HYDRODYNAMIC MODELING AND INITIAL WATER QUALITY EVALUATIONS SUPPORTING THE FEDERAL FEASIBILITY STUDY AND NEPA DOCUMENTATION – BROAD CREEK

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Prepared by:
moffatt & nichol
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 Broad Creek 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 Broad Creek 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.

Overall, negligible to minor Project related impacts were found on the computed water quality parameters. A summary of the findings from both analyses is presented below.

Water Quality Analysis for Typical Conditions

- Flushing times, tidally-averaged freshwater age and tidally-averaged salinity values show negligible differences between without Project and with Project Alternative 1 scenario.

- Higher but still minor deviations in the parameters were computed between the without Project and with Project Alternative 2 scenarios: Secondary circulation patterns and a mechanism for enhanced mixing introduced by the proposed flood control structure result in flushing times and tidally-averaged freshwater age to be slightly reduced (2 days or less), and tidally-averaged salinity to be slightly increased (about 1 ppt or less).

- 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.

Water Quality Analysis for Post-Storm Recovery Conditions

- Recovery time decreases from upstream to downstream regions in the Bay.

- No remarkable deviation in tracer concentrations and salinity through time are found between the two with Project scenarios.
• Following gate re-opening, conservative tracer concentrations are higher for the *with Project* scenarios but decline to *without Project* concentrations within 20 days (or less in downstream regions).

• Future sea-level conditions increase the amount of time required for conservative tracers to be almost completely flushed out in the upstream region of Broad Creek. The opposite occurs in downstream areas.

• Salinity for *with Project* coincides with salinity for *without Project* after about 10 days (or less in downstream regions) under present-day sea level conditions and about 20 days or less under future sea level conditions.

• Salinity recovers to pre-storm conditions (i.e. steady state conditions) after about 25 days for all conditions and all stations.
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1. Introduction

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 Broad Creek 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.

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 1-1 and 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](image-url)
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 Broad Creek. To achieve this, the scope of work included the following:

1. Model development
   A three-dimensional hydrodynamic model of the Elizabeth River and Broad Creek 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 the modeled water levels and salinities 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 Broad Creek. 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 Broad Creek. Evaluation of these metrics allowed for a qualitative assessment of potential project impacts on water quality in Broad Creek. 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 $\sigma$-grid, with a vertical layer thickness varying with the water depth, and a constant number of active layers (denoted as the $\sigma$-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

The computational domain for the Elizabeth River/Broad Creek model extends from the Elizabeth River mouth at Sewell’s Point through its western, southern, and eastern Branches; the latter of which includes Broad Creek (Figure 2-1). The model was developed into a single grid of 11,493 elements for computational efficiency purposes.

Resolution for the curvilinear modeling grid varies according to the desired degree of detail in the physical processes and the simulation results. The highest horizontal grid resolution, approximately 5 m to 20 m (16 ft. to 65 ft.), was set for the Broad Creek region (Figure 2-2) and the areas connecting with the East Branch Elizabeth River, while a coarser horizontal grid, with resolution up to 260 m (850 ft.) was set for the rest of the modeling domain. The vertical grid consists of six equally-spaced $\sigma$ layers.
The model has a single 2.5-km long open boundary at Sewell’s Point at which hydrodynamic conditions are input to force the model.

Figure 2-2 shows the proposed alignment of the CRSM flood control structure (Project) in Broad Creek, which was incorporated to the computational grid in the form of 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 2-2 Grid Resolution and proposed Structure Alignment in Broad Creek
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 2-1 provides a list of the data sets and sources included in the Elizabeth River/Broad Creek model bathymetry. The model bathymetry is depicted in Figure 2-3.

Table 2-1 Bathymetry Data Sources for the Elizabeth River/Broad Creek Model

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norfolk Harbor Project Condition Survey</td>
<td>USACE, 2016-2017</td>
</tr>
<tr>
<td>Southern Branch of the Elizabeth River Project Condition Survey</td>
<td>USACE, 2016</td>
</tr>
<tr>
<td>Hydrographic Survey H12282: Lamberts Point to Pescara Creek</td>
<td>NOAA-NOS, 2011</td>
</tr>
<tr>
<td>Hydrographic Survey H12285: Eastern Branch to Money Point</td>
<td>NOAA-NOS, 2011</td>
</tr>
<tr>
<td>Broad Creek Hydrographic Condition Survey</td>
<td>City of Norfolk, 2010</td>
</tr>
<tr>
<td>Virginia Beach, Virginia Coastal Digital Elevation Model (DEM)</td>
<td>NOAA, 2016</td>
</tr>
<tr>
<td>Norfolk, VA LiDAR</td>
<td>USGS, 2014</td>
</tr>
</tbody>
</table>
Figure 2-3 Model Bathymetry (m, NAVD88)
3. Model Calibration

