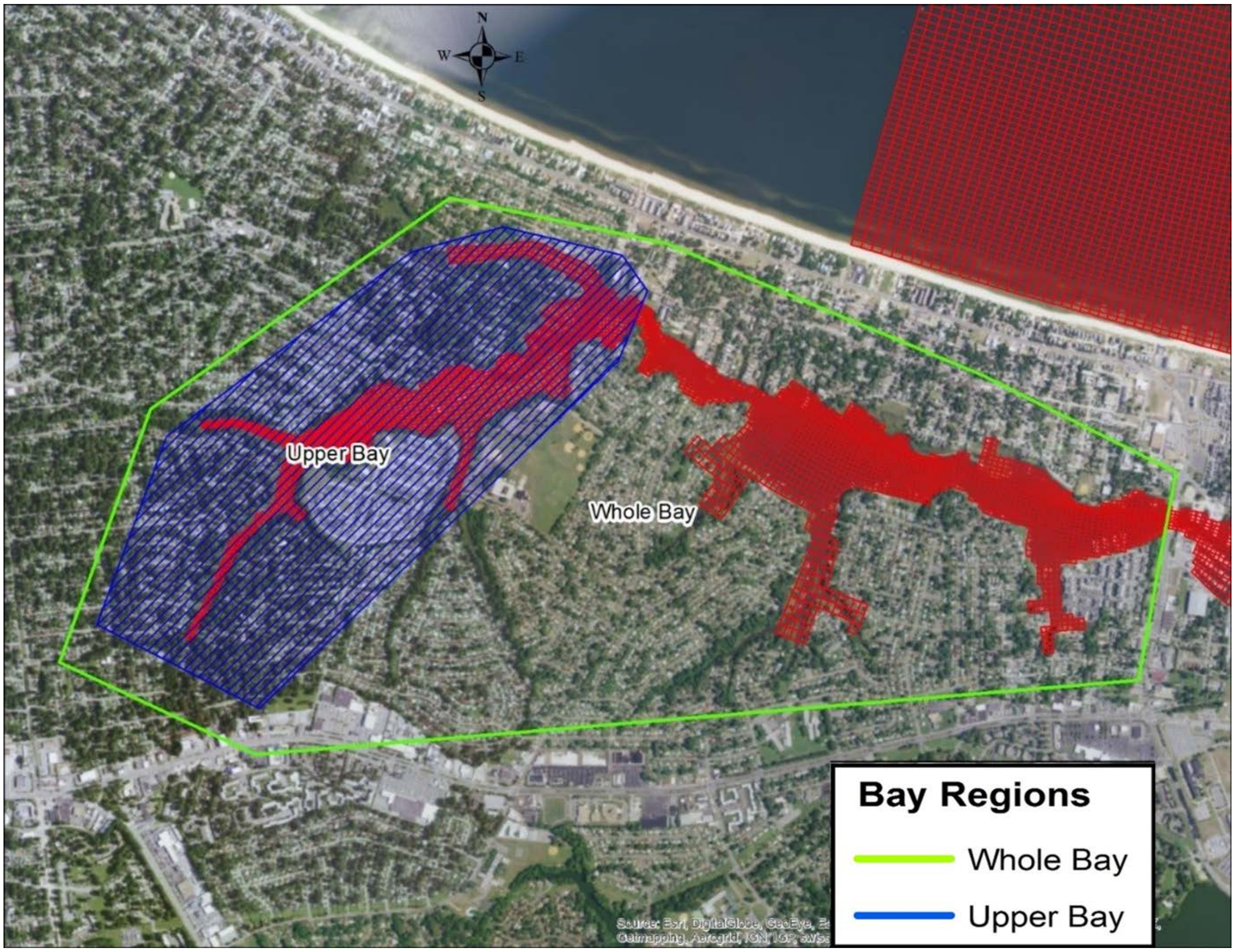


Figure 5-1 Pretty Lake Water Quality Analysis Regions

5.1. Existing Conditions

5.1.1. Flushing Time

Figure 5-2 plots the spatially-averaged tracer concentration through time for the Whole Bay and Upper Bay regions of Broad Creek. The first 20 days of results after achieving dynamic stability are used to determine flushing times. As shown in Figure 5-3 and Figure 5-4, a linear regression is applied to the natural logarithm of the tracer concentrations. The inverse slope of such curve corresponds to the flushing time.

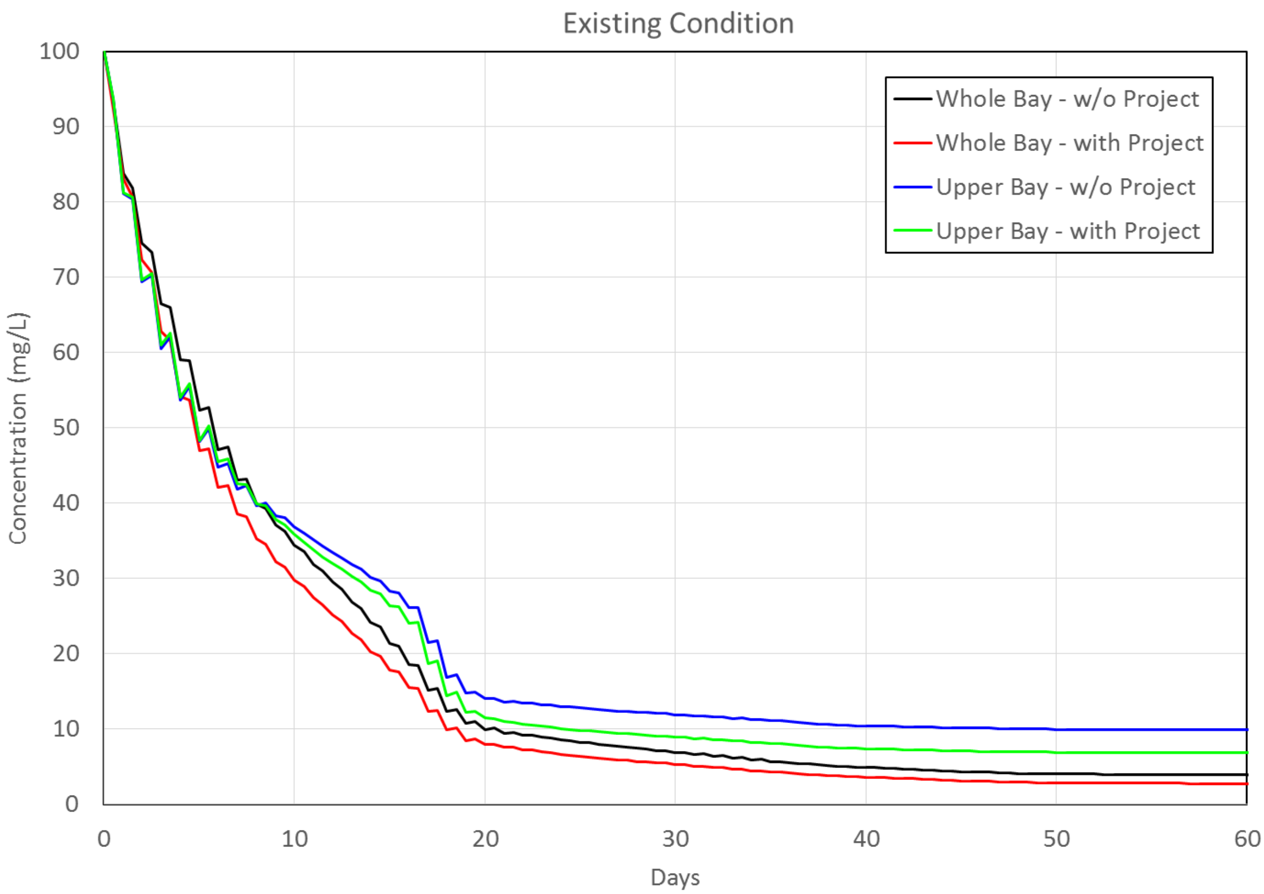
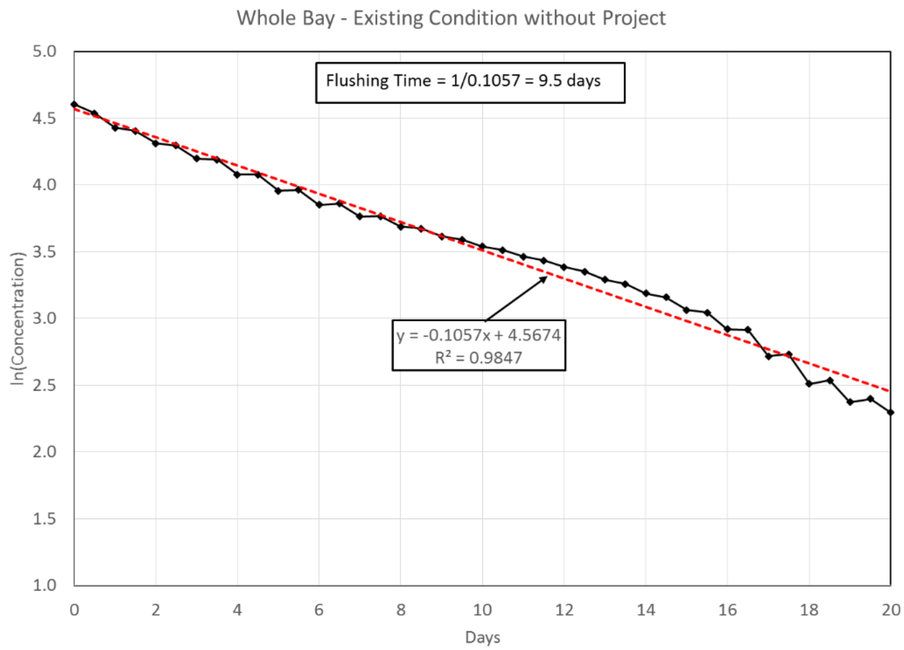


Figure 5-2 Existing Condition: Spatially-Averaged Conservative Tracer Concentration Over Time in the Whole Bay and Upper Bay Regions of Pretty Lake

Flushing time for the Whole Bay was estimated at 9.5 days *without Project* and 8.6 days *with Project,* and for the Upper Bay these were 12.3 days and 11.0 days, respectively. The results indicate that the project does not have a significant effect on flushing times. However, there is a definite trend that suggests that less cross-sectional area due to the gated structure could result in a slightly greater flushing rate (lower flushing time). Less flow area will result in higher entrance/exit velocities (with possibly no reduction in tidal prism volume exchange). Higher velocities could induce greater secondary residual circulation, such as Stokes Drift, which can enhance mixing, thus reducing flushing time slightly. Stokes drift is caused by the non-linear interaction of tidal currents (Feng et al. 1986), and greater spatial gradients in velocity (e.g., those caused by the gate structure) can increase Stokes drift, which tends to move water parcels up-bay (Dortch et al. 1992), thus increasing flushing.



