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Hydrodynamic Modeling for the Proposed Dredging Assessment in Norfolk Harbor Channel, Elizabeth River

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Mac Sisson, Harry Wang, Jian Shen, Wenping Gong, and Albert Kuo

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Virginia Institute of Marine Science
Department of Physical Sciences
Gloucester Point, Virginia 23062

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EXECUTIVE SUMMARY

1. The U.S. Navy has a critical need for access of its aircraft carriers to two key facilities located within the Elizabeth River: the Lamberts Point Deperming Station and the Norfolk Naval Shipyard. The Navy is proposing to dredge approximately 5 miles of the Norfolk Harbor Channel between Lamberts Point Deperming Station and the Norfolk Naval Shipyard. Specifically, (1) deepen a portion of the channel near Lamberts Point Deperming Station to a depth of 50 feet MLLW and (2) deepen the remainder of the navigation channel to Norfolk Naval Shipyard to 47 feet MLLW (both with 3 feet of over-dredge).

2. Deepening the ship channel can potentially have a long-term impact on the physical conditions including: (1) water elevation (2) velocity (3) salinity and (4) sediment potential. In addition, during dredging operation, portions of dredged sediments inevitably escape into the ambient waters, thus, potentially impairing the benthic habitat. Thus, the environmental impact resulting from the channel dredging is needed. In response to this need, Virginia Institute of Marine Science (VIMS) has worked with TEC, Inc. in utilizing the calibrated Hydrodynamic Eutrophication Model in 3 dimensions (HEM-3D) for the Elizabeth and James Rivers for the environmental assessment.

3. For the assessment of the proposed Norfolk Harbor Channel dredging in the Elizabeth River, two Base Cases were constructed:

   (1) Existing condition: All currently existing facilities that influence the model are included. These are the Interstate highways I-64 and I-664 and the APM Terminal facility south of Craney Island.
   (2) Built-out condition: The existing condition plus the Craney Island Eastward Expansion (CIEE) and the VDOT 3rd Crossing Alternative 9.

4. There are 10 model scenario runs that were conducted, summarized as:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Impact Assessment</th>
<th>Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Norfolk Harbor dredging impact under average tidal conditions</td>
<td>Existing</td>
</tr>
<tr>
<td>2</td>
<td>Norfolk Harbor dredging impact under average tidal conditions</td>
<td>Built-out</td>
</tr>
<tr>
<td>3</td>
<td>Norfolk Harbor dredging impact under an eventful condition of high river discharge</td>
<td>Existing</td>
</tr>
<tr>
<td>4</td>
<td>Norfolk Harbor dredging impact under an eventful condition of low river discharge</td>
<td>Existing</td>
</tr>
<tr>
<td>5</td>
<td>Norfolk Harbor dredging impact under an eventful condition of high wind</td>
<td>Existing</td>
</tr>
<tr>
<td>6</td>
<td>Norfolk Harbor dredging impact under an eventful condition of high river discharge</td>
<td>Built-out</td>
</tr>
</tbody>
</table>
5. Since the impact (e.g., on currents, etc.) could be non-local, i.e., affecting remote portions of the domain, the approach of assessment requires the use of a global analysis methodology to compare quantitatively the impacts of dredging over the far-field effect, including the areas of Hampton Roads and the Elizabeth River. This was done by determining percentages of total area associated with class intervals of change from the Base Case as differences in water surface elevation, surface and bottom salinity, surface and bottom current magnitude, surface and bottom residual current magnitude, and sedimentation potential.

6. The results from single variable runs (under average tidal conditions): Scenarios 1 and 2 show that the Norfolk Harbor dredging had minimal impact on either surface elevation or salinity, and acceptably small impacts on velocities and sedimentation potential, as shown in Table 1.

7. The results from historical runs (under eventful conditions): Scenarios 3 through 8 show that the Norfolk Harbor dredging had minimal impact on either surface elevation or salinity, and acceptably small impacts on velocities and sedimentation potential, as shown in Table 2.

Table 1. The 95th percentile values for selected model variables for Scenarios 1 and 2

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Impact Assessment</th>
<th>Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Norfolk Harbor dredging impact under an eventful condition of low river discharge</td>
<td>Built-out</td>
</tr>
<tr>
<td>8</td>
<td>Norfolk Harbor dredging impact under an eventful condition of high wind</td>
<td>Built-out</td>
</tr>
<tr>
<td>9</td>
<td>Norfolk Harbor dredging short-term impact due to the dredge-induced sediment plume</td>
<td>Existing</td>
</tr>
<tr>
<td>10</td>
<td>Norfolk Harbor dredging short-term impact due to the dredge-induced sediment plume</td>
<td>Built-out</td>
</tr>
</tbody>
</table>

Table 1. The 95th percentile values for selected model variables for Scenarios 1 and 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case I</th>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Elevation</td>
<td>0.05 cm</td>
<td>Surface Elevation</td>
<td>0.05 cm</td>
</tr>
<tr>
<td>Surface Current</td>
<td>2.3 cm/s</td>
<td>Surface Current</td>
<td>2.3 cm/s</td>
</tr>
<tr>
<td>Bottom Current</td>
<td>1.9 cm/s</td>
<td>Bottom Current</td>
<td>1.8 cm/s</td>
</tr>
<tr>
<td>Surface Salinity</td>
<td>0.03 ppt</td>
<td>Surface Salinity</td>
<td>0.03 ppt</td>
</tr>
<tr>
<td>Bottom Salinity</td>
<td>0.05 ppt</td>
<td>Bottom Salinity</td>
<td>0.04 ppt</td>
</tr>
<tr>
<td>Sedimentation Potential</td>
<td>0.5 %</td>
<td>Sedimentation Potential</td>
<td>0.5 %</td>
</tr>
</tbody>
</table>
Table 2. The 95\textsuperscript{th} percentile values for selected model variables for Scenarios 3-8

### Global Change – 95\textsuperscript{th} Percentile
(5\% of area contains change greater than value listed)

#### Historical – High Discharge Event

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case I</th>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Elevation</td>
<td>0.11 cm</td>
<td>Surface Elevation</td>
<td>0.10 cm</td>
</tr>
<tr>
<td>Surface Current</td>
<td>3.4 cm/s</td>
<td>Surface Current</td>
<td>3.2 cm/s</td>
</tr>
<tr>
<td>Bottom Current</td>
<td>2.2 cm/s</td>
<td>Bottom Current</td>
<td>2.1 cm/s</td>
</tr>
<tr>
<td>Surface Salinity</td>
<td>0.07 ppt</td>
<td>Surface Salinity</td>
<td>0.06 ppt</td>
</tr>
<tr>
<td>Bottom Salinity</td>
<td>0.07 ppt</td>
<td>Bottom Salinity</td>
<td>0.08 ppt</td>
</tr>
<tr>
<td>Sedimentation Potential</td>
<td>1.6 %</td>
<td>Sedimentation Potential</td>
<td>1.7 %</td>
</tr>
</tbody>
</table>

#### Historical – Low Discharge Event

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case I</th>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Elevation</td>
<td>0.07 cm</td>
<td>Surface Elevation</td>
<td>0.07 cm</td>
</tr>
<tr>
<td>Surface Current</td>
<td>3.1 cm/s</td>
<td>Surface Current</td>
<td>3.2 cm/s</td>
</tr>
<tr>
<td>Bottom Current</td>
<td>2.1 cm/s</td>
<td>Bottom Current</td>
<td>2.2 cm/s</td>
</tr>
<tr>
<td>Surface Salinity</td>
<td>0.11 ppt</td>
<td>Surface Salinity</td>
<td>0.15 ppt</td>
</tr>
<tr>
<td>Bottom Salinity</td>
<td>0.14 ppt</td>
<td>Bottom Salinity</td>
<td>0.16 ppt</td>
</tr>
<tr>
<td>Sedimentation Potential</td>
<td>2.0 %</td>
<td>Sedimentation Potential</td>
<td>1.8 %</td>
</tr>
</tbody>
</table>

#### Historical – High Wind Event

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case I</th>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Elevation</td>
<td>0.07 cm</td>
<td>Surface Elevation</td>
<td>0.07 cm</td>
</tr>
<tr>
<td>Surface Current</td>
<td>2.1 cm/s</td>
<td>Surface Current</td>
<td>2.0 cm/s</td>
</tr>
<tr>
<td>Bottom Current</td>
<td>1.6 cm/s</td>
<td>Bottom Current</td>
<td>1.7 cm/s</td>
</tr>
<tr>
<td>Surface Salinity</td>
<td>0.11 ppt</td>
<td>Surface Salinity</td>
<td>0.06 ppt</td>
</tr>
<tr>
<td>Bottom Salinity</td>
<td>0.14 ppt</td>
<td>Bottom Salinity</td>
<td>0.07 ppt</td>
</tr>
<tr>
<td>Sedimentation Potential</td>
<td>1.2 %</td>
<td>Sedimentation Potential</td>
<td>1.1 %</td>
</tr>
</tbody>
</table>
8. For the assessment of sediment impact under channel dredging condition, the HEM 3D sediment and turbidity model was calibrated and used for scenario runs. A depth-dependent critical shear stress formulation and a concentration dependent settling velocity were used to represent the cohesive sediment nature of the Norfolk Harbor in the Elizabeth River.

9. To be consistent with the VIMS 1978 intensive survey (Priest et al., 1981), a hydraulic dredging cutter head of 30 square feet, 2% escaping rate, and 67% sediment porosity were used for the estimate of source of the dredging material.

10. The results of modeling simulation (under Scenarios 9 and 10 conditions) show the characteristics of the dredging-induced plume at the three reaches of the Norfolk Harbor as follows:

<table>
<thead>
<tr>
<th>Reach locations</th>
<th>Horizontal extent*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Downstream (northward)</td>
</tr>
<tr>
<td>Port Norfolk</td>
<td>800 m</td>
</tr>
<tr>
<td>Town Point</td>
<td>250 m</td>
</tr>
<tr>
<td>Lower Reach</td>
<td>400 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reach Locations</th>
<th>Maximum sediment concentration in the vertical (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Layer 1 (bottom layer)</td>
</tr>
<tr>
<td>Port Norfolk</td>
<td>150</td>
</tr>
<tr>
<td>Town Point</td>
<td>100</td>
</tr>
<tr>
<td>Lower Reach</td>
<td>50</td>
</tr>
</tbody>
</table>

*The results are based on the most conservative estimate of the sediment source extending 2.5 meters above the bottom. If the cutter head is operated at or beneath the water-sediment interface, the horizontal extent could be 3-4 times less.

11. Based on the information presented above, the horizontal extent of the turbidity plume downstream, upstream, and laterally are bounded within a portion of the dredging area. The maximum sediment concentrations are mainly confined to the bottom layer (i.e., 2.5 meters above the sediment-water interface) and never extend beyond the middle layer.

12. In addition, the persistency of the dredge-induced sediment plume was investigated and it was found that the plume duration was less than 24 hours in each layer at all 3 locations. Therefore, it is concluded that the impact of the dredge-induced sediment turbidity plume in the channel is limited.
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Figure 1. Frequency distribution of elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 2. Frequency distribution of surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 3. Frequency distribution of bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I.

Figure 4. Frequency distribution of surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I.

Figure 5. Frequency distribution of bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I.

Figure 6. Frequency distribution of surface residual velocity magnitude average difference for the proposed Norfolk Harbor dredging versus Base Case I.

Figure 7. Frequency distribution of bottom residual velocity magnitude average difference for the proposed Norfolk Harbor dredging versus Base Case I.

Figure 8. Frequency distribution of sedimentation potential difference for the proposed Norfolk Harbor dredging versus Base Case I.

Figure 9. Frequency distribution of elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.

Figure 10. Frequency distribution of surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case II.

Figure 11. Frequency distribution of bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case II.

Figure 12. Frequency distribution of surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.

Figure 13. Frequency distribution of bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.

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Figure 44. Historical simulation comparison (high wind) of the surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.

Figure 45. Historical simulation comparison (high wind) of the bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.

Figure 46. Historical simulation comparison (high wind) of the surface residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case II.

Figure 47. Historical simulation comparison (high wind) of the bottom residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case II.

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Figure 2. Frequency distribution of surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I during the high discharge event of historical simulation.

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Figure 4. Frequency distribution of surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I during the high discharge event of historical simulation.

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Figure 6. Frequency distribution of surface residual velocity magnitude average difference for the proposed Norfolk Harbor dredging versus Base Case I during the high discharge event of historical simulation.

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Figure 12. Frequency distribution of surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I during the low discharge event of historical simulation.

Figure 13. Frequency distribution of bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I during the low discharge event of historical simulation.

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Figure 28. Frequency distribution of surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II during the high discharge event of historical simulation.

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Figure 47. Frequency distribution of bottom velocity residual magnitude average
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Figure 48. Frequency distribution of sedimentation potential difference for the proposed
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Appendix E. The Dredge-Induced Plume, Horizontal and Vertical Extents, and
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Figure 5. a) The location of the point source for Lower Reach, b) the dredge-induced plume at high water slack, and c) the plume at low water slack for Scenario 10.

Figure 6. The vertical extent of the Lower Reach plume shown by axial velocity and sediment concentration at each layer for Scenario 10.

Figure 7. Time history of sediment turbidity concentrations in bottom 3 layers after a 1-day release at Port Norfolk Reach at day 4.38 for Scenario 10.

Figure 8. Time history of sediment turbidity concentrations in bottom 3 layers after a 1-day release at Town Point Reach at day 5.01 for Scenario 10.