3.1. Introduction

The combined Elizabeth River/Broad Creek hydrodynamic model was calibrated for water levels and salinity. Hourly water level measurements inside the model domain are available from tide gauges at three locations: Haven Creek in the Lafayette River, Downtown Norfolk near Nauticus, and at Virginia Beach Boulevard in Broad Creek (Figure 2-1). Monthly observations of surface and bottom salinity at five point locations inside the model domain are available from the Virginia Estuarine and Coastal Observing System (VECOS). Locations of the calibration stations are indicated in Figure 2-1 and Table 3-1.

Table 3-1 Water Level and Salinity Calibration Stations

<table>
<thead>
<tr>
<th>Longitude</th>
<th>Latitude</th>
<th>Station Name</th>
<th>Measurement type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>-76.283°</td>
<td>36.884°</td>
<td>Haven Creek (HC)</td>
<td>Water Level</td>
<td>City of Norfolk</td>
</tr>
<tr>
<td>-76.193°</td>
<td>36.925°</td>
<td>Downtown Pumping Station (PS)</td>
<td>Water Level</td>
<td>City of Norfolk</td>
</tr>
<tr>
<td>-76.258°</td>
<td>36.891°</td>
<td>Virginia Beach Boulevard (VB)</td>
<td>Water Level</td>
<td>City of Norfolk</td>
</tr>
<tr>
<td>-76.338°</td>
<td>36.905°</td>
<td>LE5.6</td>
<td>Salinity</td>
<td>VECOS</td>
</tr>
<tr>
<td>-76.339°</td>
<td>36.882°</td>
<td>ELI2</td>
<td>Salinity</td>
<td>VECOS</td>
</tr>
<tr>
<td>-76.289</td>
<td>36.841°</td>
<td>EBE1</td>
<td>Salinity</td>
<td>VECOS</td>
</tr>
<tr>
<td>-76.296</td>
<td>36.769°</td>
<td>SBE5</td>
<td>Salinity</td>
<td>VECOS</td>
</tr>
</tbody>
</table>

Based on the availability of data for all calibration stations, a three-month simulation period for the calibration runs was set from August 1, 2010 to October 31, 2010. The calibration procedure consisted in performing a series of iterative runs where calibration parameters for water levels and salinity were adjusted systematically until the modeled data was found to be in good agreement with measured data. The model was first calibrated for water levels and then for salinity.
3.2. Calibration Setup

A list of the data sets and sources that were input to the Elizabeth River/Broad Creek model for calibration simulations is given in Table 3-2, and explained in the following sections.

Table 3-2 Data Sets and Sources for Calibration Simulations

<table>
<thead>
<tr>
<th>No.</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Station Name</th>
<th>Measurement type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-76.330°</td>
<td>36.946°</td>
<td>Sewell’s Point (8638610)</td>
<td>Water Level</td>
<td>NOAA-COOPS</td>
</tr>
<tr>
<td>2</td>
<td>-76.113°</td>
<td>36.960°</td>
<td>Chesapeake Bay Bridge Tunnel (8638863)</td>
<td>Wind</td>
<td>NOAA-COOPS</td>
</tr>
<tr>
<td>3</td>
<td>-76.258°</td>
<td>36.891°</td>
<td>N/A (Model Open Boundary)</td>
<td>Salinity</td>
<td>VIMS</td>
</tr>
<tr>
<td>4</td>
<td>Various</td>
<td>Various</td>
<td>N/A</td>
<td>Fresh Water Inflows</td>
<td>VADEQ via VIMS</td>
</tr>
</tbody>
</table>

3.2.1. Water Level Boundary

The hydrodynamic model was forced with measured water levels from NOAA-COOPS Sewell’s Point tide gage (8638610, see Figure 2-1), located near the model 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 surges. Positive surge events (i.e. measured water level above predicted water level) equal or higher than 0.5 m occurred around August 25, September 2 and October 4. Negative surge events of lower magnitude are observed around September 17 and October 24.
3.2.2. Salinity

The salinity boundary condition for the model consisted of an hourly time series of simulated 3D salinity at the model open boundary. The simulated data was provided by the Virginia Institute of Marine Science (VIMS) from their EFDC-HEM3D model (Shen et al., 2017) of Chesapeake Bay. Figure 3-2 depicts the salinity boundary conditions (averaged along the model boundary) for the surface and bottom layers. A decrease in salinity magnitude along with an increase in the vertical salinity gradients is observed in late September/Early October.
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. For watersheds draining into the Elizabeth River, flows computed from the VADEQ model were applied directly in the Delft3D model at source points located approximately at the downstream outflow point within the Delft3D model domain.