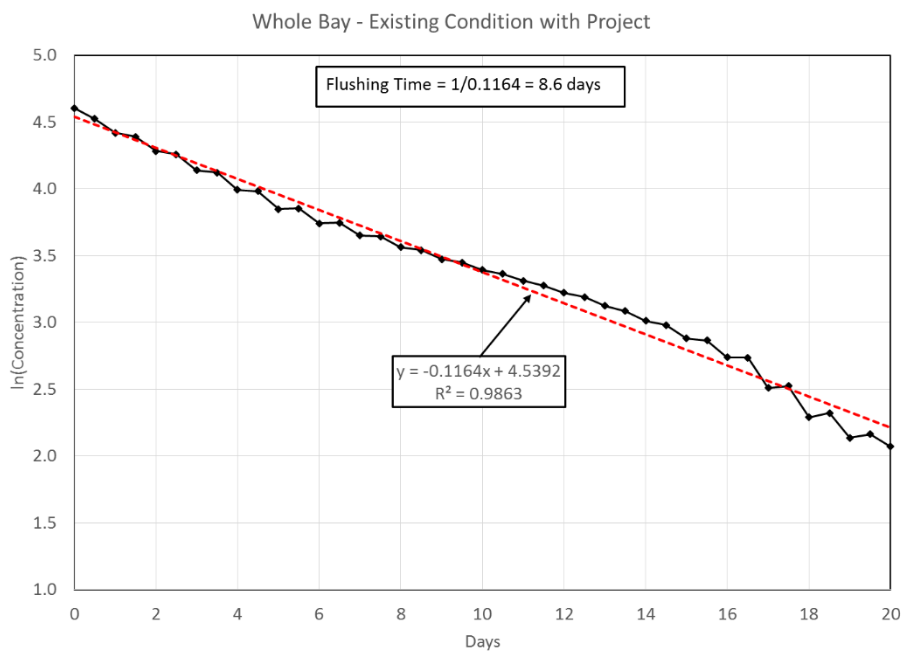


Figure 5-3 Existing Condition: Whole Bay Region Flushing Time Analysis

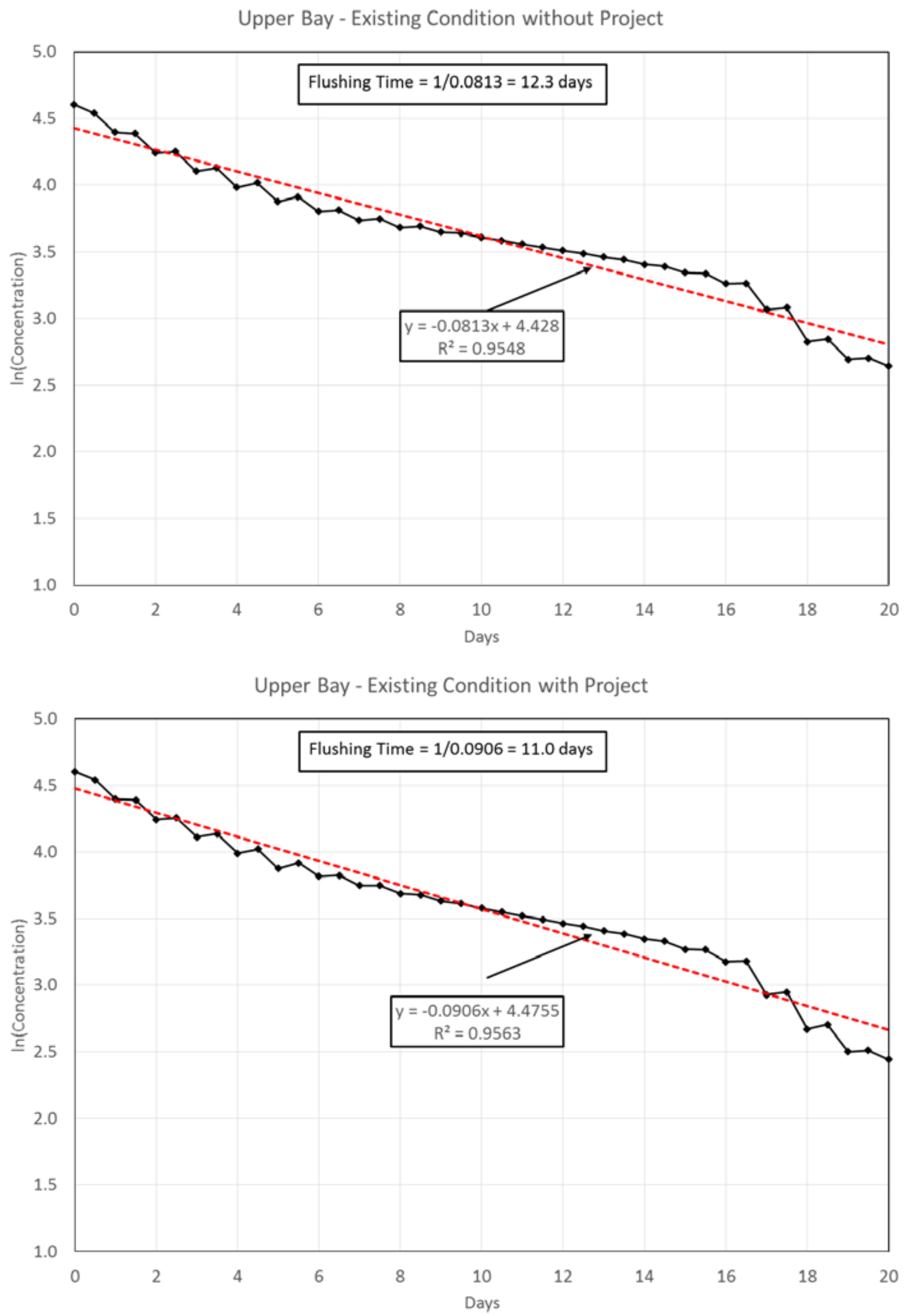


Figure 5-4 Existing Condition: Upper Bay Region Flushing Time Analysis

5.1.2. Freshwater Age

Freshwater age was computed from the relative concentrations of a conservative and decaying tracer released at the most upstream freshwater source (Figure 4-4). After the concentrations reached a dynamic steady-state, they were tidally-averaged for every computational cell in the area of interest. Figure 5-5 presents spatial variation in the steady state, tidal and depth-averaged freshwater age for *without Project* and *with Project* simulations under the existing condition. Figure 5-6 shows spatial variation in the freshwater age deviation (i.e. *with Project* minus *without Project*).

The tidal and depth-averaged freshwater age in the Whole Bay is approximately 14.6 days *without Project* and 14.4 days *with Project.* In the Upper Bay these values were estimated at 11.6 days and 11.5 days, respectively. These results indicate the Project effect on freshwater age is negligible.

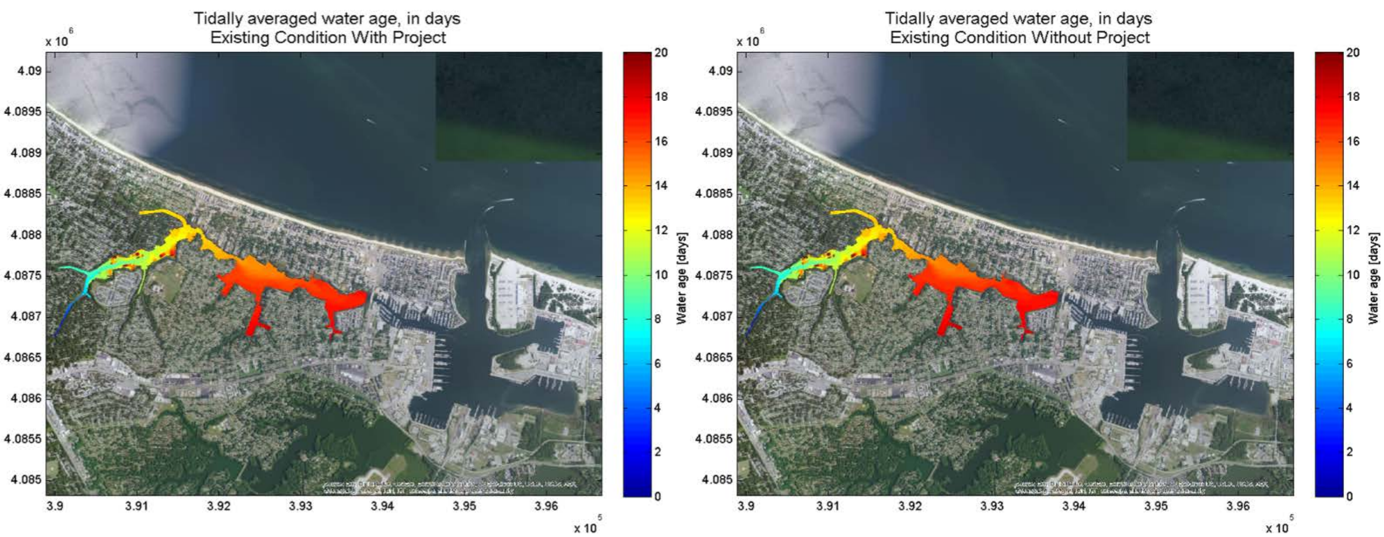


Figure 5-5 Existing Condition: Steady State, Tidal-averaged Freshwater Age Without project (Left), and With Project (Right)

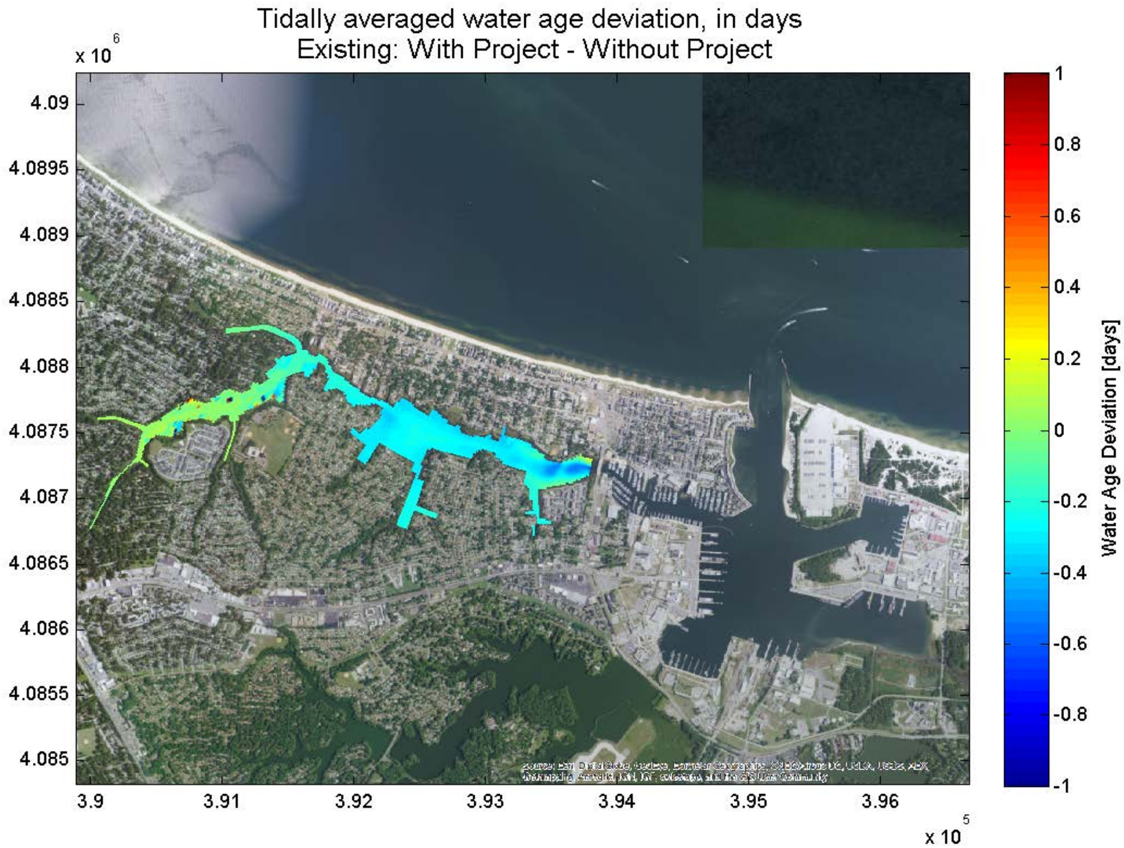


Figure 5-6 Existing Condition: Freshwater Age Deviation.
With Project - Without Project

5.1.3. Salinity

Depth and tidal-averaged salinity was computed at each computational cell once salinity had reached a dynamic steady state. Figure 5-7 presents the spatial variation in the steady-state, tidal-averaged salinity for *with* and *without Project* simulations under existing conditions. Figure 5-8 shows that the salinity deviation between the *with and without Project* simulations is negligible.

Tidal and depth-averaged salinity were estimated at 21.9 ppt *without Project* and 22.0 ppt *with Project* in the Whole Bay; and 19.9 ppt in the Upper Bay for both *with* and *without Project* scenarios. These results indicate the project effect on salinity is negligible.

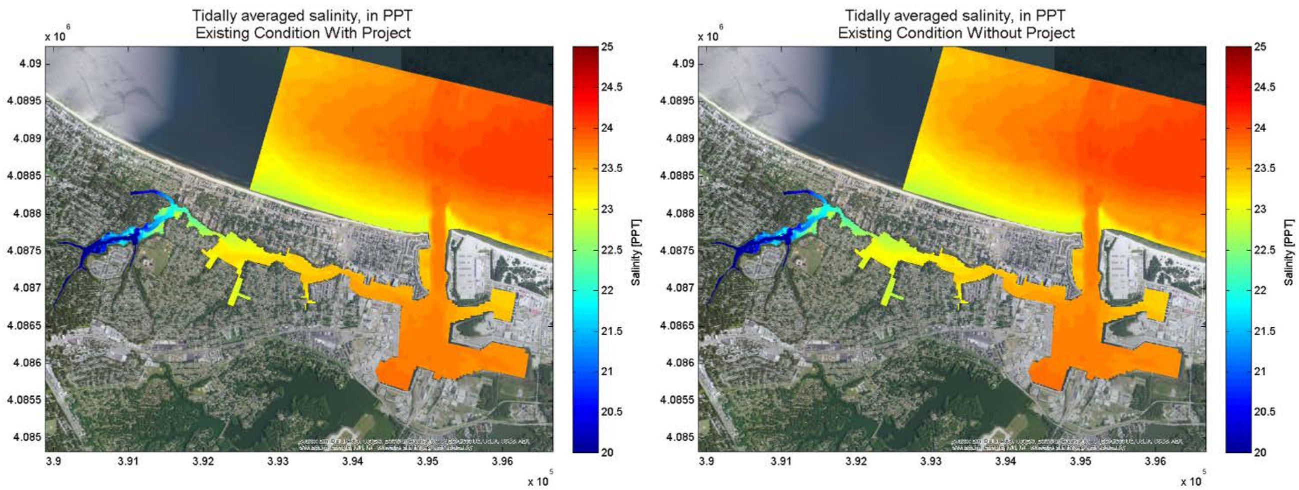


Figure 5-7 Existing Condition: Steady State, Tidal-averaged Salinity Without project (Left), and With Project (Right)

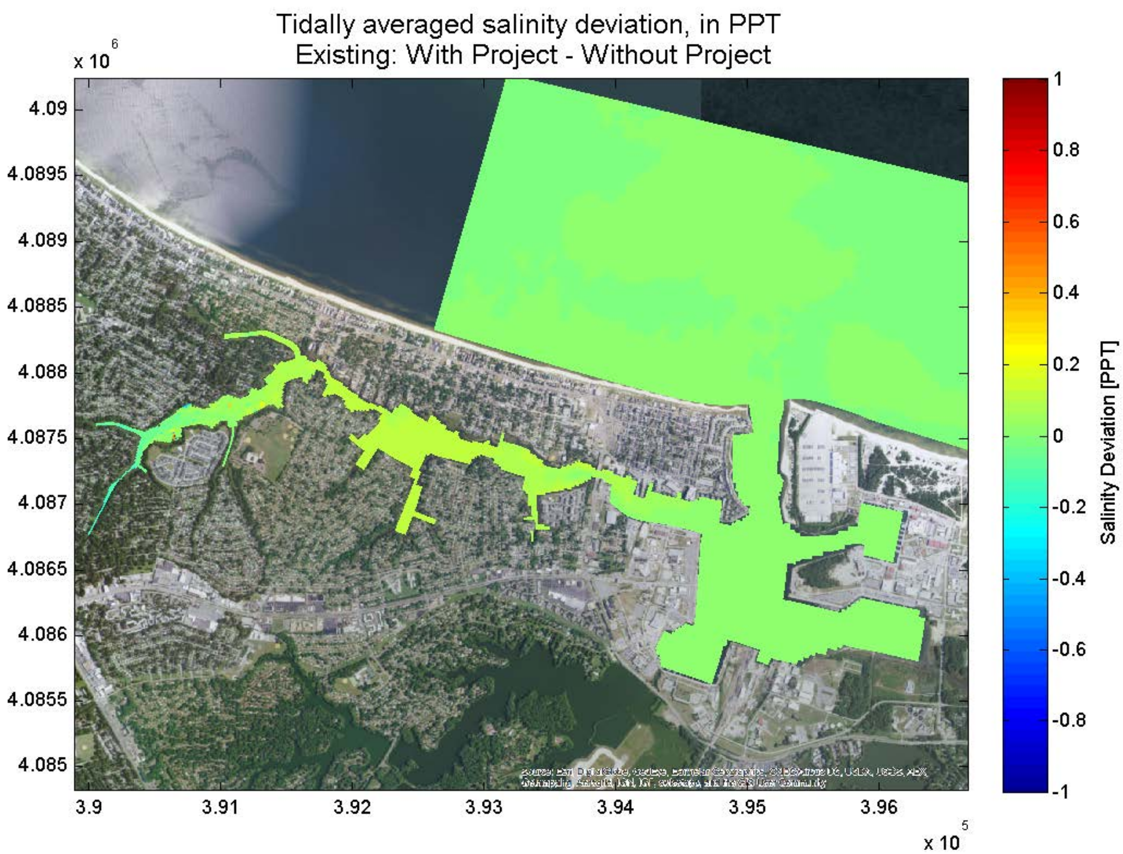


Figure 5-8 Existing Condition: Salinity Deviation. With Project - Without Project

5.2. Future Conditions

5.2.1. Flushing Time

Figure 5-9 plots the spatially-averaged tracer concentration through time for the Whole Bay and Upper Bay regions of Broad Creek. The figure shows that tracer concentrations under future conditions decrease more rapidly than under existing conditions.

