U.S. Army Corps of Engineers
Charleston District

APPENDIX K

CHARLESTON HARBOR POST 45
BENEFICIAL USE OF DREDGED MATERIAL
SUPPLEMENTAL ENVIRIONMENTAL ASSESSMENT
CHARLESTON, SOUTH CAROLINA

Coastal Modeling in Support of Beneficial Use Determination

30 September 2016

CHARLESTON HARBOR DREDGED MATERIAL BENEFICIAL USE DETERMINATION

1. INTRODUCTION

Charleston Harbor is a natural tidal estuary located at Charleston, South Carolina. The harbor covers an area of approximately 14 square miles and is formed by the confluence of the Ashley, Cooper, and Wando Rivers. The inlet is situated within a chain of barrier islands with Sullivan's Island and Isle of Palms to the north and Morris and Folly Islands to the south (figure 1).

Beneficial use of dredged material is defined as utilizing dredged sediments as resource materials in productive ways that provide environmental, economic, or social benefit (ANAMAR, 2013). Standards suggest that beach-fill material should be greater than 88% sand (Gailani, 2008). Dredged material to be removed from Charleston Entrance Channel under the deepening project is composed of approximately 80 percent sand and it does not meet general guidelines for direct beach placement. Therefore, nearshore placement of the sand is considered a beneficial use of the dredged material because it will keep the sand in the littoral system.

The purpose of this study is to assess sediment transport benefits associated with nearshore placement of potentially 400,000 m^3 of the Entrance Channel new work dredged material in the areas south of the Charleston Harbor south jetty (figure 1). This practice is expected to keep the sediment in the littoral transport zone and provide an option of beneficial use of dredge material. The study includes numerical modeling of coastal hydrodynamics, wave transformation and sedimentation in the coastal area of Charleston Harbor. The numerical modeling is used to evaluate morphology change associated with potential nearshore sites for dredged material placement. In addition, the models will address any adverse impact associated with placement.

The Coastal Modeling System (CMS) is an integrated suite of numerical models for simulating water-surface elevation, current, waves, sediment transport, and morphology change in coastal and inlet applications. CMS-Wave model (Lin et al., 2008) was used to calculate wave transformation. The CMS-Flow model (Buttolph et al., 2006) estimates water surface elevations and two components of the current and sediment transport. Sediment transport and morphology change can be computed as a user-specified option. The models calculate time-dependent water elevation, current speed and direction, erosion and accretion and sediment transport flux. CMS flow and wave models can be coupled with the Particle Tracking Model (PTM) (Demirbilek et al. 2008) to estimate sediment pathways.

Field data collected during a previous Charleston Harbor numerical modeling study (USACE, 2013) which included nearshore bathymetry, current and wave measurements, were used in the present modeling work. Astronomical tide, measured river flow and wave data were used to force the CMS-Flow and CMS-Wave models.

CMS flow and wave models used in this study were developed and applied previously for the Charleston Harbor morphology evaluation modeling study (USACE, 2016), to evaluate the potential impacts of the deepening project on hydrodynamics and coastal morphology within the Charleston Harbor coastal area. These foundation models were modified to provide better management of the Charleston Harbor Entrance Channel dredged sediment.

Two proposed locations for the nearshore placement site were identified by Charleston District (SAC). Sediment transport and morphology changes at the proposed dredged material placement sites were investigated during representative active winter month and storm periods. CMS models were used to estimate sediment transport patterns before and after material has been dredged and placed in the littoral zone, within the selected sites south of the jetties. In addition, sediment pathways during the release of dredged material at the optimal placement sites were examined.