Because of the greater detail and higher resolution needed in the Broad Creek area, M&N delineated twelve sub-watersheds within the Broad Creek watershed, and located twelve corresponding sources within the Broad Creek model region 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, as well as the larger VADEQ watersheds used for the Elizabeth River portion. 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 sub-watershed, multiple the full 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 Watersheds and Rainfall Runoff Discharge Locations for the Elizabeth River/Broad Creek Model](image)

**3.2.4. Wind**

A spatially invariant wind field was assumed for the model. Since wind data from Sewell’s point station, adjacent to the model boundary, was not available for the calibration simulation period, an hourly time series of wind speed and wind direction from the NOAA-COOPS Chesapeake Bay Bridge Tunnel station (8638863, see Figure 2-1) was input to the model. Figure 3-4 depicts the wind data set.
3.3. Water Level Calibration

Water level calibration for the Elizabeth River/Broad Creek model was achieved by adjusting the values for bed roughness coefficient. Bottom roughness was specified using the Manning formulation, with a constant Manning coefficient of n=0.02 m^{-1/3}s. A comparison between measured and modeled water levels at the different calibration stations is depicted in Figure 3-5. This figure shows that the calibrated model closely reproduces the observed water level variations.

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

- Root Mean Squared Error (RMSE, \( \varepsilon_{RMS} \)) \( \varepsilon_{RMS} = \sqrt{(x - y)^2} \)
- Mean Absolute Error (MAE, m) \( MAE = |x - y| \)
- Correlation Coefficient (R) \( R = \frac{\Sigma(x-x)(y-y)}{\sqrt{\Sigma(x-x)^2}\sqrt{\Sigma(y-y)^2}} \)
- Model Prediction Capability Index (d) \( d = 1 - \frac{(x - y)^2}{\|x - \bar{x} - y - \bar{y}\|^2} \)
Where, \( x \) and \( y \) represent the measured and modeled water level data; respectively. Results are provided in Table 3-3. Correlation coefficients (R) of 0.98 or higher, and prediction capability indices of 0.99 or higher confirm the accuracy of the modeled water levels.

### Table 3-3 Statistical Parameters for Comparison Between Measured and Modeled Water Levels

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Haven Creek</th>
<th>Downtown Pumping Station</th>
<th>Virginia Beach Boulevard</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE [m]</td>
<td>0.021</td>
<td>0.029</td>
<td>0.069</td>
</tr>
<tr>
<td>MAE [m]</td>
<td>0.02</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>R</td>
<td>1.00</td>
<td>1.00</td>
<td>0.98</td>
</tr>
<tr>
<td>( d )</td>
<td>1.00</td>
<td>1.00</td>
<td>0.99</td>
</tr>
</tbody>
</table>

A comparison between the measured and modeled amplitude and phase of the tidal constituents (i.e. the astronomical components of the tide) at the calibration stations was also made. The level of agreement varies between the compared constituents and between stations. An excellent agreement is found for the principal lunar component (M2) being under-predicted by 2.1, 5.0 and 0.6% at the calibration stations (see Figure 3-6).
Figure 3-5 Measured VS Modeled Water Levels at the Different Calibration Stations
Figure 3-6 Measured VS Modeled Tidal Constituents at the Different Calibration Stations
3.4. Salinity Calibration

Salinity calibration for the Elizabeth River/Broad Creek model was achieved by adjusting the horizontal and vertical eddy viscosity and diffusivity coefficients. Furthermore, a correction for sigma layers available in the Delft3D modeling suite was utilized in order to improve the simulation of the vertical salinity gradient observed in measurements.

The sigma layer correction introduces a more accurate discretization of the vertical domain with strictly horizontal layers. This correction reduces the potential for “artificial” vertical mixing, related to approximation of horizontal diffusion through (non-horizontal) sigma planes.

Table 3-4 provides the modeling calibration parameter settings which resulted in the best agreement between measured and modeled salinity data. Eddy viscosity and diffusivity parameters in hydrodynamic modeling are calibration parameters that help in reproducing site-specific characteristics of the flow field. The values provided below resulted in good representation of salinities as observed in measurements, but could be refined in the future with calibration to velocity measurements.