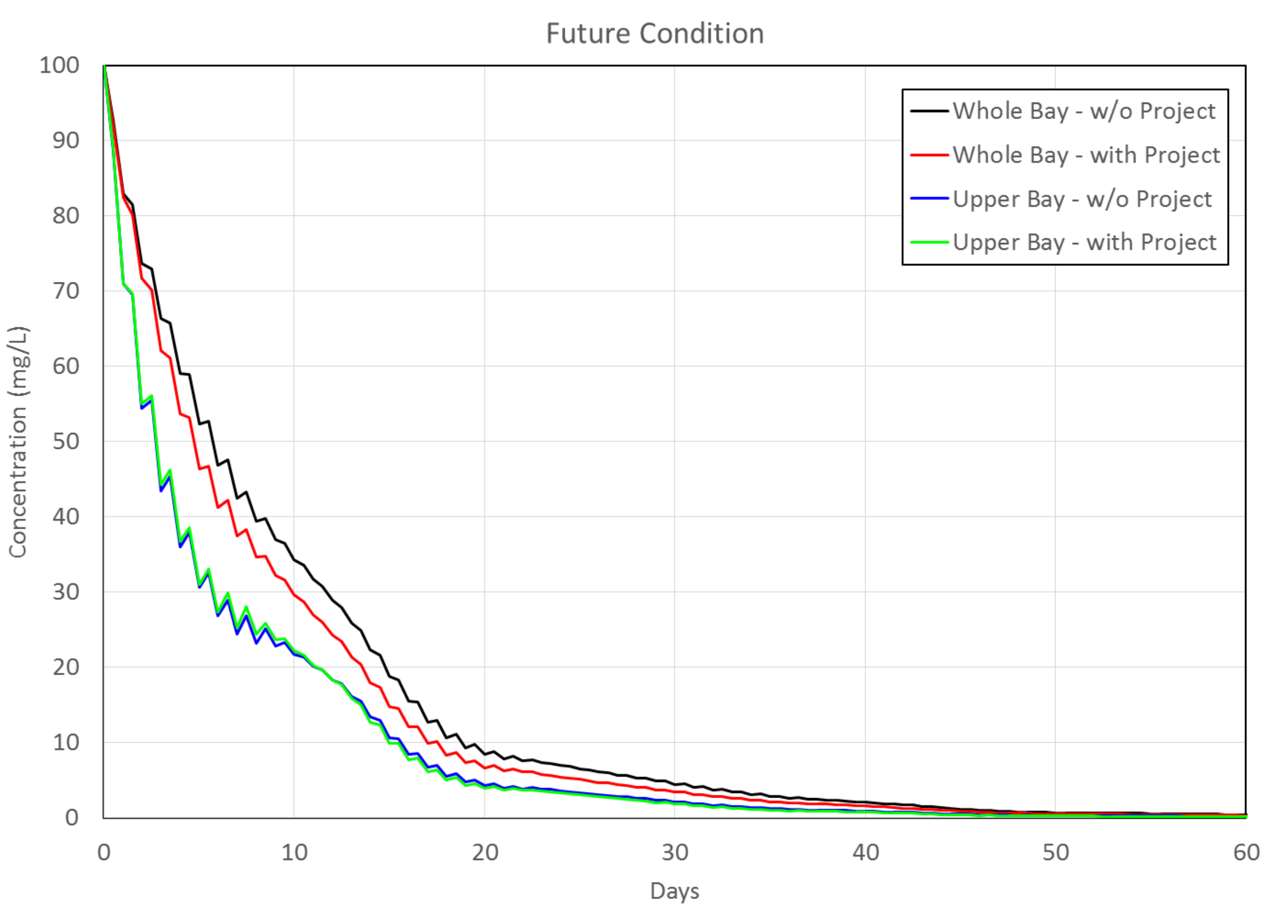
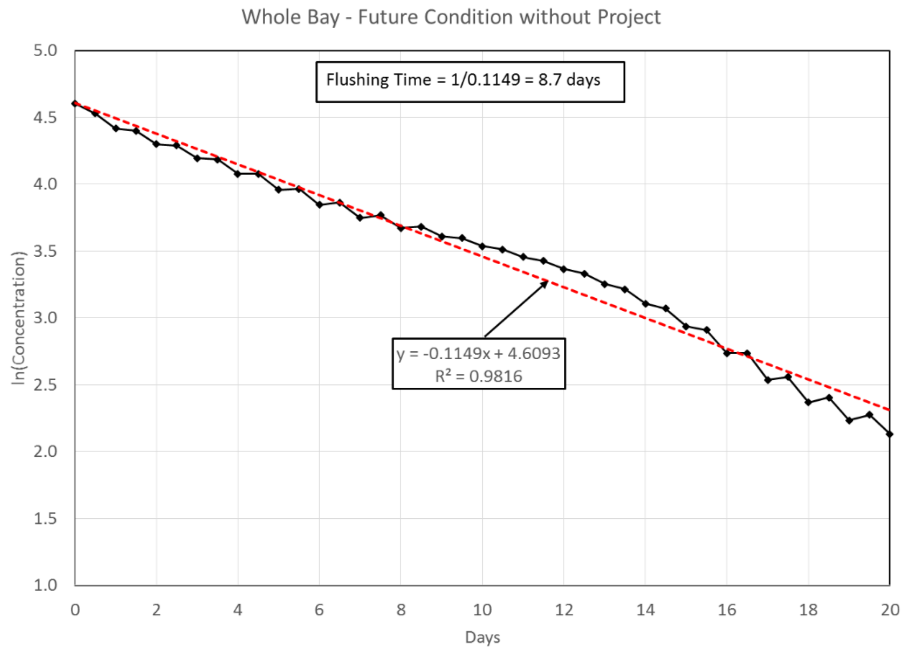


Figure 5-9 Future Condition: Spatially-Averaged Conservative Tracer Concentration Over Time in the Whole Bay and Upper Bay Regions of Pretty Lake

Flushing times were derived as described in Section 5.1.1 and the linear regression plots are presented in Figure 5-10 and

Figure 5-11.

Without Project, Whole Bay flushing time is estimated at 8.7 days: *with Project* this value becomes 7.8 days. Upper Bay flushing was estimated at 7.3 *without Project* and 7.0 days *with Project.* These results indicate a slight reduction in flushing times due to the Project. Furthermore, increased sea levels in future conditions simulation causes more rapid flushing than in existing conditions simulations.



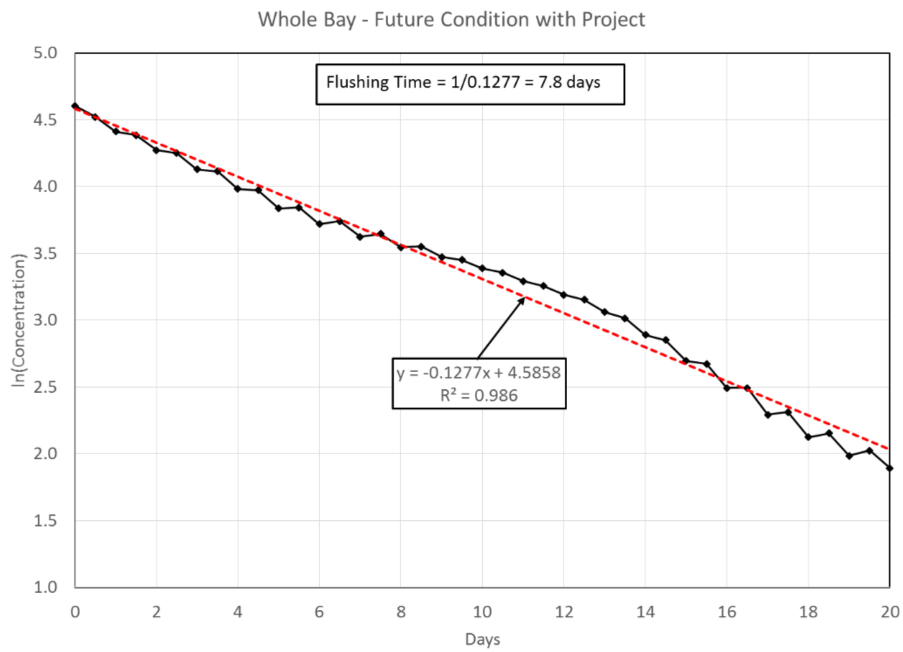
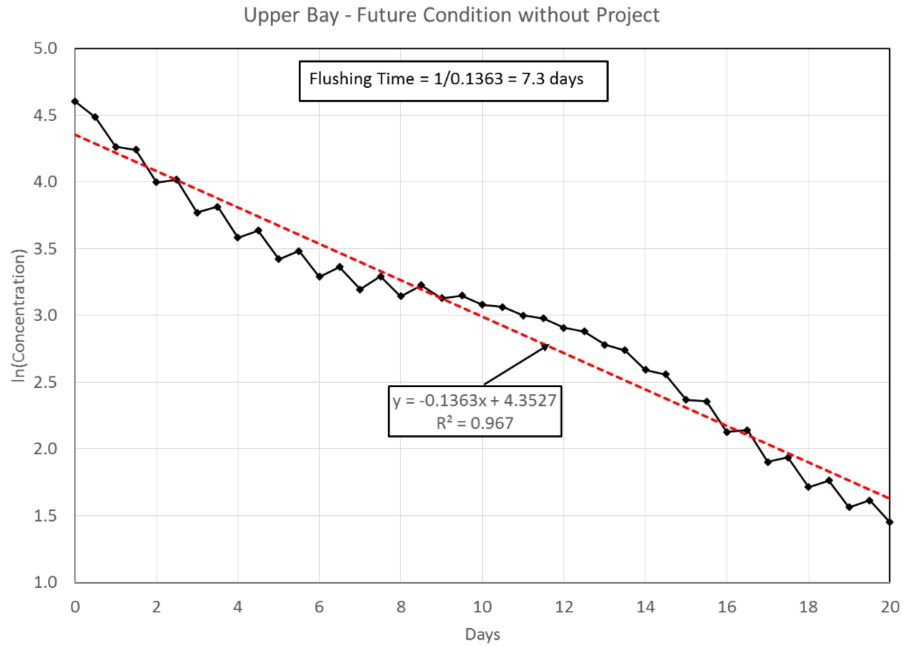


Figure 5-10 Future Condition: Whole Bay Region Flushing Time Analysis



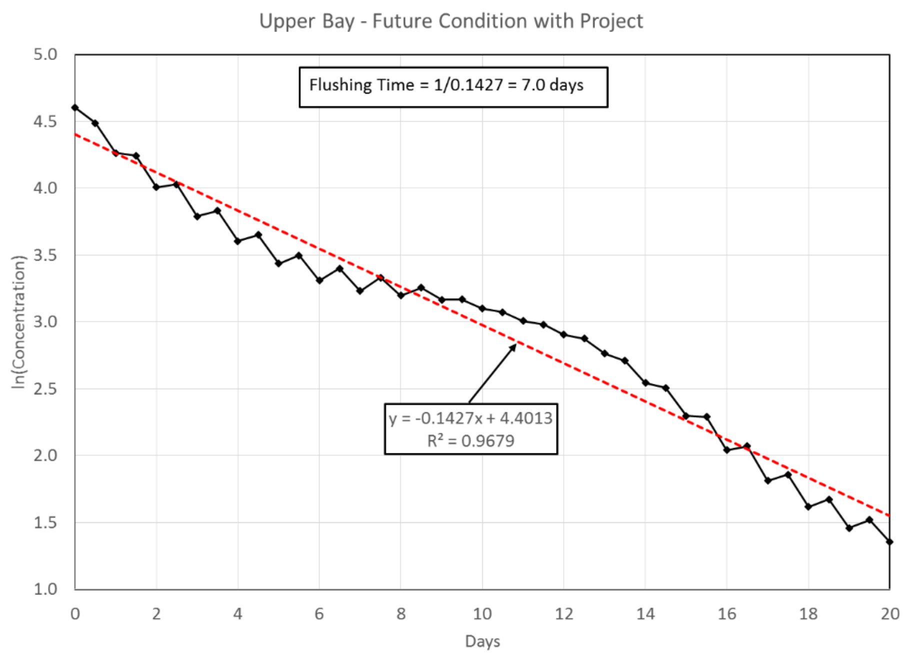


Figure 5-11 Future Condition: Upper Bay Region Flushing Time Analysis

5.2.2. Freshwater Age

Freshwater age values are somewhat reduced for future conditions with respect to existing conditions. Figure 5-12 presents the spatial variation in the steady state, tidal and depth-averaged freshwater residence time for *without Project* and *with Project* future conditions simulations, while freshwater age deviation is depicted in Figure 5-13. Averaged over the Whole Bay, freshwater age is 13.9 without project and 13.6 with Project. For the Upper Bay these values were estimated at 10.6 and 10.4, respectively. The conclusion is similar between existing and future conditions: little to very minor impacts on freshwater age are expected from the Project.