Figure 9. Time history of sediment turbidity concentrations in bottom 3 layers after a 1-day release at Lower Reach at day 7.46 for Scenario 10.
I. INTRODUCTION

A. Background

The U.S. Navy has a critical need for access of its aircraft carriers to two key facilities located within the Elizabeth River: 1) the Norfolk Naval Shipyard (for carrier maintenance and repair) and 2) the Lamberts Point Deperming Station (for hull demagnification). Currently, access to these facilities is impaired due to insufficient channel depths. The average water depth of the Norfolk Harbor Channel is approximately 40 to 43 feet between Lambert Point Deperming Station and the Norfolk Navel Shipyard. At low tide, there is only approximately 2 feet of clearance as carriers transit between these facilities. The Navy needs at least 6 feet of water between the carrier’s keel and the bottom of the river channel. The Navy is forced to depend on tides to access both the Norfolk Naval Shipyard and Lamberts Point Deperming Station. The Navy needs to be in compliance with required clearance for these carriers. Lack of compliance can allow mud and soil debris to enter the carrier engines' cooling and fire fighting systems, creating unsafe conditions and incurring significant costs to taxpayers.

B. Proposed Dredging Operation of the Norfolk Harbor Channel

Norfolk Harbor Channel extends from Hampton Roads through the Elizabeth River mainstem and then to its Southern Branch (see Figures I.1 and I.2). There are two distinct portions of the channel: 1) the portion of the channel near Lamberts Point Deperming Station, which is wider and curved, and 2) the remainder of the navigation channel moving upriver to the Norfolk Naval Shipyard, which is narrower and straighter. These two portions are outlined in blue and green, respectively, in the right panel of Figure I.2.

The Navy proposes: 1) to dredge approximately 5 miles of the Norfolk Harbor Channel between Lamberts Point Deperming Station and the shipyard, 2) to deepen a portion of the channel near Lamberts Point Deperming Station to a depth of 50 feet MLLW (with 3 feet of over-dredge), 3) deepen the remainder of the navigation channel to Norfolk Naval Shipyard to 47 feet MLLW (with 3 feet of over-dredge), and 4) place the dredged materials at a disposal site(s) that is approved by federal and state regulatory agencies. Dredging will be done by both hydraulic (pumping) and clamshell/bucket (scooping) equipment with an estimated 80% of the dredging being done hydraulically.

It is anticipated that approximately 4 million cubic yards of dredged material will need to be removed. This volume is equivalent to about 16 inches of dredged materials spread over 2,500 acres. All deepening will occur within the federally maintained channel. The widths are estimated as 600 feet in the wider section and 450 feet in the narrower section. As the dredging will be conducted mainly by hydraulic and mechanical dredging equipment, spillage will be inevitable. The information about the amount of spillage using specific dredging methods will be provided and used for simulating the dredge-induced sediment turbidity plume.
Figure I.1. Hampton Roads and the Elizabeth River Basin.
Figure I.2. The two portions of the 5-mile span of Norfolk Harbor that will require dredging (outlined on right panel in blue and green).
II. APPROACH

The modeling framework selected for use is the high-resolution HEM-3D model. The hydrodynamic portion of the model computes the spatial distributions of the time-varying water surface elevation, current speed and direction, water salinity, temperature, and turbulence diffusion coefficient over a domain that is primarily three-dimensional (grid cells arranged in three spatial dimensions). This information can then be used by the sediment transport sub-model in HEM-3D, which computes the spatial distribution of time varying sediment concentration under non-dredging and dredging conditions. Under the dredging condition, a dredge-induced sediment turbidity plume occurs. The transport, dispersion, and eventual fate of dredged material released into the marine environment depend upon the type of dredging methods, the sediment characteristics of the dredged material, and the dynamics in the water column. The current and turbulence fields ultimately determine the transport, dispersion and length of time the dredged material remains in the water column.

A. Description of Hydrodynamic Model HEM-3D

Virginia Institute of Marine Science (VIMS) has worked with TEC, Inc. and Navy personnel to utilize the calibrated Hydrodynamic Eutrophication Model in 3 dimensions (HEM-3D) model of the Elizabeth and James River for the environmental assessment. The original HEM-3D model was developed and refined at VIMS over the period 1988-1995 by Associate Professor John M. Hamrick (Hamrick, 1992; Park, 1995). It is a multi-parameter finite difference model representing estuarine flow and material transport in three dimensions. Wind stress and momentum transfer can also be represented as input at the air-water interface with salinity and freshwater discharge handled as input at the appropriate longitudinal boundary. Tidal input can be represented at the downstream open boundary by either a specific time history of water level or a simulated tide based on one or a combination of multiple tidal constituents of known amplitude and phase. The code is written in standard FORTRAN 77 and is highly portable to UNIX or DOS platforms. It is computationally efficient due to the programmer's avoidance of logical operators, and it economizes on required storage by storing only active water cell variables in memory. This code was written to be highly vectorizable, anticipating upcoming developments in parallel processing. Due to a well-designed user interface, the internal source code remains the same from application to application. The HEM-3D model can be quickly converted to a 2D model either horizontally or vertically for preliminary testing. The model's most unique features include the mass conservative scheme that it uses for drying and wetting in shallow areas. It also incorporates vegetation resistance formulations (Hamrick, 1994). The most valuable feature is the model's ability to couple with both water quality and sediment transport models. The model uses a stretched (i.e., "sigma") vertical coordinate system and a curvilinear-orthogonal horizontal coordinate system to solve vertically hydrostatic, free surface, variable density, and turbulent-averaged equations of motion. This solution is coupled with a solution of the transport equations for turbulent kinetic energy, solving the equations of motion. Integration over time involves an internal-external mode splitting procedure separating "the internal shear or baroclinic mode” from the external
turbulent length scale, salinity and temperature. A staggered grid provides the framework for the spatial finite differencing (second order accurate) used by the numerical scheme to free surface gravity wave or barotropic mode" (Hamrick, 1995).

The Elizabeth and James River HEM-3D model was developed in 2000-2001 by VIMS under contract with the Norfolk District of the Army Corps of Engineers (ACE) and the Virginia Port Authority (VPA) to apply its 3D hydrodynamic model to assess the environmental impacts of various expansion options for Craney Island (Wang et al., 2001). The model covers the entire James River and the Elizabeth River including Lafayette River, Western Branch, Eastern Branch, Deep Creek, and the Southern Branch up to Great Bridge. The model was previously calibrated for these parameters in the mainstem James River in a previous study (Boon et al., 1999). Calibration in the Elizabeth River consisted of simulating the prototype condition for the period April 24 to June 8, 2000, during which period high-frequency observations of tides, velocities (surface, mid-depth, and bottom), and salinities (surface, mid-depth, and bottom) were available. Additionally, monthly comparisons of observed versus predicted salinity throughout the water column at multiple locations throughout the Elizabeth mainstem and the Southern Branch showed the model's ability to accurately simulate the observed stratification. The model was further verified with respect to surface elevation induced by both astronomical and meteorological tides, current velocities (tidal and residual), and salinity distributions. As part of that study, VIMS developed a global analysis methodology to determine the far-field long-term effects of each expansion option on each of several hydrodynamic state variables (i.e., water elevation, current velocity, salinity, and sedimentation potential). A complete description of model calibration and verification for the Elizabeth and James River model is presented in Wang et al. (2001), Chapter IV.

VIMS’ current project with TEC, Inc. and Navy has utilized the calibrated model and accepted methodology to assess the long-term physical impact and the short-term impact of dredge-induced sediment turbidity plume caused by the dredging of the Norfolk Harbor Channel. Substantial effort has been devoted to local refinements of the HEM-3D grid over the 5-mile portion of the Norfolk Harbor Channel designated for dredging. The grid must be fine enough to resolve the channel. Figure II.1 shows the VIMS model grid near Norfolk Harbor Channel designated dredging portion between the Lamberts Point Deperming Station and Norfolk Naval Shipyard. Assessment of the impact of the Norfolk Harbor 5-mile channel dredging project involved adaptation of the VIMS HEM-3D model grid locally to adequately resolve the dredged channel, calibrate of HEM-3D sediment model under both non-dredging and dredging conditions, modify the input parameters, and conduct 10 scenario runs to reflect the post-dredging condition as compared with the existing and built-out base conditions. Finally, a quantitative impact assessment will be made based on the results of the scenario runs.
B. Sediment and Turbidity Plume Model

The governing equation for the sediment concentration and transport in the HEM-3D model is similar to that of other scalar parameters such as salinity, except that the formulations for erosion and deposition need to be explicitly specified. In specifying the rate at which a given sediment bed erodes or re-suspends is a ubiquitous challenge. Erosion and its counterpart deposition reflect a continual, dynamic adjustment between the fluid forces applied to the sediment bed and the condition of the bed itself (Sanford, 2007).

There is generally agreement that bottom shear stresses exerted by waves and currents are the dominant forces causing erosion and that site-specific sediment characteristics (including particle size distribution, particle density, cohesiveness, water content, and biological disturbance or binding) control resistance to erosion. Unfortunately, there has been little agreement about the most appropriate mathematical formulation for erosion rate. Some advocate the use of a power law relationship between erosion rate and shear stress such as:

\[ E = M \left[ \tau_b - \tau_c \right]^n \]

where \( E \) is the erosion rate, \( M \) is an empirical constant, \( \tau_b \) and \( \tau_c \) are the applied bottom shear stress and the constant critical stress, and \( n \) is an empirical constant. Others champion the use of an exponential form:
\[ E = \varepsilon \exp \left[ \alpha (\tau_b - \tau_c(z)) \right]^\beta \]

where \( \varepsilon \) is the empirical floc erosion rate and \( \alpha \) and \( \beta \) are empirical constants.

For the sediment model simulation of Norfolk Harbor, we select the erosion formula widely investigated and implemented in Baltimore Harbor, in which linear formulation was used, but allowing the critical stress to increase with depth (Maa et al., 1998; Sanford and Maa, 2001).

\[ E = M \left[ \tau_b - \tau_c(z) \right] \]

Where \( E \) is the erosion rate, \( M \) is an empirical constant, \( \tau_b \) is the applied bottom shear stress and \( \tau_c \) is the critical stress for erosion. The critical shear stress is a function of \( z \) and \( z \) is the depth of erosion. The field measured relationship between \( \tau_c \) versus eroded mass \( m \) is shown in Figure II.2. The power law relationship:

\[ \tau_c = 0.86 \ (m - 0.017) \ 0.5 \quad \text{and} \quad M = 0.027 \ (m - 0.017) \ 0.54 \]

fits the entire data set best. Lin et al. (2003) showed that general agreement was reached when applied to Baltimore Harbor. The significance of the above formula as compared to the constant critical shear stress is that it allows one to simulate the depth-

![Graph](image-url)

Figure II.2. Profiles of critical shear stress \( \tau \) vs. eroded mass \( m \) from a re-analysis of MSH data. Panel b is an expanded view of the lower left corner of panel a. (Sanford and Maa, 2001).
limited erosion as well as unlimited erosion with a seamless transition between the two behaviors. This dual (erosion) behavior was found to be prevalent in the harbor environments where the deep ship channel and the broad shoal region distinctly co-exist (Nakagawa et al., 2000).

When a source of dredged material is introduced into the water column, the dredge-induced sediment turbidity plume occurs. The HEM-3D sediment plume model follows the general approach of Kuo et al. (1985). The model includes a sediment transport sub-model that requires an input of sediment source resulting from the leakage of dredged materials during the dredging operation. It is developed within the framework of HEM-3D to find the numerical solution of an advective-diffusion equation to describe the sediment turbidity plume induced by operation of different dredging methods (i.e., hydraulic dredge, bucket dredge, or others).

The model can be used to predict the sediment concentration due to the dredge-induced sediment turbidity plume, if the source information (including cutter head and speed dimension, dredging leakage, and sediment characteristics) are given. Most of the spillage from the dredge operation includes cohesive sediments. The model uses two classes: clay and silt to simulate the behavior of cohesive sediment with a mean settling velocity depending on the concentration. The short-term scenarios that were performed include six simulations of 7 to 15 days to test the 6 combinations of spring, mean, and neap tide stages and high and low flow conditions. The excess sediment concentration due to the dredging operation is obtained by subtracting the total sediment concentration (under the dredging condition) from the ambient sediment concentration (under the non-dredging condition). In the end, the short-term impact of the dredge-induced sediment plume on the aquatic environment is achieved by comparing maximum sediment concentration near the bottom, the horizontal and vertical extents of the sediment turbidity plume, and the duration of the persistence of high turbidity concentration. The short-term impacts of Norfolk Harbor dredging on three reaches due to the dredge-induced sediment plume are included in the Scenarios 9 and 10.

C. Base Cases, Scenarios, and Assessment

1. Existing and built-out base cases

In a meeting in April 2007 attended by personnel from the Navy, TEC, VIMS, Norfolk District Corps, and DEQ-TRO, it was noted that it would be desirable to address the impact of the Norfolk Harbor dredging for both current and future (i.e., built-out) conditions. For this reason, TEC project management decided to accept the offer from the VIMS modeling group to evaluate the dredging impact against two separate base conditions, the existing base condition (i.e., Base Case I) and the built-out condition (i.e., Base Case II).
Figure II.3. The region of the Craney Island Eastward Expansion (shown in gold).
Figure II.5. Location of the APM Dredging Region.

Table II.1. Scenarios for the Norfolk Harbor Dredging Project

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Impact Assessment</th>
<th>Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Norfolk Harbor dredging impact under average tidal conditions</td>
<td>Existing</td>
</tr>
<tr>
<td>2</td>
<td>Norfolk Harbor dredging impact under average tidal conditions</td>
<td>Built-out</td>
</tr>
<tr>
<td>3</td>
<td>Norfolk Harbor dredging impact under a high discharge event</td>
<td>Existing</td>
</tr>
<tr>
<td>4</td>
<td>Norfolk Harbor dredging impact under a low discharge event</td>
<td>Existing</td>
</tr>
<tr>
<td>5</td>
<td>Norfolk Harbor dredging impact under a high wind event</td>
<td>Existing</td>
</tr>
<tr>
<td>6</td>
<td>Norfolk Harbor dredging impact under a high discharge event</td>
<td>Built-out</td>
</tr>
<tr>
<td>7</td>
<td>Norfolk Harbor dredging impact under a low discharge event</td>
<td>Built-out</td>
</tr>
<tr>
<td>8</td>
<td>Norfolk Harbor dredging impact under a high wind event</td>
<td>Built-out</td>
</tr>
<tr>
<td>9</td>
<td>Norfolk Harbor dredging short-term impact due to the dredge-induced sediment plume</td>
<td>Existing</td>
</tr>
<tr>
<td>10</td>
<td>Norfolk Harbor dredging short-term impact due to the dredge-induced sediment plume</td>
<td>Built-out</td>
</tr>
</tbody>
</table>
It should be noted that the built-out base case includes additionally the Craney Island Eastward Expansion and the Alternative 9 of the VDOT 3rd Crossing highway (Figures II.3 and II.4). The APM terminal dredging is included in both base cases since it has already occurred (see Figure II.5). Due to the need to assess the impact of the Norfolk Harbor dredging for as many conditions as possible, it was necessary to run a total of 10 scenarios for the project as shown in Table II.1.