Table 3-4 Salinity Calibration Parameters

<table>
<thead>
<tr>
<th>Horizontal</th>
<th>Vertical</th>
<th>Turbulence Closure Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background Eddy Viscosity (m²/s)</td>
<td>Background Eddy Diffusivity (m²/s)</td>
<td>Background Eddy Viscosity (m²/s)</td>
</tr>
<tr>
<td>0.01</td>
<td>0.1</td>
<td>0.001</td>
</tr>
</tbody>
</table>

VECOS salinity data consists of discrete monthly measurements of surface and bottom salinity. Since only three data points are available at each station during the model calibration period, no statistics were determined for the salinity calibration and agreement between measured and modeled salinity data was performed visually. Figure 3-7 to Figure 3-11 depict the modeled salinity at the surface and bottom sigma layers as well as the salinity gradient between both. VECOS data points are also included.

Overall, depth averaged salinities are well represented by the model, with higher salinities during the early stage of the simulation period and a decrease in salinity values during the last month of the simulation, as observed in the October 14 VECOS measurements. Both the measurements and the model results indicate a more pronounced decrease in salinity in the interior reaches of the Elizabeth River (i.e. stations EBE1, EBB01 and SBE5), which is also captured in the model results.

With respect to the salinity gradient, the model is consistent with observations in terms of reproducing well mixed water columns (stations EBE1 and SBE5) to very small vertical gradients (stations LE5.6 and ELI2) during the first two months of the simulation period, and an increase in the salinity gradient during the last month of the simulation.
Given the discussion above, the Elizabeth River/Broad Creek hydrodynamic and salinity model is calibrated to a degree appropriate for assessing Project impacts to water quality.

![LE56 Salinity Calibration](image1)

**Figure 3-7 Measured VS Modeled Salinity at Station LE5.6**

![ELI2 Salinity Calibration](image2)

**Figure 3-8 Measured VS Modeled Salinity at Station ELI2**
Figure 3-9 Measured VS Modeled Salinity at Station EBE1

Figure 3-10 Measured VS Modeled Salinity at Station EBB01
Figure 3-11 Measured VS Modeled Salinity at Station SBE5
3.5. Summary

The main findings regarding calibration of the Elizabeth River/Broad Creek hydrodynamic model are summarized below.

- Water level calibration was achieved by adjusting the value for bottom roughness and by refining model bathymetry in Broad Creek to better represent channel features.

- A Manning roughness scheme with constant Manning coefficient of $n=0.02 \text{ m}^{-1/3}\text{s}$ enabled the desired level of calibration for water levels.

- Excellent agreement between modeled and measured water level data was found for all three water level calibration stations, with correlation coefficients of 0.98 and higher.

- Salinity calibration was achieved by adjusting the horizontal and vertical eddy viscosity and diffusivity coefficients.

- Background horizontal eddy viscosity and diffusivity values of 0.1 m²/s and 0.01 m²/s and their correspondent vertical values of 0.001 m²/s and 0 m²/s resulted in the best agreement between measured and modeled salinity data.

- Implementation of the correction for sigma layers enhanced the simulation of vertical salinity gradients throughout the model domain.

- Modeled salinity data is consistent with observation in terms of reproducing variations of depth averaged salinities in time and space.

- Temporal variation in the salinity gradients is well reproduced by the model with small gradients in the early to mid-stages of the simulation period and a general increase in the salinity gradient for the last stages of the simulation period.
4. Water Quality Analysis Setup

4.1. Introduction

Potential Project impacts to circulation and water quality in Broad Creek 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 Broad Creek. 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 sources 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 3.2.1). 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 \textit{with} and \textit{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 was 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, Alternative 1**: These simulations evaluate permanent Project impacts by incorporating the proposed flood control structure to the computational grid. All of the structure’s gates (i.e., 6 gates) are open during the late-summer conditions, and are operated as necessary during the post-storm recovery simulations.

- **With Project, Alternative 2**: These simulations include a flood control structure with only two central gates open for the late-summer and following the storm in the storm-recovery scenarios.

Flood control structures were incorporated to the computational domain by specifying 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. Figure 4-1 illustrates the defined thin dams for alternatives 1 and 2 of the \textit{with Project} simulations. A sill elevation of -7 feet (2.1 m NAVD88) was set throughout the structure’s footprint.

\textit{With} and \textit{without Project} simulations 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 (as well as bathymetry data), 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 and physical modifications to the Elizabeth River system.
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 Broad Creek bathymetry will be identical between the Existing and Future conditions. However, modifications to the Elizabeth River navigation channel due to Federal Channel Deepening Project are assumed. Such modifications are based on the assumed deepening in the Norfolk Harbor / Southern Branch Elizabeth River Deepening Federal Feasibility Studies, recently completed by VIMS. Figure 4-2 shows the assumed channel deepening for the Future conditions simulations.