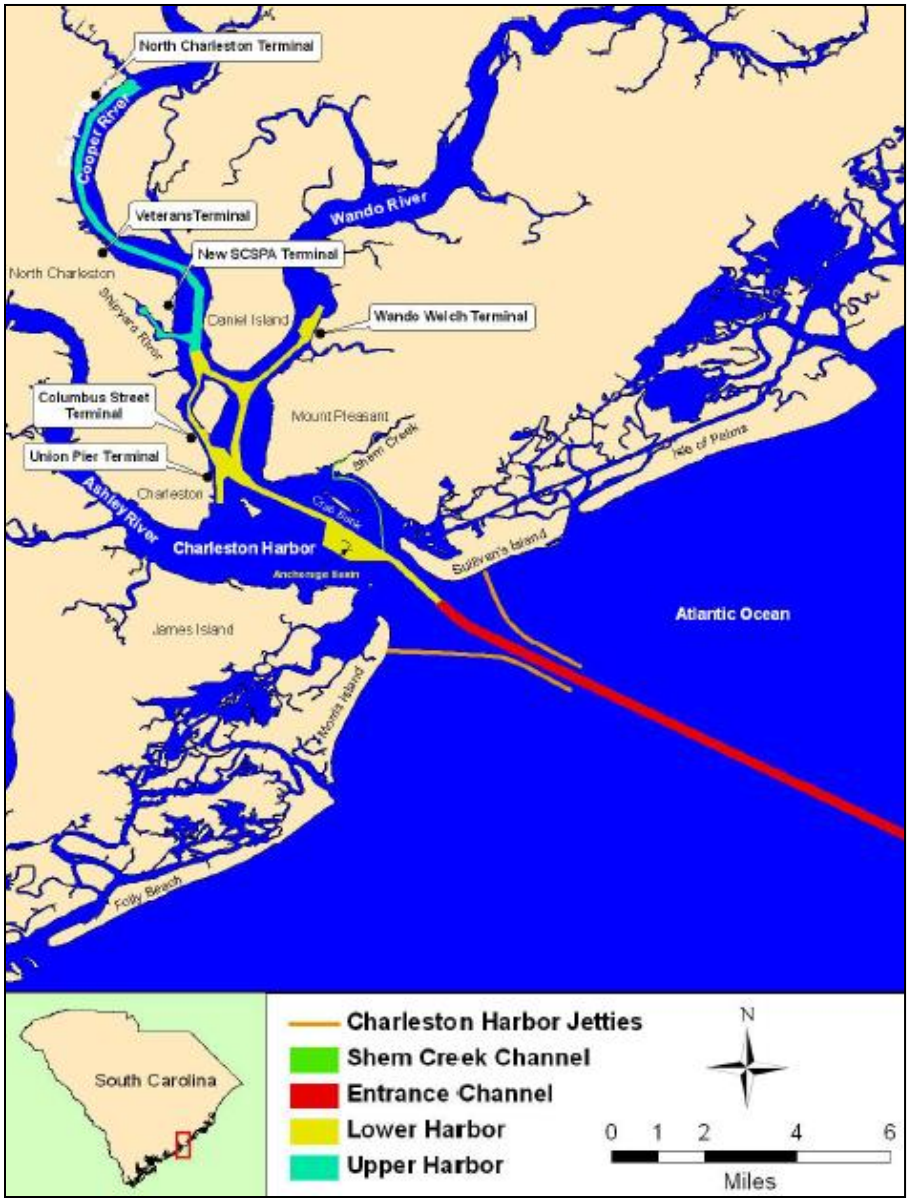

Figure 1- Charleston Harbor (USACE, 2010)

2. IDENTIFICATION OF POTENTIAL DREDGED MATERIAL NEARSHORE PLACEMENT SITES

Sediment samples from representative sites throughout the Charleston Harbor area were collected and evaluated (ANAMAR, 2013). The dredged material obtained from the entrance channel was composed of 76.3 percent sand with small percent of gravel, silt and clay (Table 1). Gailani et al. (2008) stated that dredged material composed of approximately 20 percent silt and clay does not meet guidelines for direct beach placement. Therefore, nearshore placement is considered a promising alternative to direct beach placement for which winnowing by wave action will naturally separate sand and silt fractions. The coarser sand fraction is likely to remain in the nearshore, while fine grained sediment will be suspended by high wave energy in the nearshore and transported offshore by currents.

Table 1- Grain Size Distribution of Dredged Material

Sediment	**Grain Fractions (%)**
Gravel	4
Sand	76.3
Silt	9.7
Clay	10

Figure 2 shows the two potential areas for nearshore placement suggested by SAC. Area 1 is located in front of Morris Island which is an erosional area and its main benefit is to feed sediment back into the littoral system and feed sediment toward Morris Island and Folly Island shorelines. Area 2 is proposed to be depositional area, an "Island" with elevation of 0.0 MTL (0.85 above MLLW) and can erode over time.