Scenarios 1 and 2 were model testing of the impacts of the proposed Norfolk Harbor dredging using single variable runs (varying only the tidal range of model input). Scenario 1 tested the dredging impact against the existing condition and Scenario 2 tested its impact against the built-out condition. Scenarios 3 through 8 were model testing of the impact of the proposed Norfolk Harbor dredging using historical runs (using multiple variables in real time for model input). Scenarios 3 through 5 tested the dredging impact under high flow, low flow, and high wind events, respectively, for the existing condition and Scenarios 6 through 8 tested the dredging impact under these events for the built-out condition. Scenarios 9 and 10 were model testing of the short-term impact caused by the dredge-induced sediment turbidity plume. Scenario 9 was for the existing condition and Scenario 10 was for the built-out condition. These were performed at representative locations in all 3 reaches of the dredge region (Port Norfolk Reach, Town Point Reach, and the Lower Reach).

2. Single variable runs

A basic screening approach under controlled conditions, these tests restrict the model input by allowing only a single input variable, tidal range, to vary between astronomical extremes during the course of a run. A three-constituent harmonic model is used including the M2, S2, and N2 tidal constituents with phasing adjusted to produce tides of maximum (perigean-spring), mean, and minimum (apogean-neap) range during a single run of 34 days. The generated time series, used as the boundary condition at the James River mouth in single variable runs, is shown in Figure II.6.

The purpose of the simple design of the single variable run is to isolate the long-term average impacts caused by the Norfolk Harbor dredging. Those impacts caused by eventful conditions (e.g., high discharge, low discharge, high wind) are evaluated by historical runs, discussed in Section C.3 of this chapter.

The long-term global analysis of the impact of dredging along the 5-mile portion of the Norfolk Harbor Channel that will require dredging is carried out by running the model under pre- and post-dredging bathymetry specifications. Here, the term global is used to refer to the entire spatial domain for Hampton Roads. Global analysis comprises an attempt to determine any and all far-field effects caused by dredging.
The motivation for the use of the global technique is to examine both the magnitude of changes and the spatial distribution of these changes for those parameters that can have a critical impact on the circulation in the Elizabeth River. These parameters include the surface elevation, surface and bottom salinity, surface and bottom velocity, surface and bottom residual velocity, and sedimentation potential.

A time series of 74 tidal cycles was designed and used to provide the combination of essential tidal components including spring, neap, perigean-spring and apogean-neap tides. The semi-monthly progression between the extremes in tidal range for the model is shown in Figure II.6. The duration of each single variable scenario run was 134 tidal cycles and the model results were saved every half-hour throughout the entire modeling domain after the model spin-up period of 60 tidal cycles.

In order to assess the impacts exerted on the James/Elizabeth River system, the differences between the Test Cases and the Base Cases were obtained and analyzed. From the numerical modeling point of view, what these Test Cases introduce into the system are perturbations from the change in the modeling domain itself (the Norfolk Harbor dredging impact). In measuring the effect of these perturbations, we first
conducted a global analysis using 4 key variables: tidal elevation, current velocity, salinity, and sedimentation potential.

The global technique described in this section involves the generation of a plotted spatial distribution of a long-term (i.e., 74 tidal cycles) time average comparison of parameters predicted by the model for the Base Case (i.e., pre-dredge condition) and the Test Case (i.e., dredging specifications for channel portions). The comparison is made possible by virtue of the fact that all model output for the 6-layer, 7500-cell domain of the VIMS James/Elizabeth River HEM-3D model version is saved 24 times per tidal cycle (i.e., approximately every half hour). This allows one to compare, for each location in the model domain, time series of the Base Case versus the Test Case and to characterize the difference as either an RMS (root mean square) difference or a simple average difference:

$$\text{RMS\_DIFFERENCE} = \sqrt{\frac{\sum_{i=1}^{n} (MP_{\text{test,}i} - MP_{\text{base,}i})^2}{n}}$$

for tidal elevation and velocity magnitude

$$\text{AVERAGE\_DIFFERENCE} = \frac{\sum_{i=1}^{n} (MP_{\text{test,}i} - MP_{\text{base,}i})}{n}$$

for salinity, sedimentation potential, and residual velocity

where: $n$ is number of data points, (1776 for 74 tidal cycles)

$MP_{\text{test}}$ is model prediction for the Test Case

$MP_{\text{base}}$ is model prediction for the Base Case

In this fashion, one is able to obtain, for each state variable, a simple difference between the predicted value of the Test Case and that of the Base Case for each cell and layer of the model domain. It is not only useful to know the relative size of the differences described above, but also their spatial distributions. Use of ArcView Avenue scripts allows for the mapping of the derived differences into the exact cell areas of this curvilinear, variable cell size grid. Differences will be derived for the entire Hampton Roads portion of the modeling domain and shown individually for each state variable using spatial plots spanning Hampton Roads. For the Base Case - Test Case comparisons (i.e., pre- and post-dredging conditions), the sequence of the 8 spatial plots is as follows:

1) RMS difference of tidal elevation
2) average difference of surface salinity
3) average difference of bottom salinity  
4) RMS difference of surface velocity magnitude  
5) RMS difference of bottom velocity magnitude  
6) average difference of surface residual velocity magnitude  
7) average difference of bottom residual velocity magnitude  
8) sedimentation potential difference between Test Case and Base Case

In order to quantify these differences derived from the case comparisons, a technique using percentile analysis will be incorporated. By dividing the aforementioned differences into class intervals and plotting the spatial accumulation as a percentage of the entire model surface area of Hampton Roads, a set of simple histograms will be constructed. From these diagrams, cumulative percentages can be extracted. By selecting the 95\textsuperscript{th} percentile value of this curve for a given state variable, one can determine a value that is exceeded in only 5\% of this specified domain (i.e., Hampton Roads). The results of the global analysis of the single variable runs are presented in Chapter III, Section A.

### 3. Historical runs

The second of the two types of scenario simulation comparisons performed in this project involved a real-time simulation incorporating all available input conditions (discharge at 8 locations, winds, and open boundary tidal elevation and salinity specifications). This simulation was done for the 180-day period corresponding to Julian days 60-240 of calendar year 2000 (i.e., March 1 to August 27).

From within this simulation period, three 7-day event periods were selected to represent the relatively extreme conditions of ‘high discharge event’ [Julian days 111-117], ‘high wind event’ [Julian days 149-155], and ‘low discharge event’ [Julian days 197-203]. A time series plot of discharge measurements upstream at Richmond is shown in Figure II.7 and a time series of wind measured at Sewells Pt., VA is shown in Figure II.8. Whereas the duration of these events varied, the period of analysis for comparing the Test Case to the Base Case was kept constant at 7 days.

Here, the reader is referred to Section C.2 of this chapter for a general discussion of global analysis as it was performed for the single variable runs. The difference in its use for this historical simulation is that, for the Test Case compared to the Base Case, global analysis was applied separately to the 3 event periods in the comparison. Therefore, the number of data points used is 336 (the number of half-hour intervals in a week), rather than 1776 as used for the single variable scenarios. The results of the global analysis for the historical runs are presented in Chapter III, Section B.
Figure II.7. Discharge measured at Richmond, VA

Figure II.8. Wind measured at Sewells Pt., VA.
CHAPTER III. THE RESULTS FOR THE LONG-TERM HYDRODYNAMIC ASSESSMENT

The 2 Test Cases involved in the current project for the proposed Norfolk Harbor dredging in the Elizabeth River are as follows: 1) assessment of the dredging impact for the *existing* base condition (i.e., Base Case I, which includes the constructed APM Terminal, no CIEE, and no 3rd Crossing VDOT highway alternative) and 2) assessment of the dredging impact for the *built-out* base condition (i.e., Base Case II, which includes the constructed APM Terminal, the CIEE, and the 3rd Crossing). These 2 Test Cases comprise the scenario simulations for single variable runs.

A. SINGLE VARIABLE RUNS

The methodology for analyzing the results of the single variable runs was presented fully in Section C.2 of Chapter II. Here, the results of the single variable runs are presented for both Test Case – Base Case comparisons.

Using this methodology, one is able to obtain for each state variable a simple difference between the predicted value of the Test Case and that of the Base Case for each cell and layer of the model domain.

1. Spatial Distribution – It is not only useful to know the relative size of the differences described above, but also their spatial distributions. Use of ArcView Avenue scripts allows for the mapping of the derived differences into the exact cell areas of this curvilinear, variable cell size grid. Differences were derived for the Hampton Roads portion of the model domain as shown in the spatial plots of Hampton Roads shown in Figures 1-16 of Appendix A.

Figures 1-8 represent the impact of the proposed Norfolk Harbor dredging for the existing condition (i.e., Test Case I vs. Base Case I), whereas Figures 9-16 represent the impact of the proposed Norfolk Harbor dredging for the built-out condition (i.e., Test Case II vs. Base Case II).

For both of the two Test Case – Base Case comparisons, the sequence of the 8 spatial plots is as follows:

1) RMS difference of tidal elevation
2-3) average difference of surface and bottom salinity, respectively
4-5) RMS difference of surface and bottom velocity magnitude, respectively
6-7) average difference of surface and bottom residual velocity magnitude, respectively
8) sedimentation potential difference
For purposes of comparing the analyses of the test case comparisons, both the area for display and the legend (class) intervals selected to report the differences were kept constant throughout the comparisons.

The differences are calculated and plotted for each of the test case comparisons. The following is a summary of the findings in both Test Case – Base Case comparisons.

Norfolk Harbor Dredging vs. Base Case I (Scenario 1) – Plots for the Norfolk Harbor dredging impact for the existing condition are presented in Figures 1-8 of Appendix A. For surface elevation (Figure 1), there are regions minimally impacted in the Southern Branch and its tributaries and at the head of the Eastern Branch. All surface elevation RMS differences fall below 0.2 cm except for very small areas off the Southern Branch in both Deep Creek to the west and the Inter-Coastal Waterway entrance to the east. These differences are more due to phase than amplitude. Average differences in surface salinity (Figure 2) fall below 0.2 ppt everywhere, whereas differences in bottom salinity (Figure 3) are shown to vary up to 1.0 ppt in along the dredging region. Surface velocity magnitude RMS differences (Figure 4) show RMS differences up to 12 cm/sec in small areas off the Southern Branch, again due to phase rather than amplitude. Bottom velocity (Figure 5) shows a small area impacted near Lamberts Pt., with RMS differences between 3 and 6 cm/sec. Surface and bottom residual velocity magnitude average differences (Figures 6-7) reveal small areas around the dredging regions containing differences ranging up to 5 cm/sec at the surface and up to 3 cm/sec at the bottom. Sedimentation potential is what we define as the percent of time that the bottom shear stress computed by the model remains under 0.1 pascals. The difference between the Eastward Expansion and the Base Case for this parameter is plotted in Figure 8. This plot shows a very small area (in red) near Lamberts Pt. suggesting a small tendency for more deposition in this area as a result of dredging.

Norfolk Harbor Dredging vs. Base Case II (Scenario 2) – Plots for the Norfolk Harbor dredging impact evaluated under the built-out condition are shown in Figures 9-16 of Appendix A. For the surface elevation (Figure 9), the RMS differences from the Test Case II - Base Case II appear very similar to those in the Test Case I – Base Case I comparison (Figure 1). The average difference in surface salinity due to Norfolk Harbor dredging (Figure 10) shows a small increase in salinity (0.2 to 0.6 ppt) along the entrance to the Inter-Coastal Waterway. The average difference in bottom salinity (Figure 11) shows a small increase (0.2 -1.0 ppt) extending upstream along the channel into the Southern Branch. The surface velocity magnitude RMS differences (Figure 12) show values ranging to 12 cm/sec at the head of the Southern Branch (Deep Creek and the entrance to the Inter-Coastal Waterway), again due more to phase than amplitude. Bottom velocity magnitude RMS difference (Figure 13) shows a small localized area near Lamberts Pt. where the change is on the order of 3-6 cm/sec. Surface residual velocity magnitude (Figure 14) changes between 1-5 cm/sec along the dredging area and a much smaller region shows a similarly minimal impact localized around Lambert Pt. for the bottom residual velocity magnitude (Figure 15). The sedimentation potential difference, shown in Figure 16, shows the small region impacted near Lamberts Pt. that was present
earlier for the comparison of the existing condition, as well as a small area in Deep Creek, probably again due to a change in phase rather than amplitude.

One caution to this analysis technique should be emphasized. As we compare differences in time series (either RMS or simple differences), we know these differences result from both amplitude and phase change.

The spatial distributions of the case comparison differences discussed in this section can be compared in the qualitative sense. They show regions of maximum change and the important gradients between these regions and those unaffected by expansion. An attempt to quantify these results involves the analysis described in the next section.

2. Percentile Analysis – In order to quantify these differences derived from the case comparisons, a technique using percentile analysis was incorporated. By dividing the aforementioned differences into class intervals and plotting the spatial accumulation as a percentage of the entire model surface area of Hampton Roads, a set of simple histograms can be constructed such as those shown in Appendix B, Figures 1-16.