It is noted that the existing conditions bathymetry in this study delineates a deeper navigational channel in the Elizabeth River and its southern and eastern branches when compared to VIMS’ baseline bathymetry.

Figure 4-1 Thin Dams for the with Project Simulations: Alternative 1 (Left) and Alternative 2 (Right)
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 37 harmonic constituents, as derived by NOAA-CO-OPS for Sewell’s Point (8638610, see Figure 2-1), were specified to create a purely astronomical tidal boundary condition. The generated water level time series at the model open boundary, encompassing the summer months, is depicted in Figure 4-3.

![NOAA 8638610 Astronomical Tide](image)

**Figure 4-3 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 variation of salinity along the offshore boundaries was adopted. Figure 4-4 shows the salinity boundary condition (averaged along the model offshore boundary) for the surface and bottom layers.
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 15\textsuperscript{th} through September 15\textsuperscript{th} of each year was 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 4-5 indicates the imposed freshwater discharges (for Broad Creek only) in cubic meters per day.
4.4.4. Wind

As with the freshwater inflows, the imposed wind, constant in space and time, reflected typical late summer values and allowed maintaining dynamic steady state conditions. 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 4-6 shows the late-summer wind rose for Norfolk International Airport.
Wind Speed (Annual)
Station KORF_wind_LateSummer – Norfolk International Airport, VA
Period 15-Jul-1948 to 14-Sep-2015

Direction FROM is shown
Center value indicates calms below 0 m/s
Total observations 103273, calms 0
About 82.9% of observations missing

Figure 4-6 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 Broad Creek as depicted in Figure 4-7. Tracer concentrations at the offshore boundary and freshwater sources were set to zero.

![Figure 4-7 Initial Concentrations for Flushing Time Tracers: Whole Bay (Left) and Upper Bay (Right)](image)

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 4-5) 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 open 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 were 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 Sewell’s Point (NOAA-COOPS 8638610). 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 4-8) 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 4-8) to form the water level boundary condition for the storm period, depicted by the blue curve in Figure 4-8.

The peak surge at Sewell’s Point occurred on September 18, 2003 and was approximately 1.7 m (5.6 ft.). This peak surge coincides with the high astronomical water levels and results in total water levels of up to 2.1 m at the model open boundary, as depicted in Figure 4-8.
4.5.2. Salinity

Surface salinity data for the Isabel storm period was derived from surface water temperature and conductivity data available from Sewell’s Point Station. The derived salinity data set indicated that the Sewell’s Point area had already freshened by the start of the storm simulation period (i.e., September 17th). In order to avoid significant differences between boundary and initial salinity conditions (which had already reached a dynamic steady state), the derived salinity data set was adjusted to reproduce the variation in salinity values observed during the storm period (i.e., an increase followed by a more rapid decrease) with respect to the mean value for the late-summer salinity boundary condition. A linear vertical salinity profile was assumed, with a constant gradient of 1.5 ppt (Figure 4-9), equivalent to the average salinity gradient imposed in the late-summer boundary condition.
4.5.3. Fresh Water Inflows

Daily rainfall run-off data for the Isabel storm period, available from the VADEQ hindcast model was imposed to all freshwater sources in the model domain (Figure 3-3). 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 weather station (NOAA-COOPS 8638963). 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 4-10. Wind data from the Norfolk International Airport have gaps during Isabel, and was therefore not used for the storm simulation in this study.
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 were set to zero.
5. Typical Late-Summer Conditions Results

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

![Figure 5-1 Broad Creek Water Quality Analysis Regions](image)

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.
Whole Bay flushing time was estimated at 22.2 days for the *without Project* case, 22.3 days for the *with Project Alternative 1* – all gates open case, and 21.7 days for the *with Project Alternative 2* – two gates open case. Flushing time for the Upper Bay tracer is 43 days *without Project*, 43.1 days *with Project Alternative 1*, and 41.0 days for the *with Project Alternative 2*

Due to the degree of precision of the followed approach (i.e., required regression analysis), these differences in flushing times between *with* and *without Project* cases are considered to be negligible. However, there is a definite trend that suggests that less gate opening cross-sectional area could result in a slightly greater flushing rate (lower flushing time). Less flow area due to fewer gate openings, results in higher entrance/exit velocities. 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**

- **Existing, Without Project - Whole Bay**
  - Flushing time = \(1/0.045 = 22.2\) days
  - \(y = -0.045x + 4.405\)
  - \(R^2 = 0.9766\)

- **Existing, With Project Alternative 1 - Whole Bay**
  - Flushing time = \(1/0.0449 = 22.3\) days
  - \(y = -0.0449x + 4.4193\)
  - \(R^2 = 0.9786\)