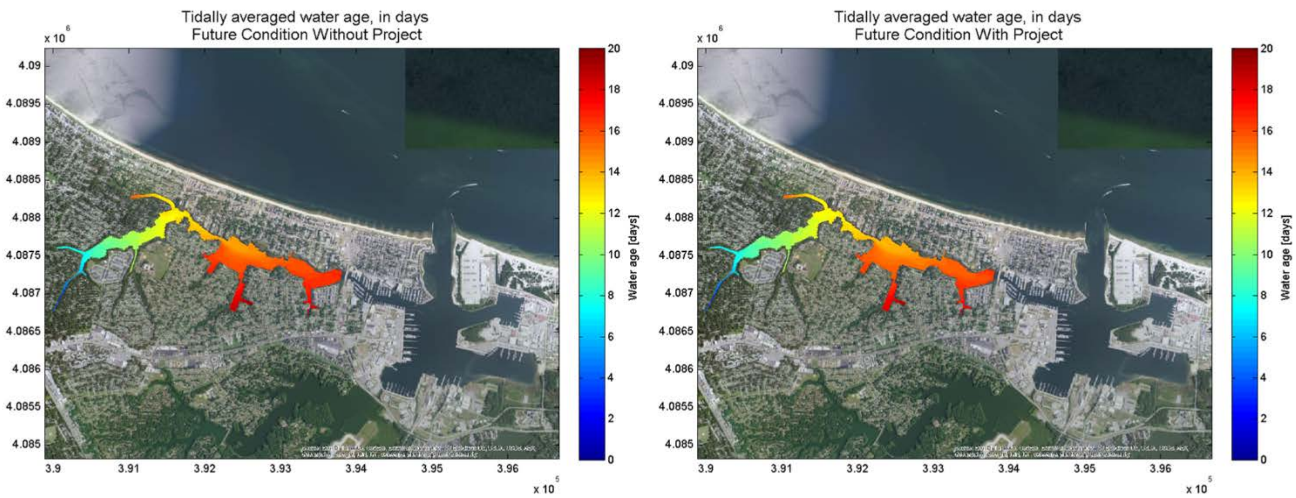


Figure 5-12 Future Condition: Steady State, Tidal-averaged Freshwater Age Without project (Left), and With Project (Right)

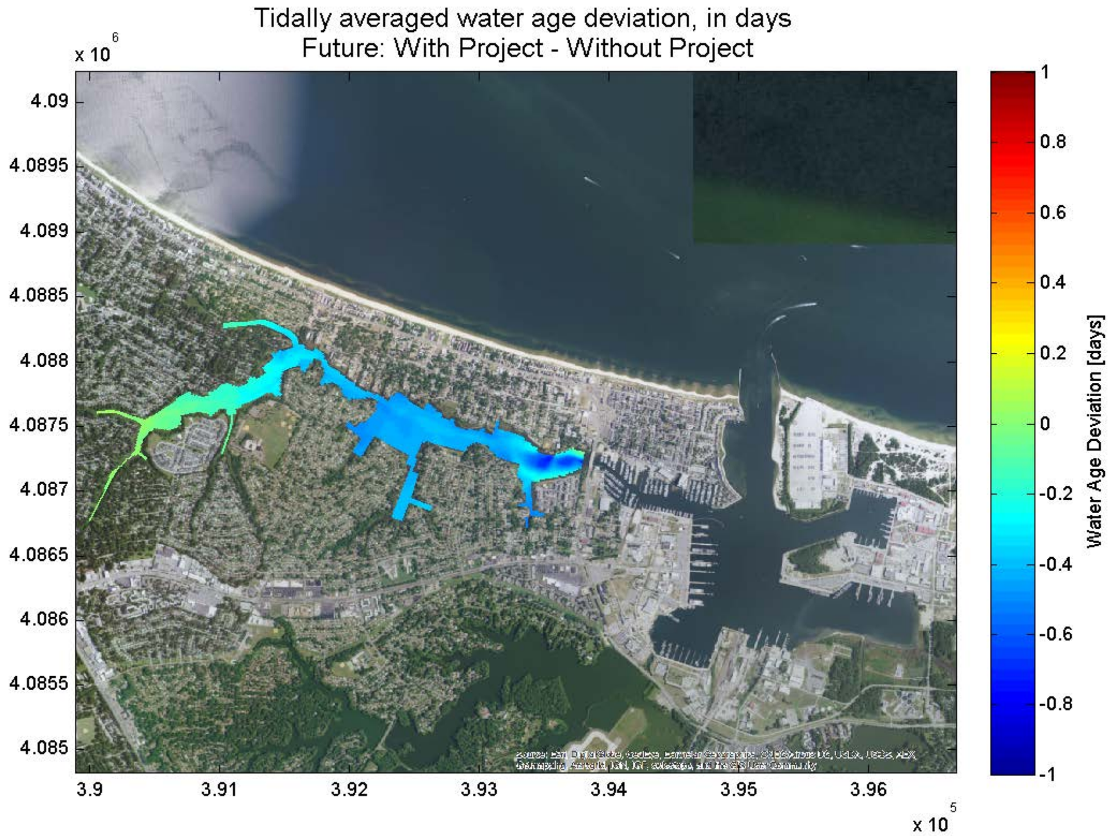


Figure 5-13 Future Condition: Freshwater Age Deviation.
With Project - Without Project

5.2.3. Salinity

Figure 5-14 and Figure 5-15 present the spatial variation in the steady-state, tidal and depth-averaged salinity for *with* and *without Project* simulations under future conditions. A slight increase in salinity values is observed with respect to the existing conditions cases.

Averaged salinities in the Whole Bay are estimated to be 22.5 ppt and 22.6 ppt, for the *without Project*, and *with Project* simulations, respectively. Upper Bay averaged salinities are 21.5 in both cases.

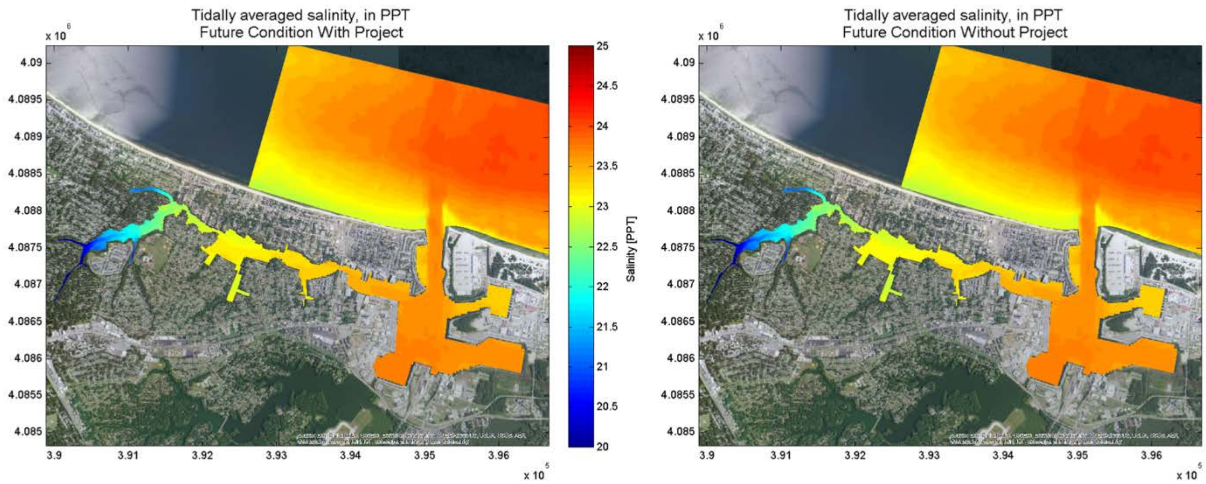


Figure 5-14 Future Condition: Steady State, Tidal-averaged Salinity Without project (Left), and With Project (Right)

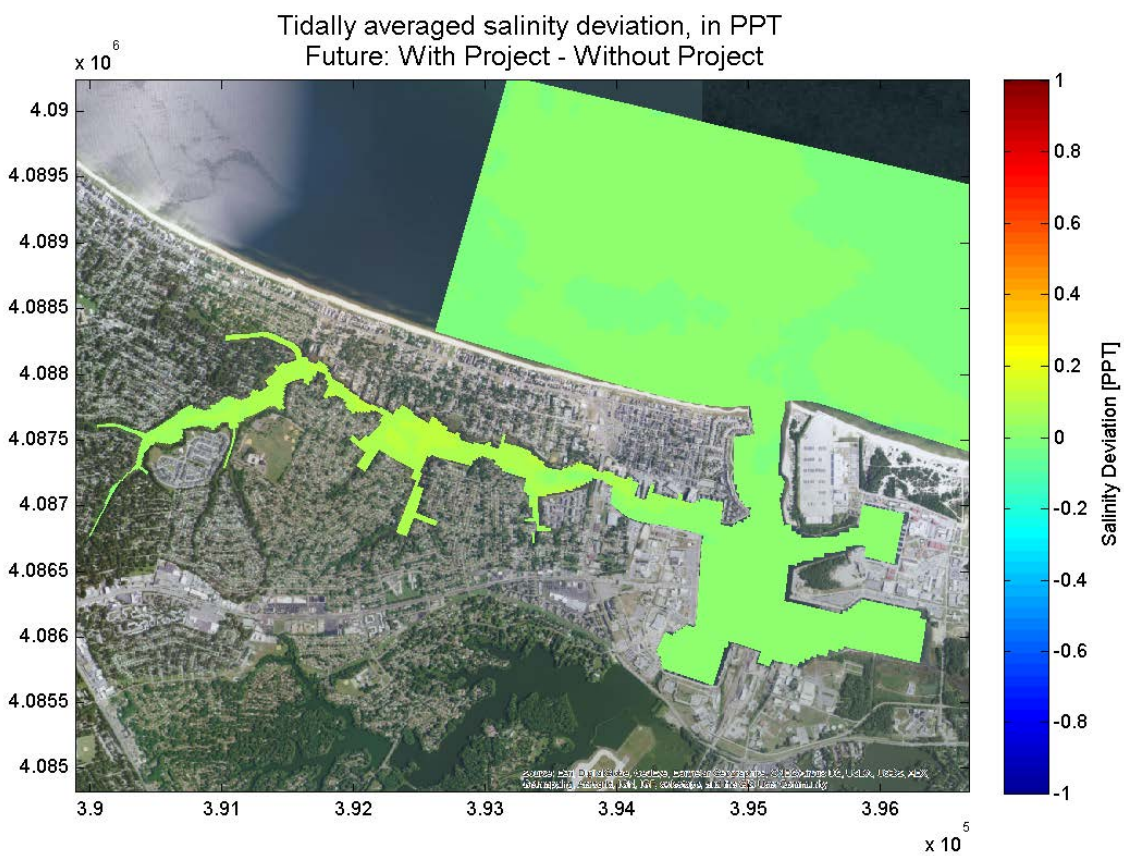


Figure 5-15 Existing Condition: Salinity Deviation. With Project - Without Project

5.3. Project Hydrodynamic Impacts

Figure 5-16 through Figure 5-19 in this section illustrate Project effects on the hydrodynamics in Pretty Lake under existing conditions. Project related impacts on future hydrodynamics are similar and are therefore not discussed in this section.

Results presented above indicate no remarkable Project related impact in water quality under typical conditions. However, *with Project* scenarios, present a trend of lower flushing times. Introduction of the proposed flood control structure in Pretty Lake reduces the cross-sectional area for flow exchange with Little Creek, resulting in alteration of the flow field. The depth-averaged velocity plots in Figure 5-16 and Figure 5-17 show the increase in peak flood and ebb velocities for the *with Project* simulations. With a narrower channel into the Bay, flow velocities, which normally accelerate at the gate alignment without the structure, are further increased from approximately 0.4 m/s *without Project* to 1.3 m/s *with Project* at peak flood and from 0.4 m/s to 1.5 m/s, respectively at peak ebb.

Figure 5-18 depicts the mean, flood and ebb tidal prism in Pretty Lake for the *with* and *without Project* simulations. The plots show no differences in the tidal prism between *with* and *without Project* scenarios, indicating that there is no tidal muting (i.e. the same amount of water being forced in and out of the Bay) introduced by the proposed structure.

Figure 5-19 shows surface flushing tracer concentrations (at six hour intervals) for the first 26 hours of simulation. The narrow channel configuration at the entrance of the Bay induces acceleration of the flow (even without the proposed structure) which promotes flushing of constituents out of the Bay. Nevertheless, a further reduction on the channel cross-sectional area, and the consequent increase in flow velocities explain the noted reduction in flushing times. For the *with Project* scenario, increased exit velocities during ebb results in a jet-like flow that exits the Bay with higher tracer concentrations than in the *without Project* scenario. The higher tracer concentrations that have exited the bay are then mixed with waters in Little Creek. A similar mechanism is observed during flood tides, where a jet with low tracer concentrations enters and enhances mixing in the Bay. For the *without Project* scenario, a less turbulent flow field results in more gradual mixing and consequently a slight reduction of the flushing rates (increase in flushing time).

It is noted that the Pretty Lake model has not been calibrated to flow velocities or salinities due to lack of on-site measurements. While the formulated conclusions regarding relative Project impacts on hydrodynamics and water quality would not change, an increase or decrease in the flow velocity magnitudes (after further calibration of the model) could result in different computed flushing times, salinities and freshwater age.