Figures 1-16 are comprised of 8 figures for each case comparison in numerical order (i.e., those figures showing the differences of the proposed Norfolk Harbor dredging vs. Base Case I are Figures 1-8 and those figures showing the differences of the proposed Norfolk Harbor dredging vs. Base Case II are Figures 9-16). The 8 figures present the order of state variables in the sequence of the last section.

1) RMS difference of tidal elevation
2-3) average difference of surface and bottom salinity, respectively
4-5) RMS difference of surface and bottom velocity magnitude, respectively
6-7) average difference of surface and bottom residual velocity magnitude, respectively
8) sedimentation potential difference

As with the range of legend intervals of the spatial plots discussed in the last section, the range of class intervals for each variable was selected to be large enough to contain the maximum variability encountered for all the case comparisons. An example of a histogram plot is shown below in Figure III.1 to facilitate discussion. For each of the histograms shown in Figures 1-16, the class interval area is a maroon bin whose percentile value is shown on the left vertical axis. The blue curve plotted shows the cumulative percent of all bins and its value is shown on the right vertical axis.

To provide a quantitative measure of the 2 Base Case – Test Case comparisons, a quantity was extracted from each of the histograms. The quantity is the 95th percentile value. Taking Figure III.1 for an example, as the cumulative percentage curve crosses the 95th percentile, the corresponding difference value (i.e., 0.05 cm) is the 95th percentile value. By definition, the value of 0.05 cm is exceeded by only 5% of the total area under consideration.
Elevation RMS Difference
Norfolk Harbor Dredging vs. Base Case I

Figure III.1. Example histogram used in percentile analysis

Tables III.1 shows the 95th percentile values for assessment of the proposed Norfolk Harbor dredging compared under both the existing (i.e., Test Case I vs. Base Case I) and built-out (i.e., Test Case II vs. Base Case II) conditions for surface elevation, surface and bottom salinity, surface and bottom velocity, and sedimentation potential.

Table III.1. The 95th percentile values for selected model variables for Single Variable Runs, Scenarios 1 and 2.

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<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case II</th>
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<td>Surface Elevation</td>
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</tr>
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<td>Surface Salinity</td>
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<td>Surface Salinity</td>
<td>0.03 ppt</td>
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<td>Bottom Salinity</td>
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<td>Bottom Salinity</td>
<td>0.04 ppt</td>
</tr>
<tr>
<td>Sedimentation Potential</td>
<td>0.5 %</td>
<td>Sedimentation Potential</td>
<td>0.5 %</td>
</tr>
</tbody>
</table>
B. HISTORICAL RUNS

The methodology for analyzing the results of the historical runs was presented fully in Section C.3 of Chapter II. Here, the results of the historical runs are presented for both Test Case – Base Case comparisons.

1. Spatial Distribution – The reader is referred to Section A.1 of this chapter for a general discussion of spatial plotting of differences of selected state variables between the Test Case and the Base Case.

It is noted here that the total number of spatial plots for the historical runs is 48, which results from 2 case comparisons each having 3 events, with each event involving the following 8 spatial plots:

1) RMS difference of surface elevation
2-3) average difference of surface and bottom salinity, respectively
4-5) RMS difference of surface and bottom velocity magnitude, respectively
6-7) average difference of surface and bottom residual velocity magnitude, respectively
8) sedimentation potential difference between Test Case and Base Case

These spatial plots are shown in Figures 1-48 of Appendix C. The sequence of presentation within this appendix is as follows:

Norfolk Harbor Dredging vs. Base Case I (High Discharge Event) (Scenario 3) – Plots revealing areas impacted by the Norfolk Harbor dredging for the existing condition (Base Case I) for the high discharge event are shown in Figures 1-8 of Appendix C. For surface elevation (Figure 1), the small portions at the heads of all Elizabeth River branches show RMS average differences that range up to 0.4 cm. Average differences in surface salinity (Figure 2) fall below ±0.2 ppt everywhere except in a small area entering the Southern Branch. Bottom salinity average differences (Figure 3) are everywhere under ±0.2 ppt except along the Norfolk Harbor Channel where differences range up to ±1.0 ppt. Surface velocity magnitude difference (Figure 4) reaches 12 cm/sec in the entrance to the Inter-Coastal Waterway, probably due to phase. Bottom velocity magnitude difference reaches 5 cm/sec in a very small area near Lamberts Pt. Surface and bottom residual velocity magnitude differences (Figures 6 and 7) show, respectively, limits of ±5 cm/sec
and ±3 cm/sec in areas immediately along the dredging region. Sedimentation potential difference is plotted in Figure 8, impacting a very small area near Lamberts Pt. with a difference of about 10%.

Norfolk Harbor Dredging vs. Base Case I (Low Discharge Event) (Scenario 4) – Plots revealing areas impacted by the Norfolk Harbor dredging for the existing condition for the low discharge event are shown in Figures 9-16 of Appendix C. For surface elevation (Figure 9), all RMS average differences fall below 0.1 cm except for the Eastern and Southern Branches, which have large areas less than 0.2 cm and a small area ranging up to 0.7 cm, probably due to phase rather than amplitude. Average differences in surface salinity (Figure 10) fall below ±0.2 ppt everywhere, except directly along the dredge region, where they range to 1.0 ppt. Bottom salinity average differences (Figure 11) are everywhere under ±0.2 ppt except over a portion of the dredge region (where they range to 1.0 ppt) and over much of the Eastern and Southern Branches (where they range to 0.6 ppt). Surface velocity magnitude difference (Figure 12) shows a difference of about 5 cm/sec over a small portion of the dredge area downstream of the Southern Branch and a bigger difference at the head of the Southern Branch (again, caused by phase rather than amplitude). The bottom velocity magnitude differences (Figure 13) are shown to be 3-6 cm/sec in very small areas near Lamberts Pt. and just north of Craney Island. Surface and bottom residual velocity magnitude differences (Figures 14 and 15) show, respectively, limits of ±5 cm/sec and ±3 cm/sec in areas immediately along the dredging region. Sedimentation potential difference is plotted in Figure 16, impacting very small areas along the northern portion of the dredging area with differences of approximately ±10%.

Norfolk Harbor Dredging vs. Base Case I (High Wind Event) (Scenario 5) – Plots showing the impact areas due to the Norfolk Harbor dredging for the existing condition for the high wind event are shown in Figures 17-24 of Appendix C. For surface elevation (Figure 17), all RMS average differences above 0.1 cm are confined primarily to the Southern and Eastern Branches, with higher values ranging to 0.7 cm at the head of the Southern Branch. Average differences in surface salinity (Figure 18) fall below ±0.2 ppt everywhere except near the head of the Southern Branch, where values range to -0.6 ppt. Bottom salinity average differences (Figure 19) are everywhere under ±0.2 ppt except along most of the dredging region where differences range to ±1.0 ppt. Surface velocity magnitude difference (Figure 20) show a small region upstream in the Southern Branch where values range to 9 cm/sec, probably due to phase. The bottom velocity magnitude differences (Figure 21) reach approximately 5 cm/sec in a very small area near Lamberts point, but are limited to 3 cm/sec over the entire far field. Surface and bottom residual velocity magnitude differences (Figures 22 and 23) show, respectively, limits of ±10 cm/sec and ±5 cm/sec in areas immediately along the dredging region. Sedimentation potential difference is plotted in Figure 24, impacting a very small area at Lamberts Pt. with a difference of about ±10%.

Norfolk Harbor Dredging vs. Base Case II (High Discharge Event) (Scenario 6) – Plots showing areas impacted by the Norfolk Harbor dredging for the built-out condition for the high discharge event are shown in Figures 25-32 of Appendix C. For surface
elevation (Figure 25), all RMS average differences fall below 0.1 cm except over the Southern and Eastern Branches (and the head of the Western Branch), where most differences fall below 0.2 cm. Average differences in surface salinity (Figure 26) fall below ±0.2 ppt everywhere except in a small portion entering the Southern Branch and an area near the head of the Southern Branch. Bottom salinity average differences (Figure 27) are everywhere under ±0.2 ppt except long the dredging region where values range to 1.0 ppt. Surface velocity magnitude difference (Figure 28) reaches 12 cm/sec in a very small area at the entrance of the Inter-Coastal Waterway at the head of the Southern Branch. Bottom velocity magnitude differences (Figure 29) reach about 5 cm/sec in a very small area near Lamberts Pt. but are limited to 3 cm/sec in the far field. Surface and bottom residual velocity magnitude differences (Figures 30 and 31) show limits of ±5 cm/sec and ±3 cm/sec, respectively, along the dredging area of the Norfolk Harbor Channel. Sedimentation potential difference from the Base Case is plotted in Figure 32, impacting a very small area near Lamberts Pt. with a difference of about ±10%.

Norfolk Harbor Dredging vs. Base Case II (Low Discharge Event) (Scenario 7) - Plots showing areas impacted by the Norfolk Harbor dredging for the built-out condition for the low discharge event are shown in Figures 33-40 of Appendix C. For surface elevation (Figure 33), all RMS average differences fall below 0.1 cm except over the Southern and Eastern Branches, where differences are primarily below 0.2 cm. Average differences in surface salinity (Figure 34) fall below ±0.2 ppt everywhere except directly along the Norfolk Harbor dredge area, part of the Eastern Branch, and much of the Southern Branch upstream of dredging. However, these differences are less than 0.6 ppt over most of this area. Bottom salinity average differences (Figure 35) are less than ±0.2 over the entire far-field and are under ±1.0 ppt along the dredging region, and in portions of the Eastern and Southern Branches. Surface velocity magnitude differences (Figure 36) and bottom velocity magnitude differences (Figure 37) are limited to 2 cm/sec in the far field and to 6 cm/sec in small portions of the dredging region. Surface and bottom residual velocity magnitude differences (Figures 38 and 39) show a more extensive area around the dredging that is bound by approximately ±5 cm/sec and ±3 cm/sec, respectively. Sedimentation potential difference from the Base Case is plotted in Figure 40, impacting primarily a very small area near Lamberts Pt. with a difference of about ±10%.

Norfolk Harbor Dredging vs. Base Case II (High Wind Event) (Scenario 8) – Plots showing areas impacted by the Norfolk Harbor dredging for the built-out condition for the high wind event are shown in Figures 41-48 of Appendix C. For surface elevation (Figure 41), all RMS average differences fall below 0.1 cm for the entire far-field downstream of the dredging, whereas most of the Southern and Eastern Branches have values between 0.1-0.2 cm. Average differences in surface salinity (Figure 42) fall below ±0.2 ppt everywhere except in small areas near the head of the Southern Branch, where values are less than ±0.6 ppt. Bottom salinity average differences (Figure 43) are everywhere under ±1.0 ppt, and only exceed 0.2 ppt along the dredge region and upstream in the Southern Branch. Surface velocity magnitude differences (Figure 44) is everywhere under 3 cm/sec, except upstream in the Southern Branch. The bottom velocity magnitude differences (Figure 45) reach 6 cm/sec only in a small area near

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Lamberts Pt. and are limited to 3 cm/sec everywhere else in the far field. Surface and bottom residual velocity magnitude differences (Figures 46 and 47) show limits of ±5 cm/sec and ±3 cm/sec, respectively, immediately along the dredging region. Sedimentation potential difference from the Base Case is plotted in Figure 48, impacting primarily a small area near Lamberts Pt. with a difference of about ±10%.

The spatial distributions of the case comparison differences are useful in delineating areas of maximum impact and yet, they are qualitative in nature. An attempt to quantify this analysis is described in the next section.

2. Percentile Analysis – As was done to compare the single variable test cases against the single variable base cases (see Section A.2 of this chapter), the differences of historical test case results for both Base Case – Test Case comparisons were divided into class intervals. Then each interval’s accumulated spatial distribution was plotted as a percentage of the entire model surface area of Hampton Roads. In this fashion, a set of simple histograms showing the distribution of class interval differences of all variables can be constructed, as shown in Appendix D, Figures 1-48.

For each of the 3 events of the 2 Test Case – Base Case comparisons, a histogram was provided for each of the following 8 selected differences in this specified sequence:

1) RMS difference of surface elevation
2-3) average difference of surface and bottom salinity, respectively
4-5) RMS difference of surface and bottom velocity magnitude, respectively
6-7) average difference of surface and bottom residual velocity magnitude, respectively
8) sedimentation potential difference between Test Case and Base Case

The differences for the high discharge, low discharge, and high wind events comparing the Norfolk Harbor dredging impact to the Base Case for the existing condition (Base Case I) are shown, respectively, in Figures 1-8, 9-16, and 17-24. Retaining this sequence of these events, those comparing the Norfolk Harbor dredging impact to the Base Case for the built-out condition (Base Case II) are shown in Figures 25-48. For each of the histograms shown in Figures 1-48, the class interval area is a maroon bin whose percentile value is shown on the left vertical axis, whereas the blue curve plotted shows a cumulative percentage of all bins the value of which is shown on the right vertical axis.

A final step in comparing the impacts from the different test cases is to construct a table with the 95th percentile values of the aforementioned cumulative curves, as shown in Table III.2. As was seen in the summary table for single variable runs, there was minimal change in the 95th percentile values for surface elevation and salinity and only small increases for both velocity and sedimentation potential for the events of high discharge, low discharge, and high wind.
Table III.2. The 95\textsuperscript{th} percentile values for selected model variables for Historical Runs, Scenarios 3 through 8.

| Global Change – 95\textsuperscript{th} Percentile |  
| (5\% of area contains change greater than value listed) |  

<p>| Historical – High Discharge Event |</p>
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IV. THE RESULTS FOR SEDIMENT AND TURBIDITY MODEL SIMULATION

A. SEDIMENT MODEL CALIBRATION (under non-dredging condition)

In 2000, there were 12 slackwater surveys conducted from April 24 to October 18. During each survey, sediment concentrations were measured at 20 stations along the mainstem of the Elizabeth and at several stations in its branches (i.e., 2 in the Eastern Branch, 3 in the Western Branch, 3 in the Lafayette River, and 3 in Deep Creek). These sampling locations are shown below in Figure IV.1, where red dots signify the locations of mainstem stations and blue dots signify those of the branch stations.