- **Existing, With Project Alternative 2 - Whole Bay**
  - Flushing time = \(1/0.0461 = 21.7\) days
  - \(y = -0.0461x + 4.3335\)
  - \(R^2 = 0.9653\)
**Figure 5-4 Existing Condition: Upper Bay Region Flushing Time Analysis**

- **Existing, Without Project - Upper Bay**
  - Equation: \( y = -0.0232x + 4.4384 \)
  - \( R^2 = 0.8089 \)
  - Flushing time = \( 1/0.0232 = 43 \text{ days} \)

- **Existing, With Project Alternative 1 - Upper Bay**
  - Equation: \( y = -0.0232x + 4.4382 \)
  - \( R^2 = 0.7963 \)
  - Flushing time = \( 1/0.0232 = 43.1 \text{ days} \)

- **Existing, With Project Alternative 2 - Upper Bay**
  - Equation: \( y = -0.0244x + 4.4423 \)
  - \( R^2 = 0.8167 \)
  - Flushing time = \( 1/0.0244 = 41.0 \text{ days} \)
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 4-5). After the concentrations reached a dynamic steady-state, they were tidally and depth averaged for every computational cell in the area of interest. Figure 5-5 plots spatial variation in the steady-state, tidal and depth-averaged freshwater age for the with and without Project simulations. The freshwater age deviation (i.e. with Project water age minus without Project water age) is depicted in Figure 5-6.

Averaged over the Whole Bay, freshwater age is 10.3 days without Project, 10.4 days with Project Alternative 1 (all six potential gates), and 10.1 days with Project Alternative 2 (two central gates). Upper Bay water age was estimated at 3.3 days without Project, 3.2 days with Project Alternative 1, and 3.8 days with Project Alternative 2. These results indicate that water age is affected very little if at all by the Project under existing conditions.

Figure 5-5 Existing Condition: Steady State, Tidal-averaged Freshwater Age Without project (Top), With Project-Alternative 1 (Bottom Left), and With Project-Alternative 2 (Bottom Right)
Tidally averaged water age deviation, in days

Existing: With Project Alternative 1 - Without Project

Existing: With Project Alternative 2 - Without Project

Figure 5-6 Existing Condition: Freshwater Age Deviation from Without Project. With Project Alternative 1 (Top) and With Project Alternative 2 (Bottom)
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 and Figure 5-8 present the spatial variation in the steady-state, tidal and depth-averaged salinity for with and without Project simulations under existing conditions.

Small differences in the spatially averaged salinities are observed between simulation cases. Averaged over the whole bay the estimated salinity is 5.4 ppt for the without Project case, 5.2 ppt with Alternative 1, and 6.2 ppt with Alternative 2. Farther from the structure, Upper Bay salinities were estimated at 1.6 ppt, 1.5 ppt, and 2.8 ppt, respectively. Although more obvious salinity deviations are observed between the without Project and two gates open (Alternative 2, bottom panel in Figure 5-8) cases, deviation values remain low (below 1 ppt) and can be considered negligible.

![Figure 5-7 Existing Condition: Steady State, Tidal-averaged Salinity Without Project (Top), With Project-Alternative 1 (Bottom Left), and With Project-Alternative 2 (Bottom Right)]
Figure 5-8 Existing Condition: Salinity Deviation from Without Project. With Project Alternative 1 (Top) and With Project Alternative 2 (Bottom)
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.

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. Flushing times are reduced when compared to existing conditions. Without Project, Whole Bay flushing time is estimated at 15.7 days. With Alternative 1, the flushing time is estimated at 16.0 days, and for Alternative 2 the flushing time is 14.0 days. Upper Bay flushing was estimated at 14.5 days for the without Project and with Project – Alternative 1 case, and at 13.6 days for the with Project – Alternative 2 case. The Project is expected to have very minor to no impacts on bay flushing times.
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

A general increase in water age in Broad Creek is observed in future conditions simulations, as shown in Figure 5-12 and Figure 5-13, when compared to existing conditions (present day) simulations. Averaged over the Whole Bay, freshwater age is 16.8 days without Project, 17.0 days with Project Alternative 1, and 15.7 days with Project Alternative 2. Upper Bay water age was estimated at 9.3 days without Project, 9.4 days with Project Alternative 1, and 8.9 days with Project Alternative 2. 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 (Top), With Project-Alternative 1 (Bottom Left), and With Project-Alternative 2 (Bottom Right)
Figure 5-13 Future Condition: Freshwater Age Deviation from Without Project. With Project Alternative 1 (Top) and With Project Alternative 2 (Bottom)
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 also observed with respect to the existing conditions cases.