For design-phase studies, M&N recommends collection of field data (e.g. ADCP/CTD deployments on site) to pursue calibration of the model to flow velocities.

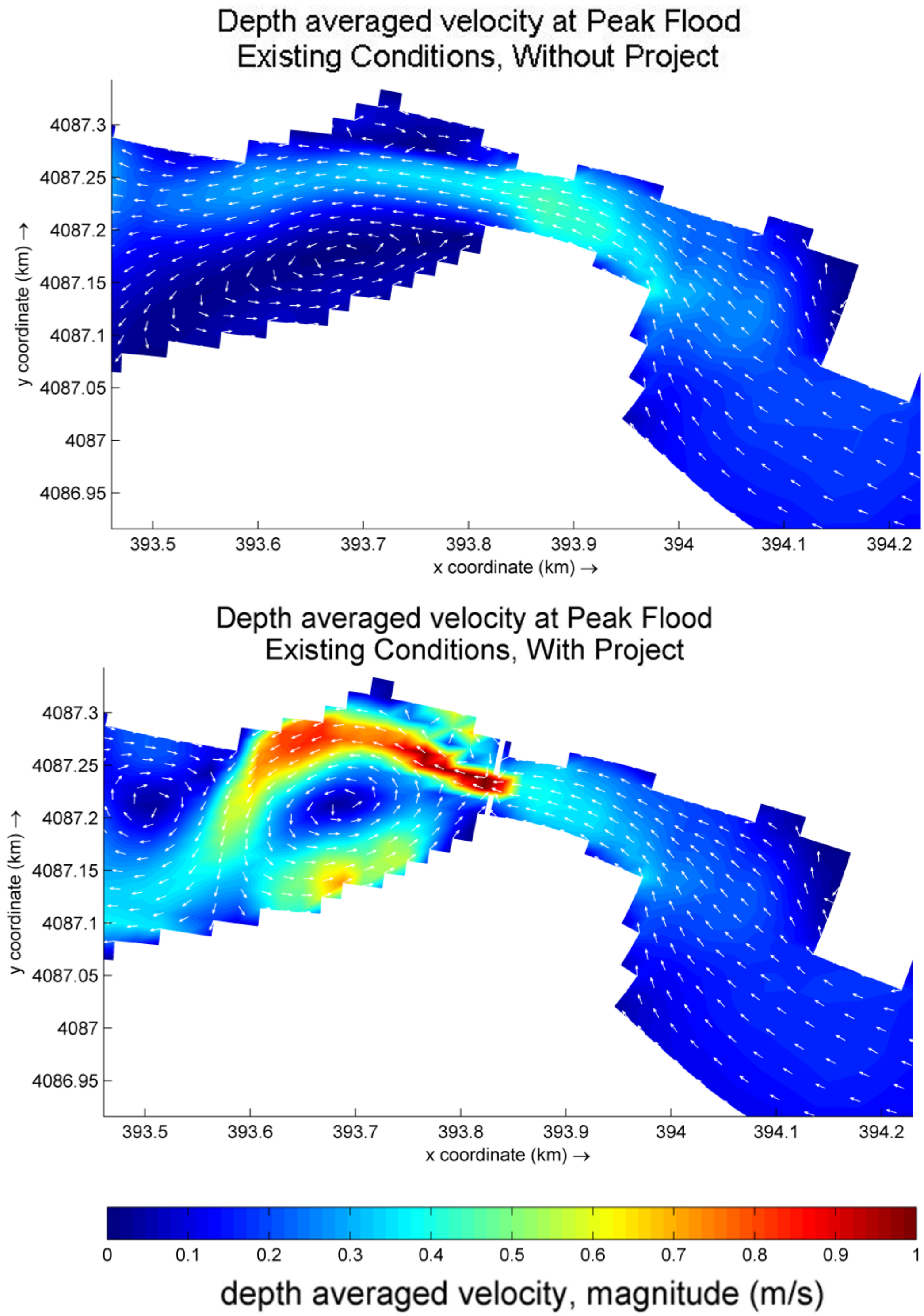


Figure 5-16 Depth Averaged Velocity at Peak Flood for the Without P Project (Top), and With Project (Bottom) Simulations

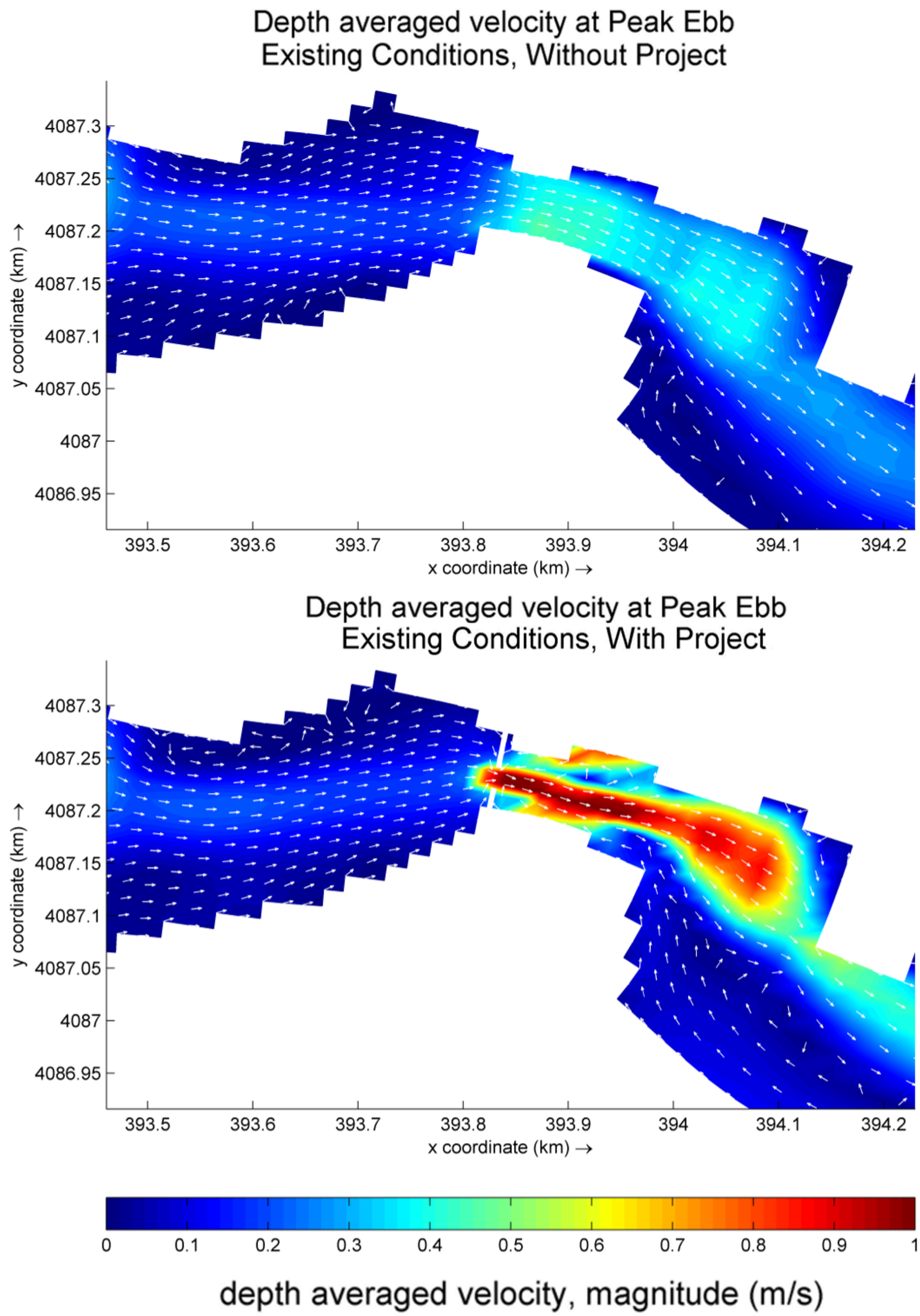


Figure 5-17 Depth Averaged Velocity at Peak Flood for the Without Project (Top), and With Project (Bottom) Simulations

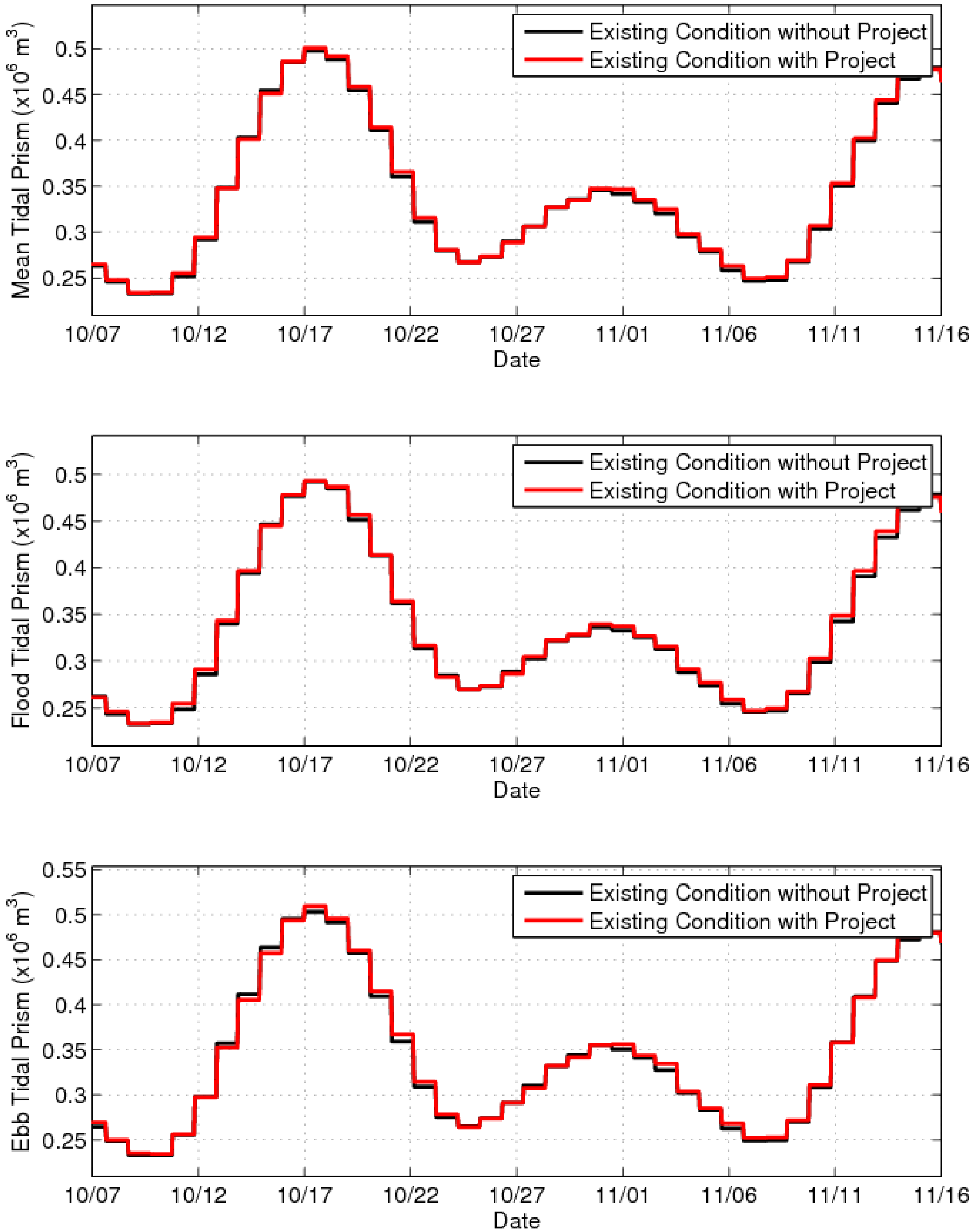
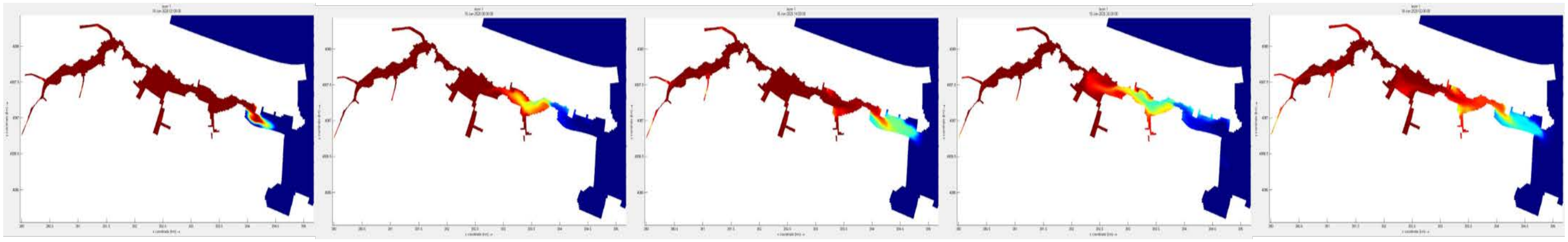
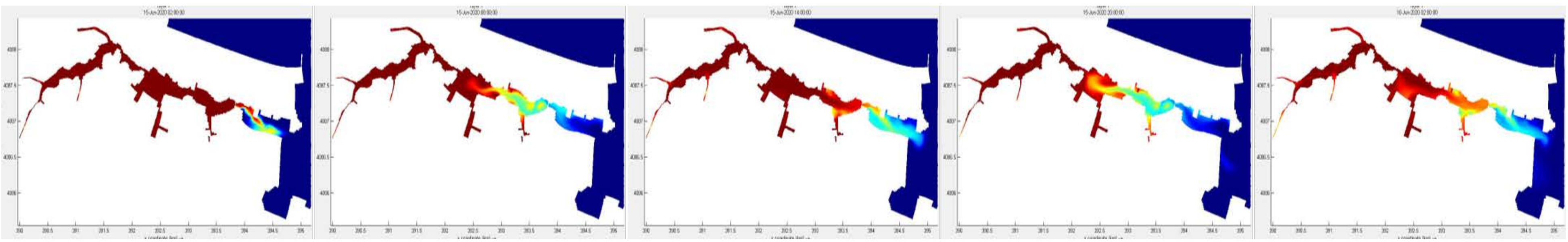


Figure 5-18 Mean (Top), Flood (Center), and Ebb (Bottom) Tidal Prism in the Bay for the With and Without Project Simulations

Tracer Concentration - Without Project
Simulation Hours: 02 to 26



Tracer Concentration - With Project
Simulation Hours: 02 to 26



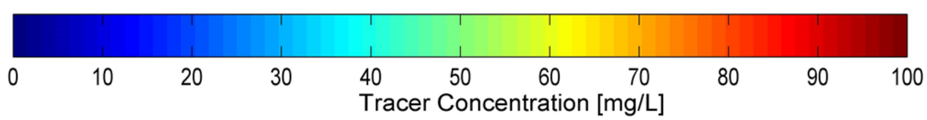


Figure 5-19 Flushing Tracer Concentrations (Simulation Hours 2-26) Without Project (Top) and With Project (Bottom)

5.4. Summary

A summary of the findings in the typical late-summer conditions simulations is provided in Table 5-1. Project impacts are negligible under both existing and future conditions. Metrics in Table 5-1 indicate slightly increased flushing rates *with Project* due to increased secondary, residual circulation associated with higher flow velocities and flow velocity gradients through the gate structure.