Figure IV.1. Slackwater survey stations in the Elizabeth River
One of the issues for the suspended sediment concentration in the Elizabeth River is the source of the sediment supply. In general, sediment within an estuary can come from several sources: (1) local bed erosion, (2) net influx from upstream or downstream, (3) bank erosion, and (4) lateral influx through runoff. Among the 4 possibilities, the first two (local bed erosion and net influx from upstream or downstream) were considered the most likely sources contributing to the total suspended load in the Elizabeth River.

Figures IV.2a through IV.2c show distributions of suspended sediment concentration in mg/l during May 2000, a month characterized by relatively high freshwater inflow. Suspended sediment concentration is relatively low (10-15 mg/l) in the upper portion of the water column but higher concentrations (20-40 mg/l) are consistently observed in a zone near the bottom extending from the Elizabeth River entrance to approximately 18 km upstream. Highest concentrations (>40 mg/l) were found within the first 5 km upstream from the entrance. Tidal phasing and advective pumping into the Elizabeth River appear to be the primary mechanisms responsible for the bottom influx observed. During late ebb in the lower James River, a part of the exiting flow is diverted south into the Elizabeth River entrance, which experiences flooding at this time.

Figures IV.3a and IV.3b show examples of the suspended sediment concentration field in the Elizabeth River on October 12 and October 18 after an extended period of low river inflow. Concentrations of 5-10 mg/l were noted everywhere within the water column except for isolated patches of higher concentration that appear to be bottom derived. One patch of unusually high concentration coincided with the passing of a large ship near the survey vessel and is marked in Figure IV.3b as propeller wash. The above findings suggest that bottom concentrations of suspended sediment may be expected to exceed 30 mg/l well into the Elizabeth River as far as Paradise Creek in the Southern Branch (km 18) during periods of high freshwater inflow into the James. At other times, concentrations of 30-40 mg/l are restricted to the entrance region and certain areas adjacent to the more active shipping channels.

The HEM-3D sediment model, with constant sediment settling velocity and an erosion mechanism based on constant critical shear stress and erosion rate, has been applied in York River for the turbidity maximum study (Lin and Kuo, 2001). The sediment transport in the Elizabeth River is dominated by cohesive sediments. The sediment sub-model has been updated to incorporate a new algorithm developed and tested in the study of sediment and toxic modeling in Baltimore Harbor (Lin et al., 2003 and Lin et al., 2004). The algorithm accounts for the change of critical shear stress for sediment erosion as consolidation occurs in the bottom sediment (see Section B, Chapter II). This formulation has the same effect as though the model had multiple layers at the bottom with different densities and critical shear stresses associated with the different layers. Initially, the model simulates three classes of suspended sediment with different particle sizes, namely, clay (3 µm), silt (18 µm), and fine sand (65 µm) with the respective
Figure IV.2. Suspended sediment concentrations (mg/l) during May 2000 along the Norfolk Harbor Channel.
settling velocities of 0.007, 0.26 and 3.3 mm s\(^{-1}\). The concentration of each class of sediment is simulated separately within the model. The total suspended sediment (TSS) concentration is the summation of the concentrations of these three classes of sediment. Analyses of bottom sediment distribution data and model tests in the Elizabeth River found that the fine sand contributes little to the total sediment suspended concentration. Therefore, only two classes, one with slow settling velocity and the other with fast settling velocity, are selected for further model simulation. The slow settling velocity is based on the Stokes’ Law used for simulating the clay size of 3 \(\mu\)m. For the fast settling
velocity class size, a formulation proposed by Fugate and Friedrichs (2002), based on the field measurement in the York River, is adopted in this study:

\[ w_s = 3.4 \times 10^{-4} C^{0.19} \]

where \( w_s \) is the settling velocity (ms\(^{-1}\)) and \( C \) (mgL\(^{-1}\)) is the sediment concentration. As for the initial critical shear stress, different initial critical shear stresses were specified in the James River and Elizabeth River, which are 0.25 Pa and 0.04 Pa, respectively.

An initial constant concentration of 15 mgL\(^{-1}\) was specified for clay in the James River and Lower Reaches of Elizabeth River (north of the Eastern Branch), and 5 mgL\(^{-1}\) was specified for clay in the Upper Reaches of Elizabeth River (south of the Eastern Branch). For silt, an equilibrium concentration, obtained from model results of a 3-month simulation by forcing tides at the open boundary and constant mean river discharges at the river inflow points, was specified.

For this study, the monthly observation data collected by Virginia Department of Environmental Quality in 2000 were used for the model calibration. Figure IV.4 shows the locations of observation data in the Elizabeth River. The model simulation period is 100 days, which is the same as that of the hydrodynamic model calibration. During the simulation period, observed water elevation, wind, and freshwater discharge were used to force the model. Model calibration results at the selected observation stations along the main channel of the Elizabeth River are shown in Figures IV.5 and IV.6. Sediment concentrations range from 10 mgL\(^{-1}\) to 150 mgL\(^{-1}\) in the Elizabeth River. Bottom sediment concentrations are higher than surface sediment concentrations. For most of the stations inside the Elizabeth River, the sediment concentrations are approximately 20 mgL\(^{-1}\). The high sediment concentrations occur near the mouth of the Elizabeth River. Because sediment concentrations are highly influenced by the effects of waves and other factors, some discrepancies can be expected. The differences between modeled and observed concentrations at some stations range from 5 to 10 mgL\(^{-1}\). Overall, model results agree with observations.

B. Turbidity Plume Model Simulation

1. Calibration

Virginia Institute of Marine Science conducted a series of experiments in September 1978 in the Elizabeth River during ship dredging conditions. Sediment concentrations were measured in and around the plume resulting from hydraulic maintenance dredging of the ship channel along the Craney Island Reach of the river (Priest et al., 1981). In the dredging operation of a hydraulic dredge, the plume is generated by an oscillating moving source, the cutter head. It was reported that the cutter head of the dredge incised a notch with a cross section of 30 square feet for a length 200 feet in a period of 5 minutes.
Figure IV.4. Locations of sediment observation stations.
Figure IV.5. Comparison of model results and observations (triangles are observations and lines are simulation predictions)
Figure IV.6. Comparison of model results and observations (triangles are observations and lines are simulation predictions)

The channel was maintained at 15.2 m (50 ft), and the measurements were made at either a depth of about 1 meter from the bottom or at mid-depth. The instrument was towed through the plume in various patterns in order to obtain the plume shape. The data were presented in the VIMS 1981 report (Priest et al., 1981) as sediment concentrations at
horizontal locations relative to the central location of the cutter head, the source of the sediment plume.

The available observation data (at 1 m above the bottom) are composed of 3 data sets collected on September 7, 19, and 26, 1978, respectively. The times of measurement relative to tidal phase in the three cases were at full ebb, late ebb, and low slack, respectively. The dredge-induced suspended sediment concentrations ranged generally from 10 to 100 mg/l, and the plume was confined within the ship channel with a longitudinal extent of 375 meters (1230 ft) or less. One of the important findings is that no observable dredge-induced sediment turbidity was measured at the mid-depth, i.e., the plume was confined in the lower half of the water column. The dredge-induced suspended sediment concentrations at several points along the axes of the plume are summarized in Table IV.1.

The ability of the model to simulate a dredge-induced sediment turbidity plume is demonstrated by comparing sediment model simulation results with the 1978 historical data. To simulate a dredge-induced plume, a suspended sediment source is required as an input data to the model. It was reported (Priest, 1981) that the cutter head of the dredge incised a notch with a cross section of 30 square feet for a length 200 feet in a period of 5 minutes. Therefore, the source strength of the turbidity plume may be computed as

\[
\text{Source} = 30 \times 200 / (5 \times 60) \times 30.48^3 \times 2.65 \times (1-p) \times e \text{ gram/second}
\]

Whereas 2.65 is the density of sediment particle in gram/cm³, p is bottom sediment porosity, and e is the fraction of the dredged sediment escaping the suction head. The bottom sediment in the Elizabeth River was reported to have an average porosity of 67%. Assuming 2% for the escaping rate, e, the source strength of the dredge amounted to 9905 grams per second (i.e., 9.9 kg/s).

The numerical model grid in the Elizabeth River is 123 m by 123 m, which is larger than the distance (200 ft) traveled by the cutter head in 5 minutes. The lack of information on the track of cutter head during the VIMS 1978 experiment and the spatial resolution of the model preclude us from simulating such a moving source. Therefore, a constant source of 9.9 kg/s is assumed at a fixed bottom model cell in the ship channel near Craney Island. The suspended sediment source is distributed uniformly over a volume of the cell size, 123 m by 123 m by 2.75 m. This has some implications on the model results, especially regarding the horizontal extent of the sediment turbidity plume. The fact that the dredged material was introduced 2.75 m above the sediment-water interface means that the sediment was artificially lifted above the bottom boundary layer near the bottom and exposed to a velocity 3-4 times higher in magnitude (estimated by the logarithmic profile). This will cause the horizontal extent of the plume to be 3 - 4 times longer. In addition, the horizontal dimension of the source is about 2 times longer than the cutter head actually traveled. Therefore, the model results should be considered as the most conservative estimate of the horizontal extent of the dredge-induced sediment turbidity plume.
Table IV.1. Dredge-induced suspended sediment concentrations (Priest, 1981).

<table>
<thead>
<tr>
<th>Time</th>
<th>Tidal phase</th>
<th>Distance from source (feet)</th>
<th>Maximum concentration (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/7/1978</td>
<td>Full ebb</td>
<td>220</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>320</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>440</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>460</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>870</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1130</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1230</td>
<td>10</td>
</tr>
<tr>
<td>9/19/1978</td>
<td>Late ebb</td>
<td>110</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>160</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>360</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td></td>
<td>680</td>
<td>8</td>
</tr>
<tr>
<td>9/26/1978</td>
<td>Low slack</td>
<td>230</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>360</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>390</td>
<td>9</td>
</tr>
</tbody>
</table>

If the cutter head is operated at or beneath the water-sediment interface, the horizontal extent could be 3-4 times less.

In the model simulations, the water elevation was specified at the open boundary using observed data from the Chesapeake Bay Bridge Tunnel and Sewells Point. As shown in Figure IV.7, the water level observed from Sewells Point from 9/1/1978 through 9/30/1978 contains the spring-neap tidal variation as well as wind tide. Wind effects were included in the model simulation using observed wind speeds and directions measured from Sewells Point during the same period (see Figure IV.8). It is obvious that there are two significant wind events that occurred on 9/14 and 9/24 which allow the model to assess the eventful response. During the period, mean river discharges were imposed at 8 river inflow points. In the sediment transport part, a constant settling velocity of $2 \times 10^{-3}$ m/s was utilized based on the analytical solution results of Kuo et al. (1985).

The eventful conditions that occurred in September 1978 are identified by time series plots of tide and wind in Figures IV.7 and IV.8, respectively. They are: average tide condition on September 7, high wind on September 19, and neap tide on September 26. The horizontal extents of the dredge-induced sediment plumes on these conditions, namely, September 7 (average tide), September 19 (high wind), and September 26 (neap tide), are shown in Figures IV.9, IV.10, and IV.11, respectively. The source locations and the resulting suspended sediment plume just after release, at high water slack, and at low water slack were presented.
Figure IV.7. Tides observed at Sewells Pt., VA in September, 1978.

Figure IV.8. Observed winds at Sewells Pt., VA in September, 1978.
Figure IV.9. The dredge-induced sediment turbidity plume a) just after release, b) at high water slack, and c) at low water slack on September 7, 1978. Axes coordinates are Virginia State Plane (South Zone, meters) and color bar shows sediment concentrations.
Figure IV.10. The dredge-induced sediment turbidity plume a) just after release, b) at high water slack, and c) at low water slack on September 19, 1978. Axes coordinates are Virginia State Plane (South Zone, meters) and color bar shows sediment concentrations.
Figure IV.11. The dredge-induced sediment turbidity plume a) just after release, b) at high water slack, and c) at low water slack on September 26, 1978. Axes coordinates are Virginia State Plane (South Zone, meters) and the color bar shows sediment concentrations.
The model results show that the dredge-induced suspended sediment concentrations can reach as high as 160 mg/L near the channel bottom. The horizontal extents are about 250 m in width, 1500 m in the flood direction, and 500 m in the ebb direction. The model results also indicate that no dredge-induced sediment ever reaches the upper half of the water column, which is consistent with the observation of the VIMS 1978 experiment.

Compared to the VIMS 1978 observation, the model predicts higher sediment concentrations and larger longitudinal plume extents. All observations in 1978 were made in the ebb direction, with the largest extent of 500 feet observed on September 7 while the model predicts a plume length of 375 m. These discrepancies may be attributed to the sediment source being spread over a large volume of the model grid at the bottom, which has the dimensions of 123 m by 123 m by 2.75 m. That would result in sediment particles taking a longer time to settle back to the bottom, thus resulting in higher concentrations and a larger plume extent. However, the overall model results can be considered qualitatively reasonable, and any quantitative discrepancies are on the conservative side.

2. Impact assessment and scenario runs for Port Norfolk, Town Point, and Lower Reaches

The environmental impact of the sediment turbidity generated by a dredging operation includes maximum sediment concentration near the bottom, horizontal and vertical extents of the turbidity plume, and the duration of the persistence of high turbidity concentration. The maximum sediment concentration is a concern because benthic organisms are susceptible to excess levels of sediment concentration, especially during their larval stages. The horizontal and vertical extents of the turbidity plume relate to the re-deposition of dredge-induced turbidity in the surrounding area, thus inflicting a negative impact on the shallow water habitat. The duration of a high turbidity concentration also can become a major environmental stress to aquatic organisms.