Averaged salinities in the Whole Bay are estimated to be 8.4 ppt, 8.2 ppt, and 8.8 ppt without Project, with Project Alternative 1, and with Project Alternative 2 scenarios, respectively. Upper Bay region averaged salinities are 4.5 ppt, 4.3 ppt, and 4.8 ppt respectively.

Figure 5-14 Future Condition: Steady State, Tidal-averaged Salinity Without Project (Top), With Project-Alternative 1 (Bottom Left), and With Project-Alternative 2 (Bottom Right)
Figure 5-15 Future Condition: Salinity Deviation from Without Project. With Project Alternative 1 (Top) and With Project Alternative 2 (Bottom)
5.3. **Project Hydrodynamic Impacts**

Results presented above indicate minor Project impacts on water quality parameters for typical conditions. As noted, with Project Alternative 2 scenarios, present a trend of lower flushing time and freshwater age, and higher salinities in the Bay. These effects can be described from Figure 5-16 through Figure 5-19, which illustrate hydrodynamic impacts of the Project under existing conditions. Project related impacts on future hydrodynamics are similar and are therefore not discussed in this section.

Introduction of the proposed flood control structure in Broad Creek reduces the cross-sectional area for flow exchange with the Elizabeth River System, resulting in alteration of the flow field. Figure 5-16 and Figure 5-17 compare peak flood and peak ebb depth averaged velocities around the structure alignment for the with and without Project simulations. With constricted openings to the Bay, flow velocities at the gate alignment increase from approximately 0.2 m/s without Project to 0.6 m/s with Project Alternative 2 at peak flood and from 0.1 m/s to 0.5 m/s, respectively at peak ebb.

Figure 5-18 depicts the mean, flood and ebb tidal prism in Broad Creek for the with and without Project simulations. The plots show no remarkable differences in the tidal prism between the 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 38 hours of simulation. For the with Project Alternative 2 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 mixed with waters from the Elizabeth River, and are not easily brought back into the Bay (during flood) due to the presence of the structure. A similar mechanism is observed during flood tides, where a jet with low tracer concentrations (but higher salinities) enters and enhances mixing and salinity intrusion 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 Broad Creek/Elizabeth River model has not been calibrated to flow velocities 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. an ADCP deployment on site) to pursue calibration of the model to flow velocities.
Figure 5-16 Existing Condition: Depth Averaged Velocity at Peak Flood for the Without Project (Left), With Project – Alternative 1 (Center), and With Project Alternative 2 (Right) Simulations
Figure 5-17 Existing Condition: Depth Averaged Velocity at Peak Ebb for the Without Project (Left), With Project – Alternative 1 (Center), and With Project Alternative 2 (Right) 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 38

Flushing Tracer Concentration With Project - Alternative 2
Simulation Hours: 02 to 38

Figure 5-19 Flushing Tracer Concentrations (Simulation Hours 2-38) Without Project (Top) and With Project Alternative 2 (Bottom)
5.4. Summary

A summary of the findings in the typical late-summer conditions simulations is provided in Table 5-1. The estimated values for flushing time, freshwater age and salinity indicate negligible to minor Project impacts on water quality under typical hydrodynamic conditions. Slightly increased flushing rates are computed with Project-Alternative 2, due to secondary, residual circulation associated with higher flow velocities and flow velocity gradients through the gate structure.

Table 5-1 Typical Conditions Simulation Results Summary

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Whole Bay</th>
<th>Upper Bay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flushing Time (days)</td>
<td>Freshwater Age (days)</td>
</tr>
<tr>
<td>Existing condition without Project</td>
<td>22.2</td>
<td>10.3</td>
</tr>
<tr>
<td>Existing condition with Project Alternative 1</td>
<td>22.3</td>
<td>10.4</td>
</tr>
<tr>
<td>Existing condition with Project Alternative 2</td>
<td>21.7</td>
<td>10.1</td>
</tr>
<tr>
<td>Future condition without Project</td>
<td>15.7</td>
<td>16.8</td>
</tr>
<tr>
<td>Future condition with Project Alternative 1</td>
<td>16.0</td>
<td>17.0</td>
</tr>
<tr>
<td>Future condition with Project Alternative 2</td>
<td>14.0</td>
<td>15.7</td>
</tr>
</tbody>
</table>
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](image)

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 (Upper BC and Virginia Beach Boulevard stations), which is more influenced by runoff sources. For the *without Project* scenario, the non-interrupted flow exchange with the Elizabeth River system results in flushing of the freshwater tracers during the storm period, consequently exhibiting lower concentrations through time, when compared to the *with Project* scenarios.
After the gates re-open, conservative tracer concentrations for both the *with Project* scenarios are about the same and greater than those *without Project*, but eventually (i.e., after about 20 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 5 days or less.