Table 5-1 Typical Conditions Simulation Results Summary

Scenario	Whole Bay			Upper Bay		
	Flushing Time (days)	**Freshwater Age (days)**	**Salinity (ppt)**	**Flushing Time (days)**	**Freshwater Age (days)**	**Salinity (ppt)**
Existing condition *without Project*	9.5	14.6	21.9	12.3	11.6	19.9
Existing condition *with Project*	8.6	14.4	22.0	11.0	11.6	19.9
Future condition *without Project*	8.7	13.9	22.5	7.3	10.6	21.5
Future condition *with Project*	7.8	13.6	22.6	7.0	10.4	21.5

6. Post-Storm Recovery Results

To evaluate post-storm recovery, time series of freshwater tracer concentrations and salinity at four locations upstream of the proposed flood control structure are presented in the following sections. Figure 6-1 depicts the location of the monitoring stations.

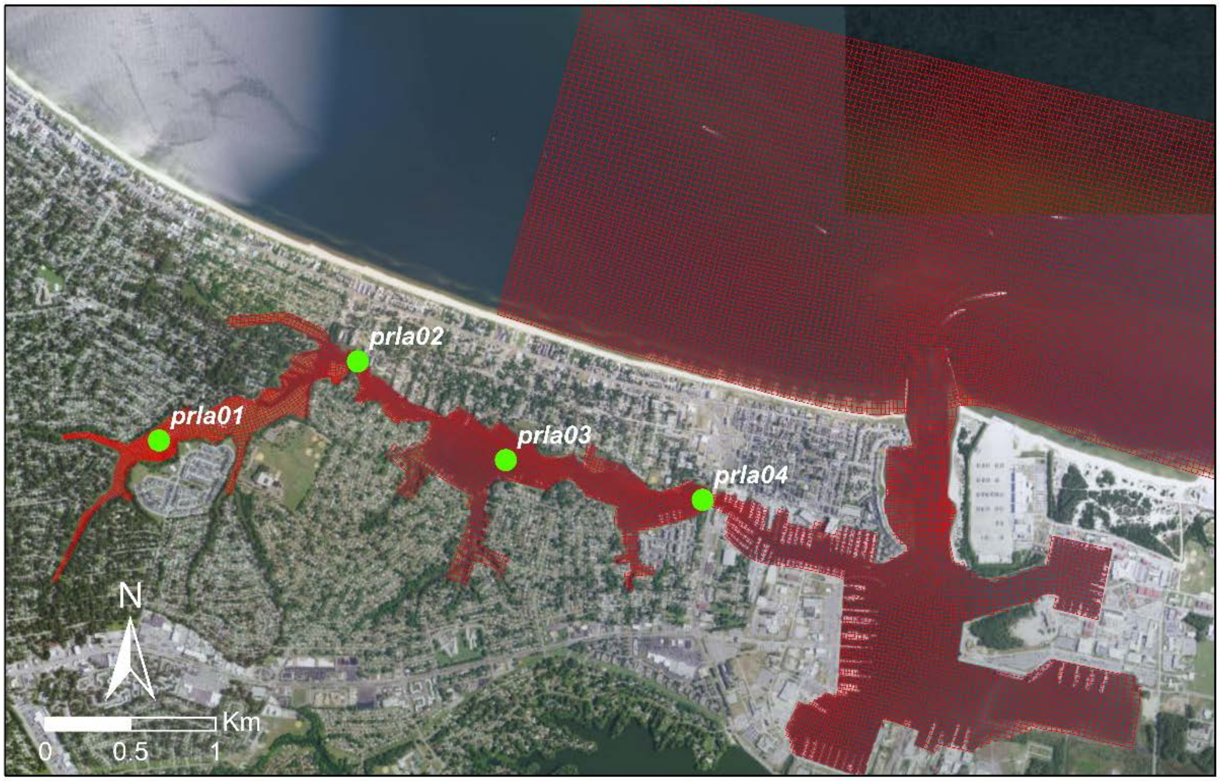


Figure 6-1 Monitoring Stations for Water Quality Evaluation

6.1. Existing Conditions

Depth averaged freshwater tracer concentrations and salinity are plotted through time in Figure 6-2 through. Figure 6-5. Time *zero* in the plots corresponds to the beginning of the storm simulation, when the flood gates are closed. *Gate Open* on the time axes indicates the time of gate re-opening after the storm.

With Project, and prior to gate re-opening, freshwater tracer concentrations exhibit higher values in the upstream area, which is more influenced by runoff sources. For the *without Project* scenario, the non-interrupted flow exchange with Little River results in flushing of the freshwater tracers during the storm period, consequently exhibiting lower concentrations through time, when compared to the *with Project* scenario.

After the gates re-open, conservative tracer concentrations for the *with Project* scenario are greater than those *without Project*, but eventually (i.e., after about 30 days in upstream stations) decrease to similar values of *without Project* concentrations. For the more downstream stations, conservative tracer concentrations reach the same low levels sooner. Flushing of the decaying tracers practically occurs at the same rate for the *with* and *without Project* scenarios at all stations.

The freshwater conservative tracer is almost completely flushed out after 30 days or less of gate re-opening for all simulated scenarios at all stations, while the decaying tracer has decayed and flushed after about 7 days or less.

In upstream stations, an approximate period of 25 days after gate re-opening is required for salinity values in the *with Project* scenarios to coincide with those in the *without Project* scenario. Salinity coincidence occurs much faster for the downstream stations (almost immediately after gate re-opening).

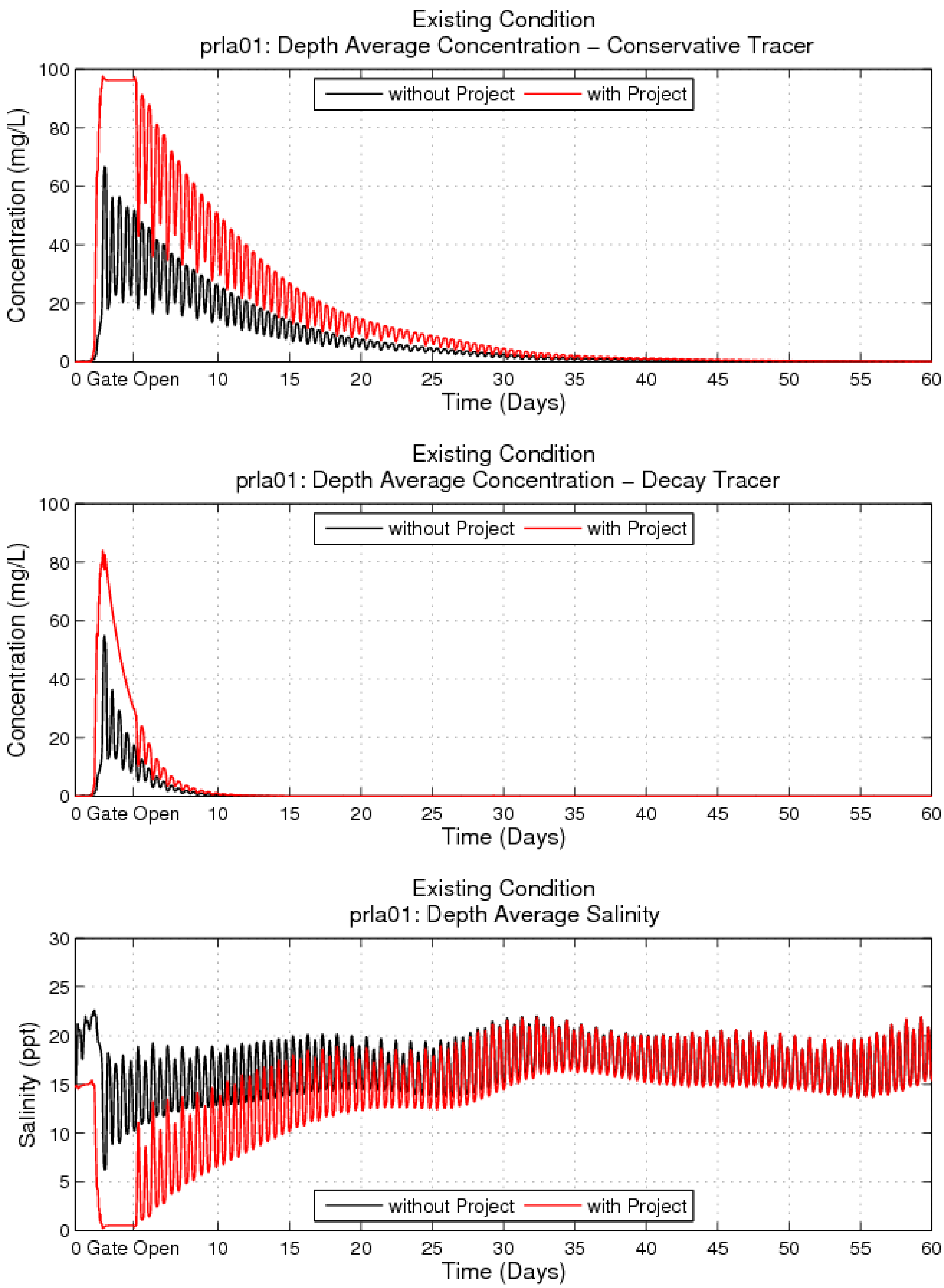


Figure 6-2 Existing Condition: Depth Averaged Tracer Concentrations and Salinity at prla01 Station

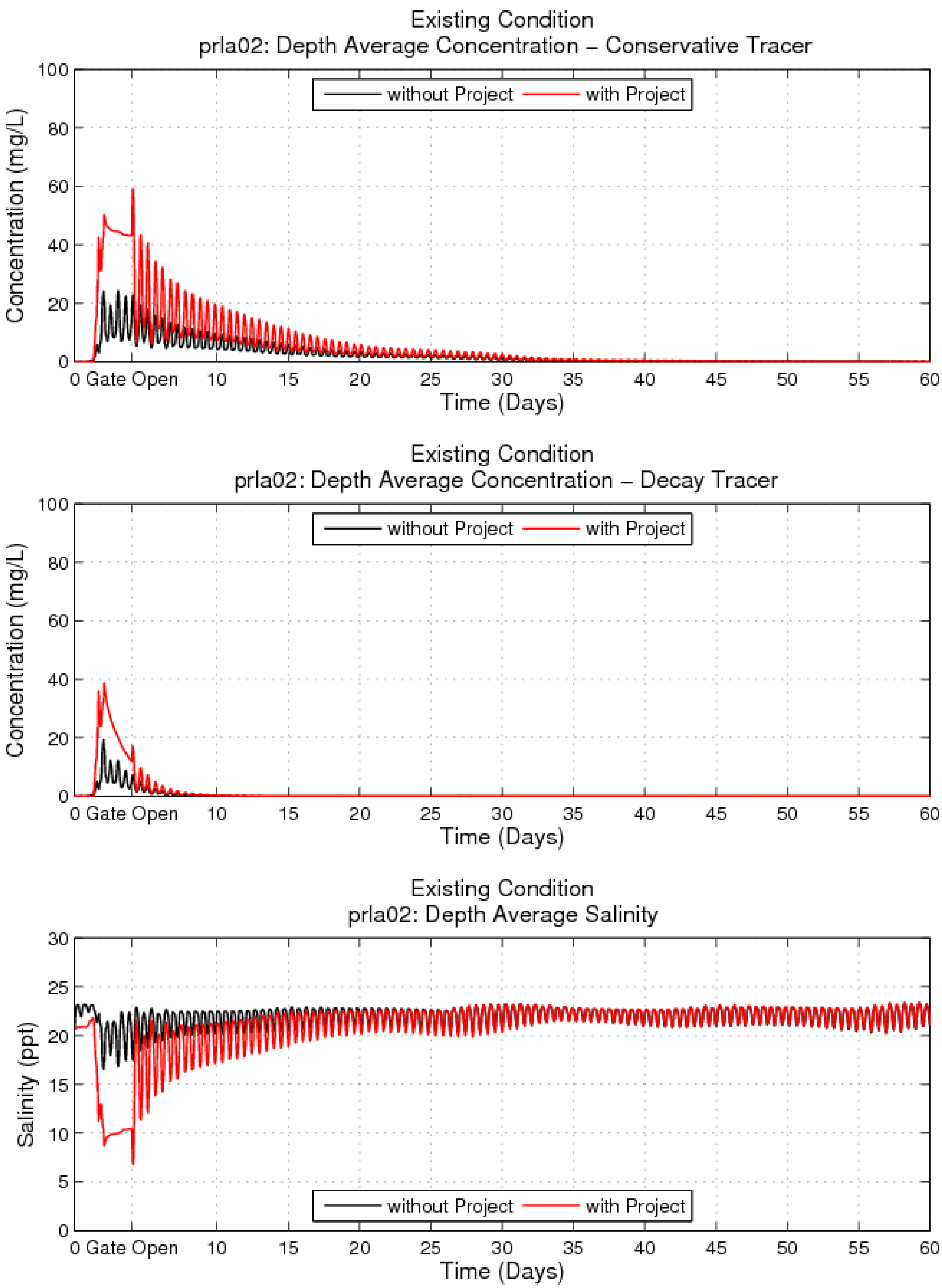


Figure 6-3 Existing Condition: Depth Averaged Tracer Concentrations and Salinity at prla02 Station