The nature and extent of sediment plume concentrations are dependent on a number of site specific characteristics including: the current condition, porosity of the sediment, sediment grain size, amount of organic and fine-grained material in the sediment, and the amount of sediment release. Thus, the entire dredging region was sub-divided into three major reaches: Port Norfolk, Town Point, and Lower Reaches, and the key environmental parameters were determined by a series of model simulations. The hydraulic dredge was assumed, and the point source production was specified similar to the VIMS 1978 experiment. Given the fact that the dredging operation occurred during normal conditions, the period for scenario runs was from August 26 through September 10 (a duration of 15 days) during the average tidal condition.

Two scenarios runs (Scenarios 9 and 10) were conducted: one for comparison with the existing base condition and the other for comparison with the built-out base condition. Under each scenario run, three separate model simulations were performed with sediment source locations in the northernmost region of the planned dredging channel (i.e., Port Norfolk Reach), in the middle section of the channel at a turning point near the junction...
with the Eastern Branch of the river (i.e., Town Point Reach), and in the southernmost region of the planned channel dredging (i.e., Lower Reach). The forcing boundary conditions, initial conditions, and sediment simulation parameters were all kept identical to those used in the model calibration run. The dredge-induced sediment concentration was obtained by subtracting the total sediment concentration (under the dredging condition) from the ambient sediment concentration (under the non-dredging condition); thereby, this represents the excess sediment concentration due to the dredging operation. The results for Scenario 9 are presented as follows:

Port Norfolk

Figure IV.12 shows the plan view of the dredge-induced sediment concentration at Port Norfolk Reach at day 8 of simulation when the extent of the sediment plume was the largest and the suspended sediment concentration the highest. It can be seen that the maximum downstream extent of the plume is 800 m, and the maximum upstream extent is 3000 m. The maximum width of the plume is around 150 m. As a complement to the plan view, Figure IV.13 shows the vertical extent of the Norfolk Harbor Reach plume. The upper panel shows the axial velocity for the bottom layer (layer 1), middle layer (layer 3), and the surface layer (layer 6); positive velocity is northward while the negative velocity is southward. The bottom panel shows the sediment concentrations for the 3 bottom layers (layers 1, 2, and 3). The maximum concentrations are about 150 mg/l in the bottom (layer 1), 20 mg/l in the layer above (layer 2), and 3 mg/l in the middle layer (layer 3). The turbidity plume is practically confined to the lower half of the water column.

Town Point

Figure IV.14 shows the plan view of the dredge-induced sediment turbidity concentration in Town Point Reach at day 8 of simulation when the extent of the sediment plume was the largest and the suspended sediment concentration the highest. It can be seen that the maximum downstream extent of the plume is 250 m, and the maximum upstream extent is 1000 m. The maximum width of the plume is around 100 m. It can be seen that the plume was confined in the channel area and did not intrude into the Eastern Branch of the Elizabeth River. As a complement to the plan view, Figure IV.15 shows the vertical extent of the Town Point Reach plume. The upper panel shows the axial velocity for the bottom layer (layer 1), middle layer (layer 3), and the surface layer (layer 6). It is obvious that the bottom velocity has a residual component of velocity towards the south. The bottom panel shows the sediment concentrations for the 3 bottom layers (layers 1, 2, and 3). The maximum concentrations are approximately 100 mg/l in the bottom (layer 1), 20 mg/l in the layer above (layer 2), and 5 mg/l in the middle layer (layer 3).

Lower Reach

Figure IV.16 shows the plan view of the dredge-induced sediment turbidity concentration in the Lower Reach at day 8 of simulation when the extent of the sediment plume was the largest and the suspended sediment concentration the highest. It can be seen that the
maximum downstream extent of the plume is 400 m, the maximum upstream extent is 6000 m, and the maximum width of the plume is around 50 m. However, the plume does spread over the entire cross-section at this release site.

As a complement to the plan view, Figure IV.17 shows the vertical extent of the Lower Reach plume. The upper panel shows the axial velocity for the bottom layer (layer 1), middle layer (layer 3), and the surface layer (layer 6). It is shown that, along the Lower Reach in the Southern Branch of the Elizabeth River, the current becomes much weaker and again shows a residual component of velocity towards the south. The extent of the sediment plume is much more restricted: the maximum upstream extent is about 600 m, and the maximum downstream extent is about 400 m. The bottom panel shows sediment concentrations for the 3 bottom layers (layers 1, 2, and 3). The maximum concentrations are approximately 50 mg/l in the bottom 2 layers (layers 1 and 2) and 9 mg/l in the middle layer (layer 3). It can be seen that the sediment plumes follow the channel alignment, and extend farther upstream during the flood period than they extend downstream during the ebb period.

In summary, the spatial extents of the turbidity plumes and the vertical distributions of concentrations for the Port Norfolk, Town Point, and Lower Reaches are summarized in Table IV.2 below:

Table IV.2. Horizontal extents and vertical sediment concentrations for each reach.

<table>
<thead>
<tr>
<th>Reach locations</th>
<th>Horizontal extent</th>
<th>Maximum sediment concentration in the vertical (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Downstream (northward)</td>
<td>Upstream (southward)</td>
</tr>
<tr>
<td>Port Norfolk</td>
<td>800 m</td>
<td>3000 m</td>
</tr>
<tr>
<td>Town Point</td>
<td>250 m</td>
<td>1000 m</td>
</tr>
<tr>
<td>Lower Reach</td>
<td>400 m</td>
<td>600 m</td>
</tr>
</tbody>
</table>

The Port Norfolk Reach release has the largest plume, followed by those at Town Point Reach and the Lower Reach. The sediment plume generated at Town Point does not enter into the Eastern Branch of the Elizabeth River. The modeling results of the horizontal extent for the sediment turbidity plume in the downstream, upstream, and lateral directions are approximately 3-4 times larger than the actual field observations obtained from the VIMS 1978 survey. The proper explanation lies in the question of the position of the hydraulic dredging cutter head relative to the sediment-water interface. The model assumes that the sediment source will be distributed uniformly 2.5 m above
Figure IV.12. a) The location of the point source for Port Norfolk Reach, b) the dredge-induced plume at high water slack, and c) the plume at low water slack for Scenario 9. Axes coordinates are Virginia State Plane (South Zone, meters) and the color bar shows sediment concentrations.
Port Norfolk Reach

Figure IV.13. The vertical extent of the Port Norfolk Reach plume shown by axial velocity and sediment concentration at each layer (layer thickness 2.4 m) for Scenario 9.
Figure IV.14. a) The location of the point source for Town Point Reach, b) the dredge-induced plume at high water slack, and c) the plume at low water slack for Scenario 9. Axes coordinates are Virginia State Plane (South Zone, meters) and the color bar shows sediment concentrations.
Figure IV.15. The vertical extent of the Town Point Reach plume shown by axial velocity and sediment concentration at each layer (layer thickness 2.2 m) for Scenario 9.
Figure IV.16.  a) The location of the point source for Lower Reach, b) the dredge-induced plume at high water slack, and c) the plume at low water slack for Scenario 9. Axes coordinates are Virginia State Plane (South Zone, meters) and the color bar shows sediment concentrations.
Figure IV.17. The vertical extent of the Lower Reach plume shown by axial velocity and sediment concentration at each layer (layer thickness 2.3 m) for Scenario 9.
the sediment-water interface, which will allow a larger ambient current (beyond bottom boundary layer) to carry and disperse the sediment plume further. If the cutter head is operated beneath the sediment-water interface, the sediment turbidity generated by the hydraulic dredge cutter head will likely remain within the bottom boundary layer, a few centimeters above the sediment-water interface. In this situation, the bottom current magnitude at the boundary layer will be approximately 30% of that at 2.5 meters above. Thus, the horizontal extent over which the turbidity plume is carried will be 3 to 4 times less than the model results.

Therefore, what the model simulation presents is based on the most conservative estimate of the sediment source that was extended 2.5 meters above the bottom. If the cutter head is operated at or beneath the sediment-water interface, the actual horizontal extent could be 3 to 4 times less.

When the turbidity plume is generated by the dredging operation, it is desirable to know the duration in which high TSS concentration will be persistent. Each organism has a certain tolerance period for adverse environmental conditions such as high TSS concentration. Knowing the duration of the persistence can be used to assess the exposure risk for various living organisms. To examine the persistence of the turbidity plume, the dredging operation was simulated continuously for one full day, and then stopped, after which the time histories of the sediment concentrations were recorded. In doing so, the demise of the turbidity plume was fully captured.

The persistence of the dredge-induced turbidity plume was investigated at all 3 reach locations by tracking the time history of sediment turbidity concentrations in the bottom 3 layers subsequent to a 1-day release. For Scenario 9, these concentrations are shown in Figures IV.18, IV.19, and IV.20 for releases in the Port Norfolk, Town Point, and Lower Reaches, respectively.

In each instance, the release occurred at the time of the peak flood. It was found that the plume persistence ranged from 0.345 to 0.902 days, depending on location and model layer. The dredge-induced plume was the most persistent in the middle layer at the Port Norfolk Reach (i.e., duration of 0.902 days) and the least persistent in the bottom layer at the Lower Reach (i.e., duration of 0.345 days). In all cases, the persistence in the higher layers was slightly longer than that at the bottom layer. The persistency durations of each plume at the bottom 3 model layers are shown in Table IV.3 for Scenario 9 results.

The horizontal and vertical extents of the dredge-induced sediment plume for the Scenario 10 simulations were found to be almost identical to those found for Scenario 9. For this reason, the plots showing the Scenario 10 concentrations and extents are included in Figures 1 through 2, 3 through 4, and 5 through 6 of Appendix E for the Port Norfolk, Town Point, and Lower Reaches, respectively. Additionally, the persistence of the sediment turbidity due to the dredge-induced plume was investigated for Scenario 10 as well. Since these results were almost identical to those found for Scenario 9, the results for the plume durations at Port Norfolk, Town Point, and Lower Reaches for Scenario 10 are shown in Figures 7 through 9, respectively, of Appendix E.
Table IV.3. Persistence of turbidity plumes in lower 3 layers after a 1-day sediment release at each reach location.

<table>
<thead>
<tr>
<th>Reach location</th>
<th>Release start / end (days)</th>
<th>Modeled Layers</th>
<th>Time (days) of last detectable concentration</th>
<th>Plume duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port Norfolk</td>
<td>4.38 / 5.38</td>
<td>Layer 1 (bottom)</td>
<td>5.865</td>
<td>0.485</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Layer 2</td>
<td>6.052</td>
<td>0.672</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Layer 3</td>
<td>6.282</td>
<td>0.902</td>
</tr>
<tr>
<td></td>
<td>4.01 / 5.01</td>
<td>Layer 1 (bottom)</td>
<td>5.468</td>
<td>0.458</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Layer 2</td>
<td>5.532</td>
<td>0.522</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Layer 3</td>
<td>5.555</td>
<td>0.545</td>
</tr>
<tr>
<td>Lower Reach</td>
<td>7.46 / 8.46</td>
<td>Layer 1 (bottom)</td>
<td>8.805</td>
<td>0.345</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Layer 2</td>
<td>8.840</td>
<td>0.380</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Layer 3</td>
<td>8.845</td>
<td>0.385</td>
</tr>
</tbody>
</table>

Figure IV.18. Time history of sediment turbidity concentrations in bottom 3 layers after a 1-day release at Port Norfolk Reach starting at day 4.38 for Scenario 9.
Figure IV.19. Time history of sediment turbidity concentrations in bottom 3 layers after a 1-day release at Town Point Reach starting at day 5.01 for Scenario 9.

Figure IV.20. Time history of sediment turbidity concentrations in bottom 3 layers after a 1-day release at Lower Reach starting at day 7.46 for Scenario 9.
V. CONCLUSIONS

Hydrodynamic modeling was conducted for the Proposed Dredging Assessment in Norfolk Harbor Channel, Elizabeth River using the VIMS hydrodynamic Model HEM-3D. For the assessment of the proposed Norfolk Harbor Channel dredging in the Elizabeth River, two Base Cases were constructed:

(1) Existing condition: All currently existing facilities that influence the model are included. These are the Interstate highways I-64 and I-664 and the APM Terminal facility south of Craney Island.

(2) Built-out condition: The existing condition plus the Craney Island Eastward Expansion (CIEE) and the VDOT 3rd Crossing Alternative 9.

There are 10 model scenario runs that were conducted, summarized as:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Impact Assessment</th>
<th>Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Norfolk Harbor dredging impact under average tidal conditions</td>
<td>Existing</td>
</tr>
<tr>
<td>2</td>
<td>Norfolk Harbor dredging impact under average tidal conditions</td>
<td>Built-out</td>
</tr>
<tr>
<td>3</td>
<td>Norfolk Harbor dredging impact under an eventful condition of high river discharge</td>
<td>Existing</td>
</tr>
<tr>
<td>4</td>
<td>Norfolk Harbor dredging impact under an eventful condition of low river discharge</td>
<td>Existing</td>
</tr>
<tr>
<td>5</td>
<td>Norfolk Harbor dredging impact under an eventful condition of high wind</td>
<td>Existing</td>
</tr>
<tr>
<td>6</td>
<td>Norfolk Harbor dredging impact under an eventful condition of high river discharge</td>
<td>Built-out</td>
</tr>
<tr>
<td>7</td>
<td>Norfolk Harbor dredging impact under an eventful condition of low river discharge</td>
<td>Built-out</td>
</tr>
<tr>
<td>8</td>
<td>Norfolk Harbor dredging impact under an eventful condition of high wind</td>
<td>Built-out</td>
</tr>
<tr>
<td>9</td>
<td>Norfolk Harbor dredging short-term impact due to the dredge-induced sediment plume</td>
<td>Existing</td>
</tr>
<tr>
<td>10</td>
<td>Norfolk Harbor dredging short-term impact due to the dredge-induced sediment plume</td>
<td>Built-out</td>
</tr>
</tbody>
</table>

Scenarios 1 and 2 are tested for the normal tidal condition whereby average river discharge, calm wind, and M2, S2, and N2 tidal constituents are included. Scenarios 3 and 6 are test for the eventful condition of high river discharge with a highest river discharge of 1033 cms (36,480 cfs) measured at Richmond. Scenarios 4 and 7 are tested for the eventful condition of low river discharge with a lowest river discharge of 47 cms (1660 cfs) measured at Richmond. Scenarios 5 and 8 are tested for the eventful condition of high wind measured at Sewells Pt., VA. The maximum wind that occurred during this
event was 20 m/sec. Scenarios 9 and 10 are tested for the short-term impact due to the
dredge-induced sediment plume.