In upstream stations (Upper BC and Virginia Beach Boulevard), an approximate period of 10 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 for the Lower BC station). Steady-state, pre-storm salinity conditions are restored after an approximate period of 25 days for all scenarios and all stations.
Figure 6-2 Existing Condition: Depth Averaged Tracer Concentrations and Salinity at Upper BC Station
Figure 6-3 Existing Condition: Depth Averaged Tracer Concentrations and Salinity at Virginia Beach Boulevard Station
**Figure 6-4 Existing Condition: Depth Averaged Tracer Concentrations and Salinity at Central BC Station**

- **Existing Condition**
  - **Central BC: Depth Averaged Concentration - Conservative Tracer**
  - **Central BC: Depth Averaged Concentration - Decay Tracer**
  - **Central BC: Depth Averaged Salinity**
Figure 6-5 Existing Condition: Depth Averaged Tracer Concentrations and Salinity at Lower BC Station
6.2. **Future Conditions**

Under future conditions, the larger flow exchange in the bay with the Elizabeth River 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 (Figure 6-6 through Figure 6-9), when compared to existing conditions.

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

The time required for the conservative tracer to be almost completely flushed out is increased some (by about 7 days) for the upstream stations, while the opposite occurs in downstream stations.

The period required for salinity values in the *with Project* scenarios to coincide with those in the *without Project* scenario is also increased (by about 10 days) in upstream stations, and decreased in downstream stations.

Response in salinity between the *with* and *without Project* scenarios is also similar to that observed under existing conditions.
Figure 6-6 Future Condition: Depth Averaged Tracer Concentrations and Salinity at Upper BC Station
Figure 6-7 Future Condition: Depth Averaged Tracer Concentrations and Salinity at Virginia Beach Boulevard Station
Figure 6-8 Future Condition: Depth Averaged Tracer Concentrations and Salinity at Central BC Station
Figure 6-9 Future Condition: Depth Averaged Tracer Concentrations and Salinity at Lower BC 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:

- No remarkable deviation in tracer concentrations and salinity through time are found between the with Project scenarios.

- 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 20 days (or less in downstream stations).

- Under future conditions, the time required for the conservative tracer to be almost completely flushed out of upstream regions of the bay is somewhat increased (about 7 days), while the opposite occurs in the downstream regions.

- All decaying tracer concentrations are gone in 5 days or less for all stations and all scenarios.

- Salinity for with Project coincides with salinity for without Project after about 10 days (or less in downstream stations) under existing conditions scenarios, and after 20 days or less under future conditions scenarios.

- Salinity recovers to pre-storm conditions (i.e. dynamic steady-state) after about 25 days for all conditions and all stations.
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 Broad Creek. 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:

- Flushing times, tidally-averaged freshwater age and tidally-averaged salinity values show negligible differences between without Project and with Project Alternative 1 scenarios.

- Higher but still minor deviations in the parameters were computed between the without Project and with Project Alternative 2 scenarios: secondary, residual circulation caused by increased velocity gradients associated with the gate structure can enhance tidal flushing, resulting in slightly reduced flushing times and tidally-averaged freshwater age, and increased tidally-averaged salinity.

- 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.

- No remarkable deviation in tracer concentrations and salinity through time are found between the two with Project scenarios.

- Following gate re-opening, conservative tracer concentrations are higher for the with Project scenarios but decline to without Project concentrations within 20 days (or less in downstream regions) for existing (present-day) conditions.

- Future sea-level conditions increase the amount of time required for conservative tracers to be almost completely flushed out in the upstream region of the bay. The opposite occurs in downstream areas.

- Decaying tracer concentrations are gone in 5 days or less for all stations and all scenarios.
• Salinity for *with Project* coincides with salinity for *without Project* after about 10 days (or less in downstream regions) under present-day sea level conditions and about 20 days or less under future sea level conditions.

• Salinity recovers to pre-storm conditions (i.e. dynamic steady state conditions) after about 25 days for all conditions and all stations.

### 7.3. Further Recommendations

M&N recommends collection of field data (e.g. an ADCP deployment on site) to pursue calibration of the model to flow velocities. 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 and salinities), modeled flow velocities, affecting primarily flushing rates, could differ some from those presented herein.

Later phases of the CRSM Project would benefit from ADCP (or equivalent) measurements that will support the Elizabeth River/Broad Creek model to be used as a design-phase tool.
8. References