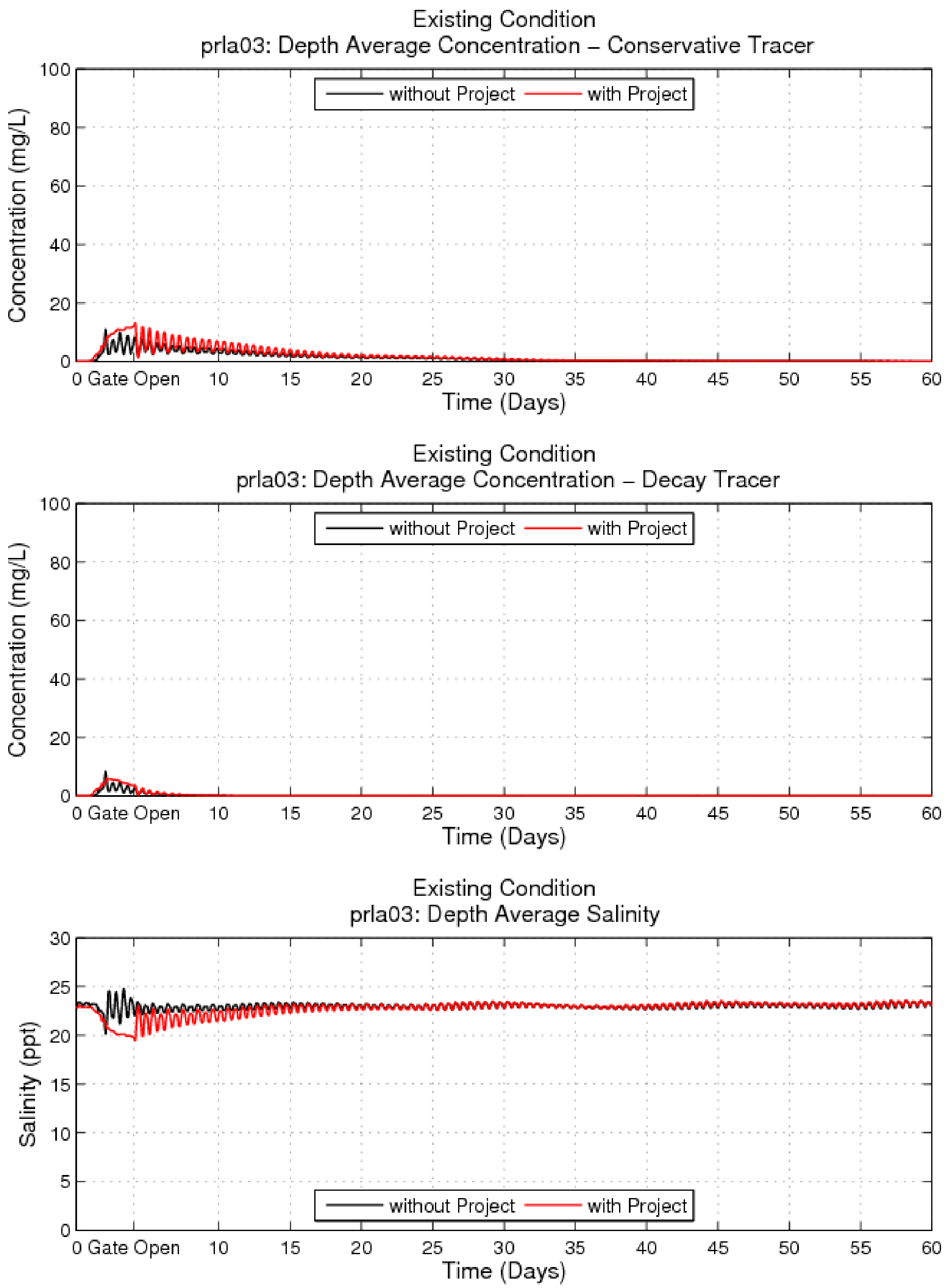


Figure 6-4 Existing Condition: Depth Averaged Tracer Concentrations and Salinity at prla03 Station

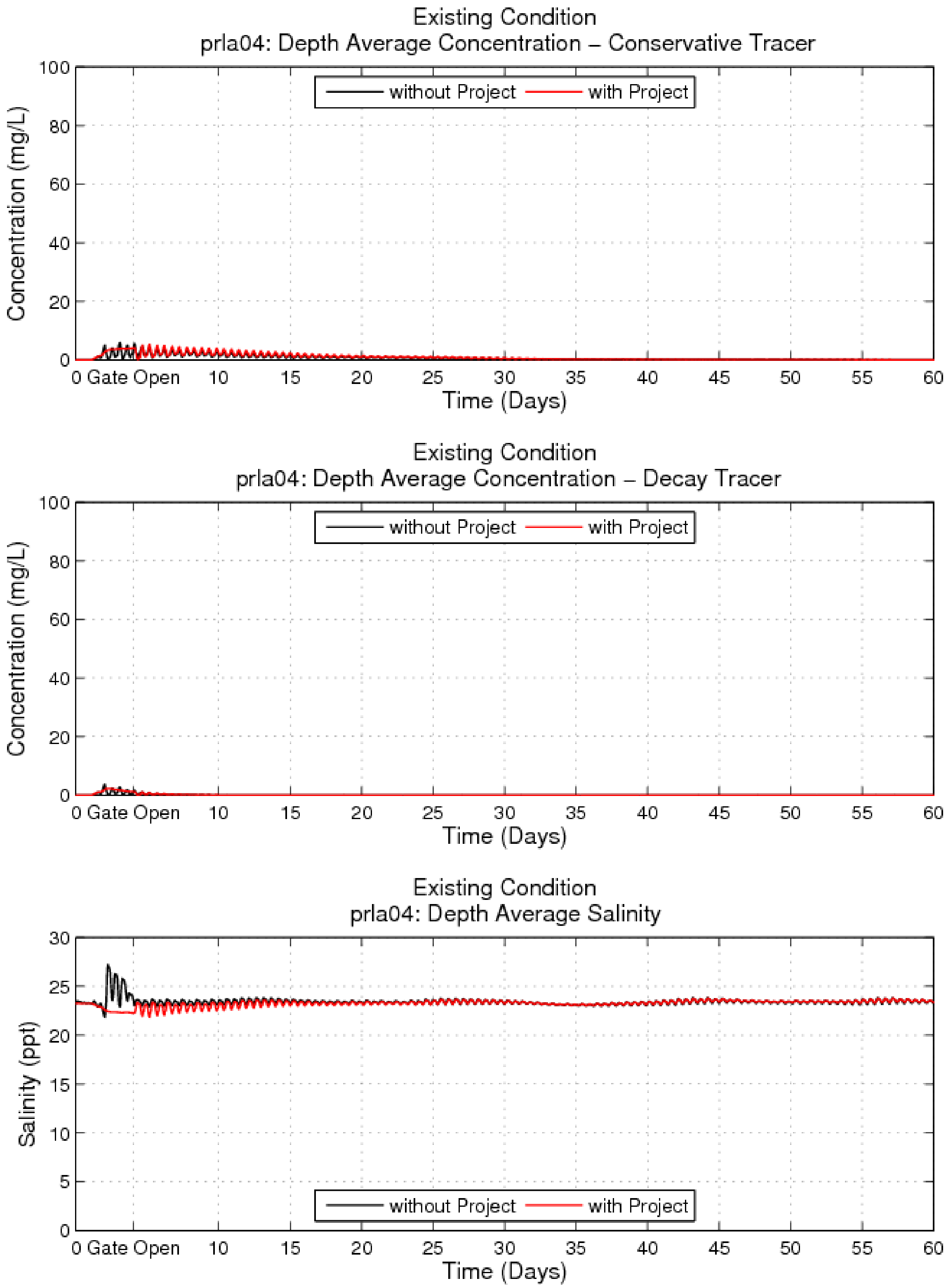


Figure 6-5 Existing Condition: Depth Averaged Tracer Concentrations and Salinity at prla04 Station

6.2. Future Conditions

Under future conditions, the larger flow exchange in the bay with the Little Creek system, resulting from increased sea levels, is reflected in the higher deviation of tracer concentrations and salinity between the *with* and *without Project* scenarios at the moment of gate re-opening when compared to the existing conditions.

The time required for the conservative tracer to be almost completely flushed out of the bay is somewhat reduced (by about 7 days) for all stations and all future conditions scenarios.

The period required for salinity values in the *with Project* scenarios to coincide with those in the *without Project* scenario is also decreased (by about 5 days).

Similar conclusions can be drawn for the flushing time and salinity responses between the *with* and *without Project* scenarios, when compared to the existing conditions.

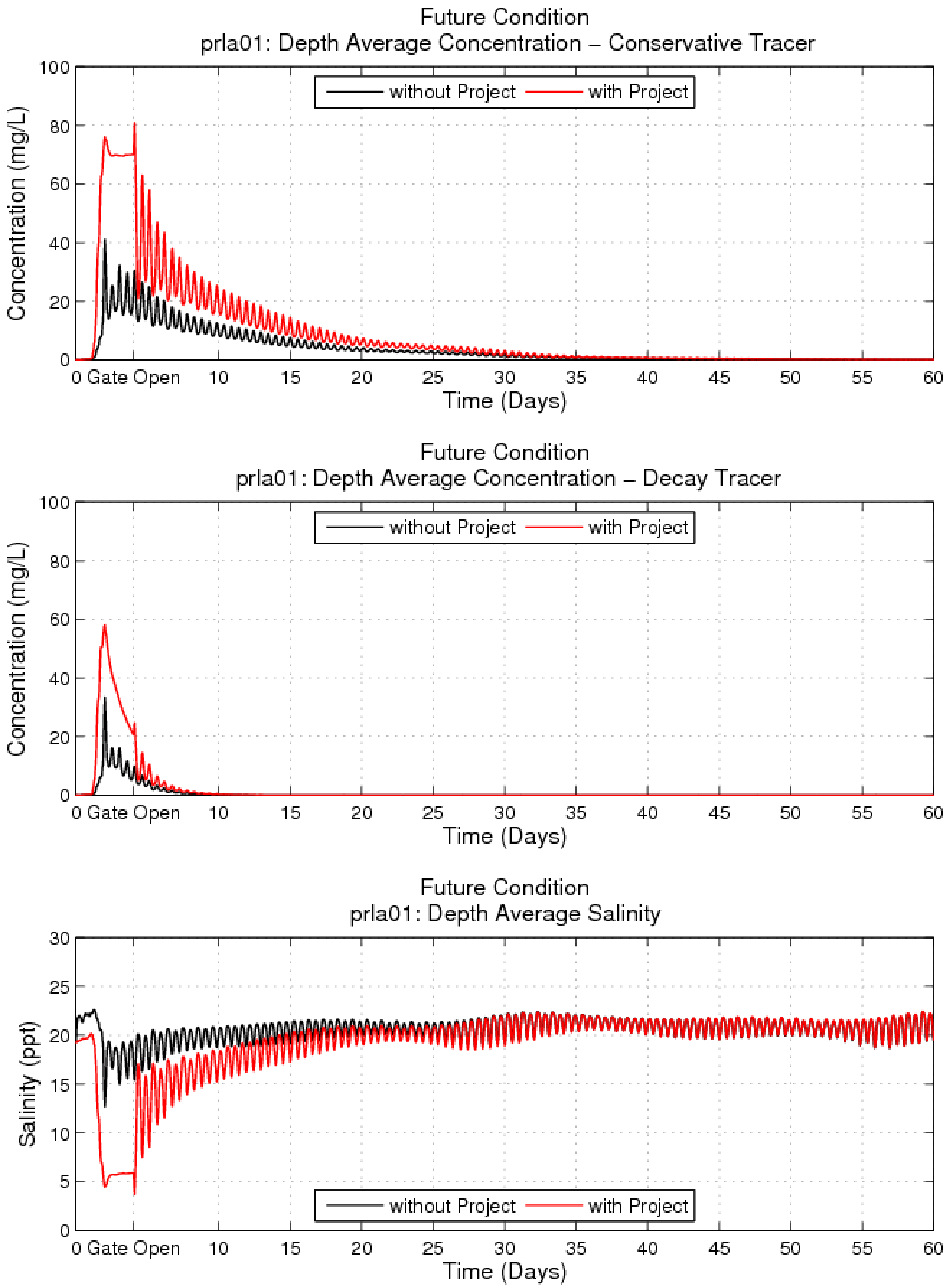


Figure 6-6 Future Condition: Depth Averaged Tracer Concentrations and Salinity at prla01 Station