When the above scenarios were conducted, the single variable runs were used to simulate
the long-term average flow and predicted tidal harmonics as model input and historical runs were conducted to assess the impacts of dredging during eventful conditions. In the
historical run simulation scenarios, the impacts of dredging are tested against eventful
conditions comprised of high and low discharge and high wind during a six-month
simulation for which the input variables (i.e., discharges, wind, boundary conditions) are
taken from historical records measured between April and October 2000. Both single
variable run and historical runs are tested against both Base Cases I and II (existing and
built-out conditions).

Since the impact could be non-local, specifically it could affect remote portions of the
domain, the approach of assessment was to use a methodology to compare the impacts of
dredging over the far-field, including the areas of Hampton Roads and the Elizabeth
River. In order to compare quantitatively the impacts, the approach of global analysis
methodology was used. This was done by determining percentages of total area
associated with class intervals of change from the Base Case as differences in water
surface elevation, surface and bottom salinity, surface and bottom current magnitude,
surface and bottom residual current magnitude, and sedimentation potential. The results
are shown in the following tables for single variable runs and historical runs,
respectively:

<table>
<thead>
<tr>
<th></th>
<th>Norfolk Harbor Dredging versus Base Case I</th>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Elevation</td>
<td>0.05 cm</td>
<td>Surface Elevation</td>
<td>0.05 cm</td>
</tr>
<tr>
<td>Surface Current</td>
<td>2.3 cm/s</td>
<td>Surface Current</td>
<td>2.3 cm/s</td>
</tr>
<tr>
<td>Bottom Current</td>
<td>1.9 cm/s</td>
<td>Bottom Current</td>
<td>1.8 cm/s</td>
</tr>
<tr>
<td>Surface Salinity</td>
<td>0.03 ppt</td>
<td>Surface Salinity</td>
<td>0.03 ppt</td>
</tr>
<tr>
<td>Bottom Salinity</td>
<td>0.05 ppt</td>
<td>Bottom Salinity</td>
<td>0.04 ppt</td>
</tr>
<tr>
<td>Sedimentation Potential</td>
<td>0.5 %</td>
<td>Sedimentation Potential</td>
<td>0.5 %</td>
</tr>
</tbody>
</table>
## Global Change – 95th Percentile
(5% of area contains change greater than value listed)

### Historical – High Discharge Event

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case I</th>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Elevation</td>
<td>0.11 cm</td>
<td>Surface Elevation</td>
<td>0.10 cm</td>
</tr>
<tr>
<td>Surface Current</td>
<td>3.4 cm/s</td>
<td>Surface Current</td>
<td>3.2 cm/s</td>
</tr>
<tr>
<td>Bottom Current</td>
<td>2.2 cm/s</td>
<td>Bottom Current</td>
<td>2.1 cm/s</td>
</tr>
<tr>
<td>Surface Salinity</td>
<td>0.07 ppt</td>
<td>Surface Salinity</td>
<td>0.06 ppt</td>
</tr>
<tr>
<td>Bottom Salinity</td>
<td>0.07 ppt</td>
<td>Bottom Salinity</td>
<td>0.08 ppt</td>
</tr>
<tr>
<td>Sedimentation</td>
<td>1.6 %</td>
<td>Sedimentation</td>
<td>1.7 %</td>
</tr>
</tbody>
</table>

### Historical – Low Discharge Event

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case I</th>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Elevation</td>
<td>0.07 cm</td>
<td>Surface Elevation</td>
<td>0.07 cm</td>
</tr>
<tr>
<td>Surface Current</td>
<td>3.1 cm/s</td>
<td>Surface Current</td>
<td>3.2 cm/s</td>
</tr>
<tr>
<td>Bottom Current</td>
<td>2.1 cm/s</td>
<td>Bottom Current</td>
<td>2.2 cm/s</td>
</tr>
<tr>
<td>Surface Salinity</td>
<td>0.11 ppt</td>
<td>Surface Salinity</td>
<td>0.15 ppt</td>
</tr>
<tr>
<td>Bottom Salinity</td>
<td>0.14 ppt</td>
<td>Bottom Salinity</td>
<td>0.16 ppt</td>
</tr>
<tr>
<td>Sedimentation</td>
<td>2.0 %</td>
<td>Sedimentation</td>
<td>1.8 %</td>
</tr>
</tbody>
</table>

### Historical – High Wind Event

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case I</th>
<th>Parameters</th>
<th>Norfolk Harbor Dredging versus Base Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Elevation</td>
<td>0.07 cm</td>
<td>Surface Elevation</td>
<td>0.07 cm</td>
</tr>
<tr>
<td>Surface Current</td>
<td>2.1 cm/s</td>
<td>Surface Current</td>
<td>2.0 cm/s</td>
</tr>
<tr>
<td>Bottom Current</td>
<td>1.6 cm/s</td>
<td>Bottom Current</td>
<td>1.7 cm/s</td>
</tr>
<tr>
<td>Surface Salinity</td>
<td>0.11 ppt</td>
<td>Surface Salinity</td>
<td>0.06 ppt</td>
</tr>
<tr>
<td>Bottom Salinity</td>
<td>0.14 ppt</td>
<td>Bottom Salinity</td>
<td>0.07 ppt</td>
</tr>
<tr>
<td>Sedimentation</td>
<td>1.2 %</td>
<td>Sedimentation</td>
<td>1.1 %</td>
</tr>
</tbody>
</table>
The results of the impact on surface elevation are shown to range from 0.05 cm for the single variable run analysis to a maximum of 0.11 cm for the historical run analysis of the eventful condition of high river discharge. This variation due to the dredging operation amounts to a maximum change of 0.2% when compared with the natural variability of tidal elevation change ranging from -50 cm to 50 cm.

The results of the impact on the surface current are shown to range from 2.3 cm/sec for the single variable run analysis to a maximum of 3.4 cm/sec for the historical run analysis of the eventful condition of high river discharge. This variation amounts to less than a 10% change when compared with the base condition surface current, which ranges from -40 cm/sec to 40 cm/sec. The results of the impact on the bottom current show a range of 1.8 - 1.9 cm/sec for the single variable run analysis to a maximum of 2.2 cm/sec for the historical run analysis of the eventful condition of high river discharge. This variation amounts to less than a 10% change when compared with the base condition bottom current, which ranges from -30 cm/sec to 30 cm/sec.

The results of the impact on both surface and bottom salinity show a range from 0.03 ppt – 0.05 ppt for the single variable run analysis to a maximum of 0.16 ppt for the historical run analysis for the eventful condition of low river discharge. This variation amounts to a maximum of a 1% change when compared with the base condition of 15 ppt – 25 ppt of salinity in the Elizabeth River.

The sedimentation potential percentage change ranges from a 0.5% change for the single variable run analysis to a maximum of a 2% change for the historical run analysis of the eventful condition of low river discharge.

Overall, the results for both single variable runs and historical runs show that the Norfolk Harbor dredging had a minimal impact on either surface elevation or salinity and an acceptably small impact on velocity and sedimentation potential.

In order to assess sediment impacts under the channel dredging condition, the HEM-3D sediment and turbidity model was calibrated and used for scenario runs. A depth-dependent critical shear stress formulation and a concentration-dependent settling velocity were used to represent the background cohesive sediment nature of the Norfolk Harbor in the Elizabeth River. Additionally, the dredge-induced sediment source was estimated and added at the bottom layer of the model to simulate the hydraulic dredging condition. To be consistent with the VIMS 1978 intensive survey (Priest et al., 1981), a hydraulic dredging cutter head of 30 square feet, 2% escaping rate, and 67% sediment porosity were used for the estimate of source of the dredging material.

The results of modeling simulation (under Scenario 9 and 10 conditions) show the characteristics of the dredge-induced plume at the three reaches of the Norfolk Harbor as follows:
<table>
<thead>
<tr>
<th>Reach locations</th>
<th>Horizontal extent</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Downstream (northward)</td>
<td>Upstream (southward)</td>
<td>Width</td>
</tr>
<tr>
<td>Port Norfolk</td>
<td>800 m</td>
<td>3000 m</td>
<td>150 m</td>
</tr>
<tr>
<td>Town Point</td>
<td>250 m</td>
<td>1000 m</td>
<td>100 m</td>
</tr>
<tr>
<td>Lower Reach</td>
<td>400 m</td>
<td>600 m</td>
<td>50 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reach Locations</th>
<th>Maximum sediment concentration in the vertical (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Layer 1 (bottom layer)</td>
</tr>
<tr>
<td>Port Norfolk</td>
<td>150</td>
</tr>
<tr>
<td>Town Point</td>
<td>100</td>
</tr>
<tr>
<td>Lower Reach</td>
<td>50</td>
</tr>
</tbody>
</table>

The modeling results of the horizontal extent for the sediment turbidity plume in the downstream, upstream, and lateral directions are approximately 3-4 times larger than the actual field observations obtained from the VIMS 1978 survey. The proper explanation lies in the question of the position of the hydraulic dredging cutter head relative to the sediment-water interface. The model assumes that the sediment source will be distributed uniformly 2.5 m above the sediment-water interface, which will allow a larger ambient current (beyond bottom boundary layer) to carry and disperse the sediment plume further. If the cutter head is operated beneath the sediment-water interface, the sediment turbidity generated by the hydraulic dredge cutter head will likely remain within the bottom boundary layer, a few centimeters above the sediment-water interface. In this situation, the bottom current magnitude at the boundary layer will be approximately 30% of that at 2.5 meters above. Thus, the horizontal extent over which the turbidity plume is carried will be 3 to 4 times less than the model results.

Therefore, what the model simulation presents is based on the most conservative estimate of the sediment source that was extended 2.5 meters above the bottom. If the cutter head is operated at or beneath the sediment-water interface, the actual horizontal extent could be 3 to 4 times less.

Based on the dredge-induced maximum sediment concentration (below 150 mg/l) and the extent of the sediment plume, we conclude that the impacts are primarily restricted to the immediate vicinity of the dredge site, a radius of a few hundred meters in the horizontal and within 5 meters of the bottom in the vertical. Tidal and wind generated current will usually provide sufficient mixing and dilution to return the water to near background levels within one to two days over this distance.
VI. REFERENCES


APPENDIX A

Global Comparisons of Single Variable Runs

Spatial Distributions
Figure 1. Single variable simulation comparison of surface elevation RMS difference for the proposed Norfolk Harbor Dredging versus Base Case I.
Figure 2. Single variable simulation comparison of the surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 3. Single variable simulation comparison of the bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Surface Velocity Magnitude RMS difference Norfolk Harbor Dredging vs. Base Case I

Figure 4. Single variable simulation comparison of the surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 5. Single variable simulation comparison of the bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 6. Single variable simulation comparison of the surface residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 7. Single variable simulation comparison of the bottom residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 8. Single variable simulation comparison of the sedimentation potential difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 9. Single variable simulation comparison of the surface elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.
Surface Salinity
Average Difference
Norfolk Harbor Dredging vs. Base Case II

Figure 10. Single variable simulation comparison of the surface salinity average difference for the proposed Norfolk Harbor dredging vs. Base Case II.
Figure 11. Single variable simulation comparison of the bottom salinity average difference for the proposed Norfolk Harbor dredging vs. Base Case II.
Figure 12. Single variable simulation comparison of the surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 13. Single variable simulation comparison of the bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 14. Single variable simulation comparison of the surface residual velocity average difference for the proposed Norfolk Harbor dredging vs. Base Case II.
Figure 15. Single variable simulation comparison of the bottom residual velocity average difference for the proposed Norfolk Harbor dredging vs. Base Case II.
Figure 16. Single variable simulation comparison of the sedimentation potential difference for the proposed Norfolk Harbor dredging vs. Base Case II.
APPENDIX B

Global Comparisons of Single Variable Runs

Percentile Analysis
Figure 1. Frequency distribution of elevation RMS difference for the proposed Norfolk Harbor Dredging versus Base Case I.

Figure 2. Frequency distribution of surface salinity average difference for the proposed Norfolk Harbor Dredging versus Base Case I.
Figure 3. Frequency distribution of bottom salinity average difference for the proposed Norfolk Harbor Dredging versus Base Case I.

Figure 4. Frequency distribution of surface velocity RMS difference for the proposed Norfolk Harbor Dredging versus Base Case I.
Figure 5. Frequency distribution of bottom velocity RMS difference for the proposed Norfolk Harbor Dredging versus Base Case I.

Figure 6. Frequency distribution of surface residual velocity magnitude average difference for the proposed Norfolk Harbor Dredging versus Base Case I.
Figure 7. Frequency distribution of bottom residual velocity magnitude average difference for the proposed Norfolk Harbor Dredging versus Base Case I.

Figure 8. Frequency distribution of sedimentation potential difference for the proposed Norfolk Harbor Dredging versus Base Case I.
Figure 9. Frequency distribution of elevation RMS difference for the proposed Norfolk Harbor Dredging versus Base Case II.

Figure 10. Frequency distribution of surface salinity average difference for the proposed Norfolk Harbor Dredging versus Base Case II.
Figure 11. Frequency distribution of bottom salinity average difference for the proposed Norfolk Harbor Dredging versus Base Case II.

Figure 12. Frequency distribution of surface velocity RMS difference for the proposed Norfolk Harbor Dredging versus Base Case II.
Figure 13. Frequency distribution of bottom velocity RMS difference for the proposed Norfolk Harbor Dredging versus Base Case II.

Figure 14. Frequency distribution of surface residual velocity magnitude average difference for the proposed Norfolk Harbor Dredging versus Base Case II.
Figure 15. Frequency distribution of bottom residual velocity magnitude average difference for the proposed Norfolk Harbor Dredging versus Base Case II.

Figure 16. Frequency distribution of sedimentation potential difference for the proposed Norfolk Harbor Dredging versus Base Case II.
APPENDIX C

Global Comparisons of Historical Runs

Spatial Distributions
Figure 1. Historical simulation comparison (high discharge) of the surface elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 2. Historical simulation comparison (high discharge) of the surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 3. Historical simulation comparison (high discharge) of the bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 4. Historical simulation comparison (high discharge) of the surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 5. Historical simulation comparison (high discharge) of the bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 6. Historical simulation comparison (high discharge) of the surface residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 7. Historical simulation comparison (high discharge) of the bottom residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Sedimentation Potential Difference
High Discharge (Julian days 111-117)
Norfolk Harbor Dredging
vs. Base Case I

Figure 8. Historical simulation comparison (high discharge) of the sedimentation potential difference for the proposed Norfolk Harbor dredging versus Base Case I.
Surface Elevation RMS Difference
Low Discharge (Julian days 197-203)
Norfolk Harbor Dredging
vs. Base Case I

RMS difference
- 0.0 to 0.1 cm
- 0.1 to 0.2 cm
- 0.2 to 0.4 cm
- 0.4 to 0.7 cm
- 0.7 to 1.0 cm

Figure 9. Historical simulation comparison (low discharge) of the surface elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 10. Historical simulation comparison (low discharge) of the surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 11. Historical simulation comparison (low discharge) of the bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 12. Historical simulation comparison (low discharge) of the surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 13. Historical simulation comparison (low discharge) of the bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I.
Surface Residual Current Magnitude
Low Discharge (Julian days 197-203)
Norfolk Harbor Dredging
vs. Base Case I

Figure 14. Historical simulation comparison (low discharge) of the surface residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 15. Historical simulation comparison (low discharge) of the bottom residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 16. Historical simulation comparison (low discharge) of the sedimentation potential difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 17. Historical simulation comparison (high wind) of the surface elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case I.
Surface Salinity Average Difference
High Wind (Julian days 149-155)
Norfolk Harbor Dredging vs. Base Case I

Figure 18. Historical simulation comparison (high wind) of the surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 19. Historical simulation comparison (high wind) of the bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Surface Velocity Magnitude
RMS Difference
High Wind (Julian Days 149-155)
Norfolk Harbor Dredging
vs. Base Case I

Figure 20. Historical simulation comparison (high wind) of the surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 21. Historical simulation comparison (high wind) of the bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I.
Surface Residual Current Magnitude
High Wind (Julian days 149-155)
Norfolk Harbor Dredging
vs. Base Case I

Average difference
-10 to -5 cm/sec
-5 to -0.5 cm/sec
-0.5 to 0.5 cm/sec
0.5 to 5 cm/sec
5 to 10 cm/sec

Figure 22. Historical simulation comparison (high wind) of the surface residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Figure 23. Historical simulation comparison (high wind) of the bottom residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case I.
Sedimentation Potential Difference
High Wind (Julian days 149-155)
Norfolk Harbor Dredging
vs. Base Case I

Figure 24. Historical simulation comparison (high wind) of the sedimentation potential difference for the proposed Norfolk Harbor dredging versus Base Case I.
Surface Elevation RMS Difference
High Discharge (Julian days 111-117)
Norfolk Harbor Dredging
vs. Base Case II

Figure 25. Historical simulation comparison (high discharge) of the surface elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 26. Historical simulation comparison (high discharge) of the surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 27. Historical simulation comparison (high discharge) of the bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case II.
Surface Velocity Magnitude
RMS Difference
High Discharge (Julian Days 111-117)
Norfolk Harbor Dredging
vs. Base Case II

Figure 28. Historical simulation comparison (high discharge) of the surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 29. Historical simulation comparison (high discharge) of the bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.
Surface Residual Current Magnitude
High Discharge (Julian days 111-117)
Norfolk Harbor Dredging
vs. Base Case II

Figure 30. Historical simulation comparison (high discharge) of the surface residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 31. Historical simulation comparison (high discharge) of the bottom residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 32. Historical simulation comparison (high discharge) of the sedimentation potential difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 33. Historical simulation comparison (low discharge) of the surface elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 34. Historical simulation comparison (low discharge) of the surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 35. Historical simulation comparison (low discharge) of the bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 36. Historical simulation comparison (low discharge) of the surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 37. Historical simulation comparison (low discharge) of the bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.
Surface Residual Current Magnitude
Low Discharge (Julian days 197-203)
Norfolk Harbor Dredging
vs. Base Case II

Figure 38. Historical simulation comparison (low discharge) of the surface residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case II.
Bottom Residual Current Magnitude
Low Discharge (Julian days 197-203)
Norfolk Harbor Dredging
vs. Base Case II

Average difference
-5 to -3 cm/sec
-3 to -1 cm/sec
-1 to 1 cm/sec
1 to 3 cm/sec
3 to 5 cm/sec

Figure 39. Historical simulation comparison (low discharge) of the bottom residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 40. Historical simulation comparison (low discharge) of the sedimentation potential for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 41. Historical simulation comparison (high wind) of the surface elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.
Surface Salinity Average Difference
High Wind (Julian days 149-155)
Norfolk Harbor Dredging vs. Base Case II

Average difference
- 1.0 to -0.6 ppt
- 0.6 to -0.2 ppt
- 0.2 to 0.2 ppt
- 0.2 to 0.6 ppt
- 0.6 to 1.0 ppt

Figure 42. Historical simulation comparison (high wind) of the surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 43. Historical simulation comparison (high wind) of the bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case II.
Surface Velocity Magnitude
RMS Difference
High Wind (Julian days 149-155)
Norfolk Harbor Dredging
vs. Base Case II

Figure 44. Historical simulation comparison (high wind) of the surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 45. Historical simulation comparison (high wind) of the bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II.
Surface Residual Current Magnitude
High Wind (Julian days 149-155)
Norfolk Harbor Dredging
vs. Base Case II

Figure 46. Historical simulation comparison (high wind) of the surface residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 47. Historical simulation comparison (high wind) of the bottom residual velocity average difference for the proposed Norfolk Harbor dredging versus Base Case II.
Figure 48. Historical simulation comparison (high wind) of the sedimentation potential difference for the proposed Norfolk Harbor dredging versus Base Case II.
APPENDIX D

Global Comparisons of Historical Runs

Percentile Analysis
Figure 1. Frequency distribution of elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case I during the high discharge event of historical simulation.

Figure 2. Frequency distribution of surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I during the high discharge event of historical simulation.
Figure 3. Frequency distribution of bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I during the high discharge event of historical simulation.

Figure 4. Frequency distribution of surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I during the high discharge event of historical simulation.
Figure 5. Frequency distribution of bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I during the high discharge event of historical simulation.

Figure 6. Frequency distribution of surface residual velocity magnitude average difference for the proposed Norfolk Harbor dredging versus Base Case I during the high discharge event of historical simulation.
Figure 7. Frequency distribution of bottom residual velocity magnitude average difference for the proposed Norfolk Harbor dredging versus Base Case I during the high discharge event of historical simulation.

Figure 8. Frequency distribution of sedimentation potential difference for the proposed Norfolk Harbor dredging versus Base Case I during the high discharge event of historical simulation.
Figure 9. Frequency distribution of elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case I during the low discharge event of historical simulation.

Figure 10. Frequency distribution of surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I during the low discharge event of historical simulation.
Figure 11. Frequency distribution of bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I during the low discharge event of historical simulation.

Figure 12. Frequency distribution of surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I during the low discharge event of historical simulation.
Figure 13. Frequency distribution of bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I during the low discharge event of historical simulation.

Figure 14. Frequency distribution of surface residual velocity magnitude average difference for the proposed Norfolk Harbor dredging versus Base Case I during the low discharge event of historical simulation.
Figure 15. Frequency distribution of bottom residual velocity magnitude average difference for the Eastward Expansion versus Base Case I during the low discharge event of historical simulation.

Figure 16. Frequency distribution of sedimentation potential difference for the proposed Norfolk Harbor dredging versus Base Case I during the low discharge event of historical simulation.
Figure 17. Frequency distribution of elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case I during the high wind event of historical simulation.

Figure 18. Frequency distribution of surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I during the high wind event of historical simulation.
Figure 19. Frequency distribution of bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case I during the high wind event of historical simulation.

Figure 20. Frequency distribution of surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I during the high wind event of historical simulation.
Figure 21. Frequency distribution of bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case I during the high wind event of historical simulation.

Figure 22. Frequency distribution of surface residual velocity magnitude average difference for the proposed Norfolk Harbor dredging versus Base Case I during the high wind event of historical simulation.
Figure 23. Frequency distribution of bottom residual velocity magnitude average difference for the proposed Norfolk Harbor dredging versus Base Case I during the high wind event of historical simulation.

Figure 24. Frequency distribution of sedimentation potential difference for the proposed Norfolk Harbor dredging versus Base Case I during the high wind event of historical simulation.
Figure 25. Frequency distribution of elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case II during the high discharge event of historical simulation.

Figure 26. Frequency distribution of surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case II during the high discharge event of historical simulation.
Figure 27. Frequency distribution of bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case II during the high discharge event of historical simulation.

Figure 28. Frequency distribution of surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II during the high discharge event of historical simulation.
Figure 29. Frequency distribution of bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II during the high discharge event of historical simulation.

Figure 30. Frequency distribution of surface residual velocity magnitude average difference for the proposed Norfolk Harbor dredging versus Base Case II during the high discharge event of historical simulation.
Figure 31. Frequency distribution of bottom residual velocity magnitude average difference for the proposed Norfolk Harbor dredging versus Base Case II during the high discharge event of historical simulation.

Figure 32. Frequency distribution of sedimentation potential difference for the proposed Norfolk Harbor dredging versus Base Case II during the high discharge event of historical simulation.
Figure 33. Frequency distribution of elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case II during the low discharge event of historical simulation.

Figure 34. Frequency distribution of surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case II during the low discharge event of historical simulation.
Figure 35. Frequency distribution of bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case II during the low discharge event of historical simulation.

Figure 36. Frequency distribution of surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II during the low discharge event of historical simulation.
Figure 37. Frequency distribution of bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II during the low discharge event of historical simulation.

Figure 38. Frequency distribution of surface residual velocity magnitude average difference for the proposed Norfolk Harbor dredging versus Base Case II during the low discharge event of historical simulation.
Figure 39. Frequency distribution of bottom residual velocity magnitude average difference for the proposed Norfolk Harbor dredging versus Base Case II during the low discharge event of historical simulation.

Figure 40. Frequency distribution of sedimentation potential difference for the proposed Norfolk Harbor dredging versus Base Case II during the low discharge event of historical simulation.
Figure 41. Frequency distribution of elevation RMS difference for the proposed Norfolk Harbor dredging versus Base Case II during the high wind event of historical simulation.

Figure 42. Frequency distribution of surface salinity average difference for the proposed Norfolk Harbor dredging versus Base Case II during the high wind event of historical simulation.
Figure 43. Frequency distribution of bottom salinity average difference for the proposed Norfolk Harbor dredging versus Base Case II during the high wind event of historical simulation.

Figure 44. Frequency distribution of surface velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II during the high wind event of historical simulation.
Figure 45. Frequency distribution of bottom velocity RMS difference for the proposed Norfolk Harbor dredging versus Base Case II during the high wind event of historical simulation.

Figure 46. Frequency distribution of surface velocity residual magnitude average difference for the proposed Norfolk Harbor dredging versus Base Case II during the high wind event of historical simulation.
Figure 47. Frequency distribution of bottom velocity residual magnitude average difference for the proposed Norfolk Harbor dredging versus Base Case II during the high wind event of historical simulation.

Figure 48. Frequency distribution of sedimentation potential difference for the proposed Norfolk Harbor dredging versus Base Case II during the high wind event of historical simulation.
APPENDIX E

The Dredge-Induced Plume, Horizontal and Vertical Extents, and Duration of Plume (Scenario 10 results)
Figure 1. a) The location of the point source for Port Norfolk Reach, b) the dredge-induced plume at high water slack, and c) the plume at low water slack for Scenario 10. Axes coordinates are Virginia State Plane (South Zone, meters) and the color bar shows sediment concentrations.
Figure 2. The vertical extent of the Port Norfolk Reach plume shown by axial velocity and sediment concentration at each layer (layer thickness 2.4 m) for Scenario 10.
Figure 3. a) The location of the point source for Town Point Reach, b) the dredge-induced plume at high water slack, and c) the plume at low water slack for Scenario 10. Axes coordinates are Virginia State Plane (South Zone, meters) and the color bar shows sediment concentrations.

Figure 4. The vertical extent of the Town Point Reach plume shown by axial velocity and sediment concentration at each layer (layer thickness 2.2 m) for Scenario 10.
Figure 5. a) The location of the point source for Lower Reach, b) the dredge-induced plume at high water slack, and c) the plume at low water slack for Scenario 10. Axes coordinates are Virginia State Plane (South Zone, meters) and the color bar shows sediment concentrations.
Figure 6. The vertical extent of the Lower Reach plume shown by axial velocity and sediment concentration at each layer (layer thickness 2.3 m) for Scenario 10.
Figure 7. Time history of sediment turbidity concentrations in bottom 3 layers after a 1-day release at Port Norfolk Reach starting at day 4.38 for Scenario 10.

Figure 8. Time history of sediment turbidity concentrations in bottom 3 layers after a 1-day release at Town Point Reach starting at day 5.01 for Scenario 10.
Figure 9. Time history of sediment turbidity concentrations in bottom 3 layers after a 1-day release at Lower Reach starting at day 7.46 for Scenario 10.