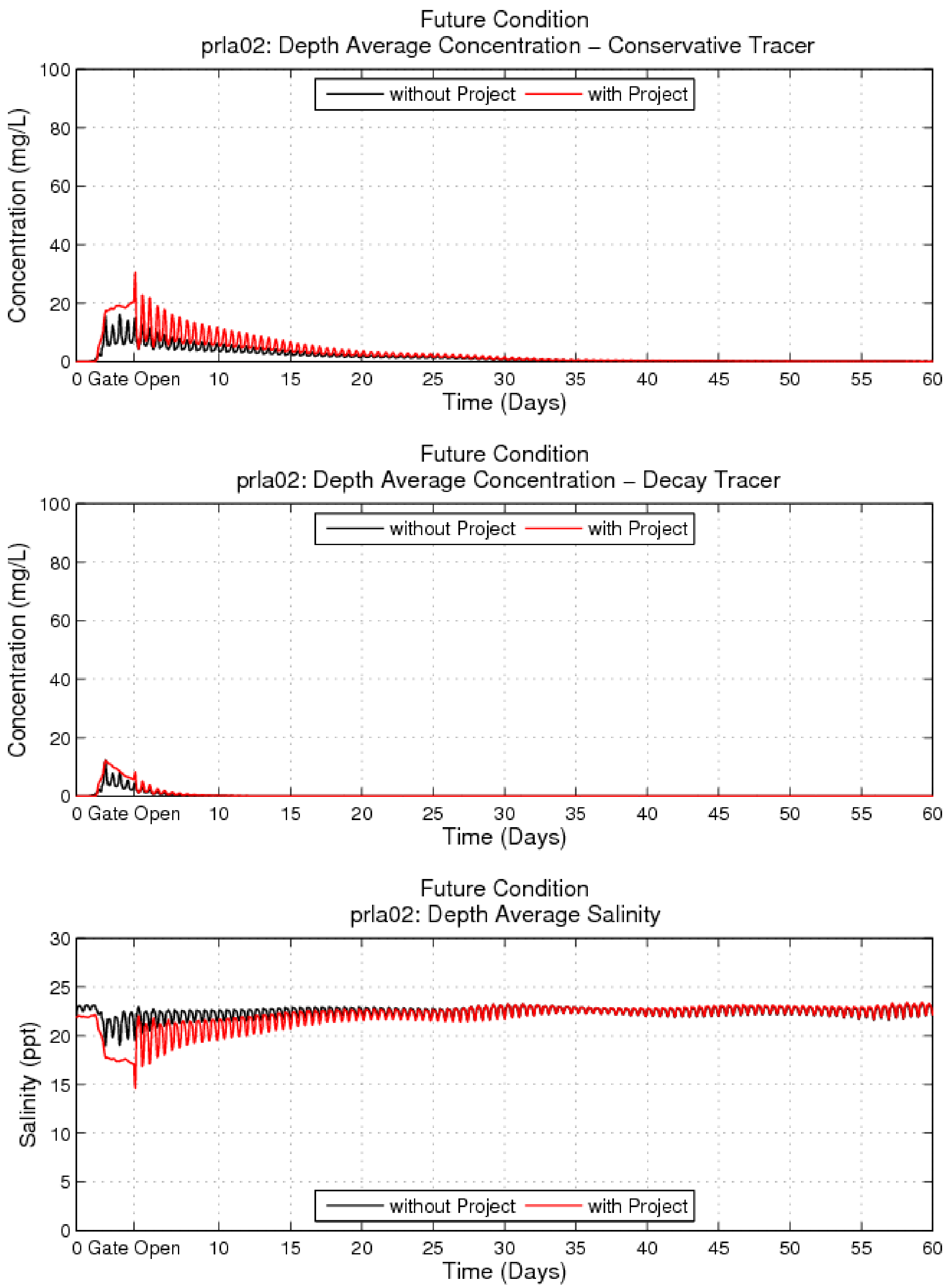


Figure 6-7 Future Condition: Depth Averaged Tracer Concentrations and Salinity at prla02 Station

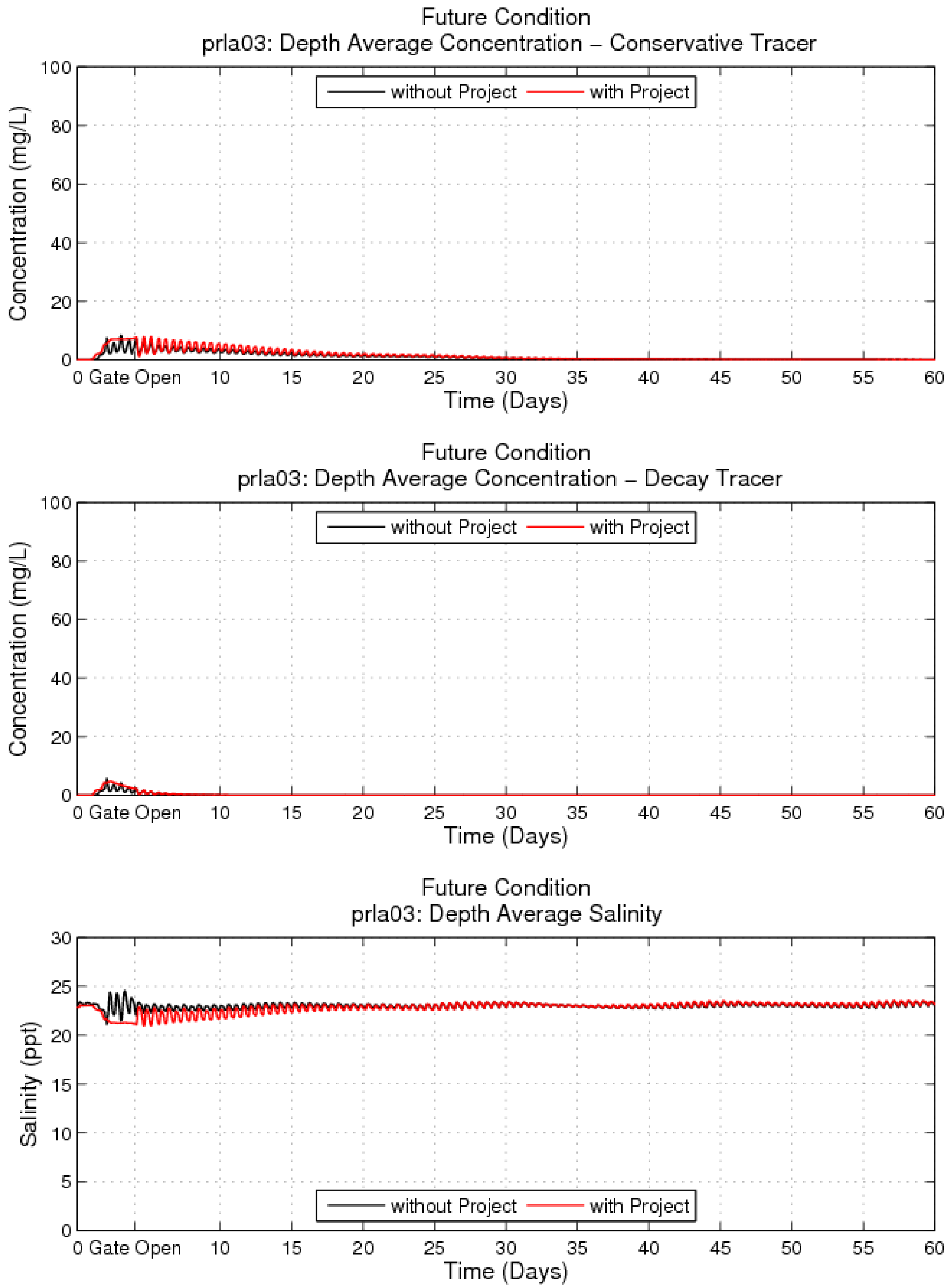


Figure 6-8 Future Condition: Depth Averaged Tracer Concentrations and Salinity at prla03 Station

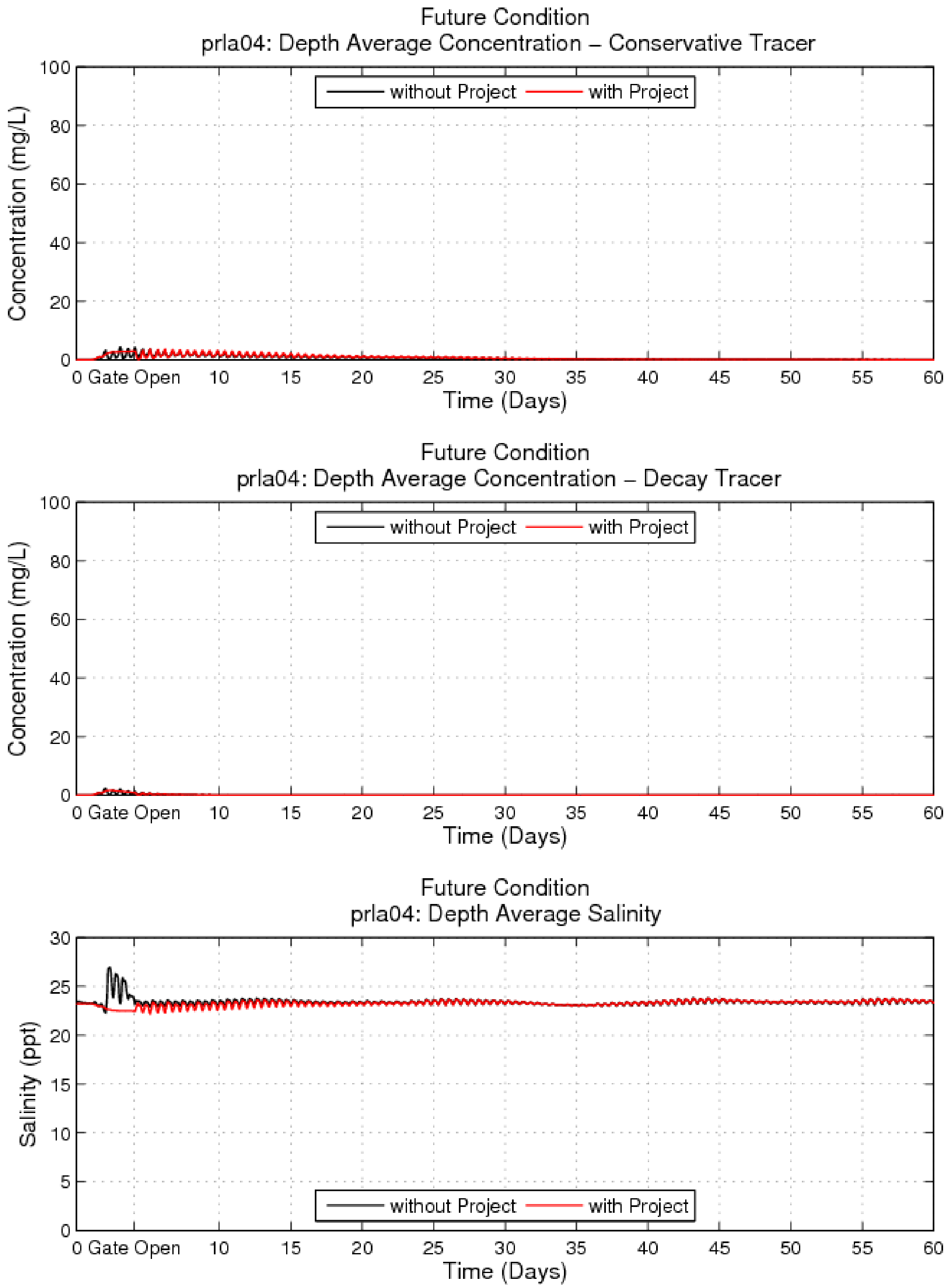


Figure 6-9 Future Condition: Depth Averaged Tracer Concentrations and Salinity at prla04 Station

6.3. Summary

Results provided above suggest minor project impacts on water quality recovery time after gate closure during storms and following re-opening. In summary:

- Recovery time decreases from upstream to downstream stations.
- Conservative tracer concentrations *with Project* are higher during and immediately following gate re-opening, but decline to *without Project* concentrations within 30 days (or less in downstream stations).
- The time required for the conservative tracer to be almost completely flushed out of the bay is somewhat reduced for all stations for all future conditions scenarios.
- All decaying tracer concentrations are gone in 7 days or less for all stations and all scenarios.
- Salinity for *with Project* coincides with salinity for *without Project* after about 25 days (or less in downstream stations) under existing conditions scenarios, and after 20 days or less under future conditions scenarios.

7. Summary and Conclusions

Hydrodynamic modeling and computation of water quality parameters (in terms of flushing, residence time, and salinity) were conducted in this study to determine potential CRSM Project impacts in Pretty Lake. Overall, negligible to minor Project related impacts were found on the computed water quality parameters.

7.1. Typical Conditions Water Quality Impacts

Regarding project impacts on typical conditions water quality, the following conclusions are drawn:

- Deviations in the tidally-averaged freshwater age and tidally-averaged salinity between the between *without Project* and *with Project* scenario are negligible under both existing and future conditions.
- Slightly increased flushing rates (decreasing flushing times) are computed for the *with Project* scenarios, which can be explained by an increase in secondary, residual circulation caused by increased velocity gradients associated with the gate structure.
- Relative Project impacts are consistent between existing and future conditions simulations.
- Future rise in sea levels result in overall higher flushing rates (decreased flushing times) and tidally-averaged salinities than under present-day sea levels.

7.2. Post-storm Recovery Water Quality Impacts

Regarding Project impacts on post-storm water quality recovery time, the following conclusions are drawn:

- Recovery time decreases from upstream to downstream regions in the Bay.
- Following gate re-opening, conservative tracer concentrations are higher for the *with Project* scenarios but decline to *without Project* concentrations with 30 days (or less in downstream regions).
- The time required for the conservative tracer to be almost completely flushed out of the bay is somewhat reduced for all stations for all future conditions scenarios
- Salinity for *with Project* coincides with salinity for *without Project* after about 25 days (or less in downstream regions) under present-day sea level conditions and about 20 days or less under future sea level conditions.

7.3. Further Recommendations

M&N recommends collection of field data (e.g. ADCP and CTD deployments on site) to pursue calibration of the model to both flow velocities and salinities. While a refined analysis with a calibrated model would not alter the formulated conclusions regarding relative Project impacts (nor the current model calibration to water levels), modeled flow velocities, affecting primarily flushing rates, and salinities could differ some from those presented herein.

Later phases of the CRSM Project would benefit from on-site measurements that will support the Elizabeth River/Broad Creek model to be used as a design-phase tool.

8. References

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