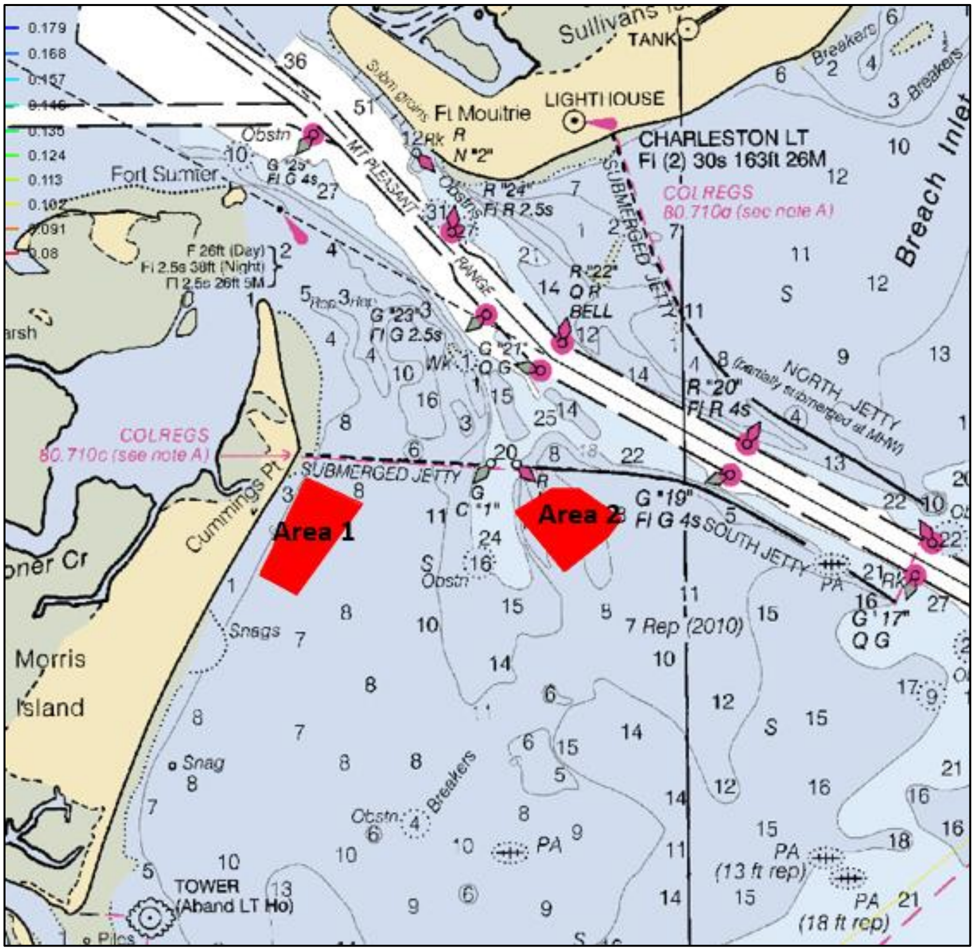

Figure 2 - Proposed areas for dredged material placement

3. HYDRODYNAMIC AND WAVE MODELING

CMS flow and wave models used in this study were developed and applied previously for the Charleston Harbor Morphology Evaluation modeling study (USACE, 2016). The present modeling effort adopted the same models with increasing the grids resolution in the vicinity of the potential dredged material placement sites.

Figure 3 shows the boundaries of the CMS-Flow and CMS-Wave models. The CMS-Flow model was forced at the ocean boundary with time series of water level extracted for each cell along the ocean cellstring. The water levels were extracted from the U. S. East Coast Tidal Database (EC2001) calculated with the Finite Element model ADCIRC (Mukai et al., 2002). The Surface Modeling System (SMS) 11.0 does not extract the tidal constituents for CMS. Therefore, CMS-Flow Advanced Cards were used to define the tidal constituents forcing.

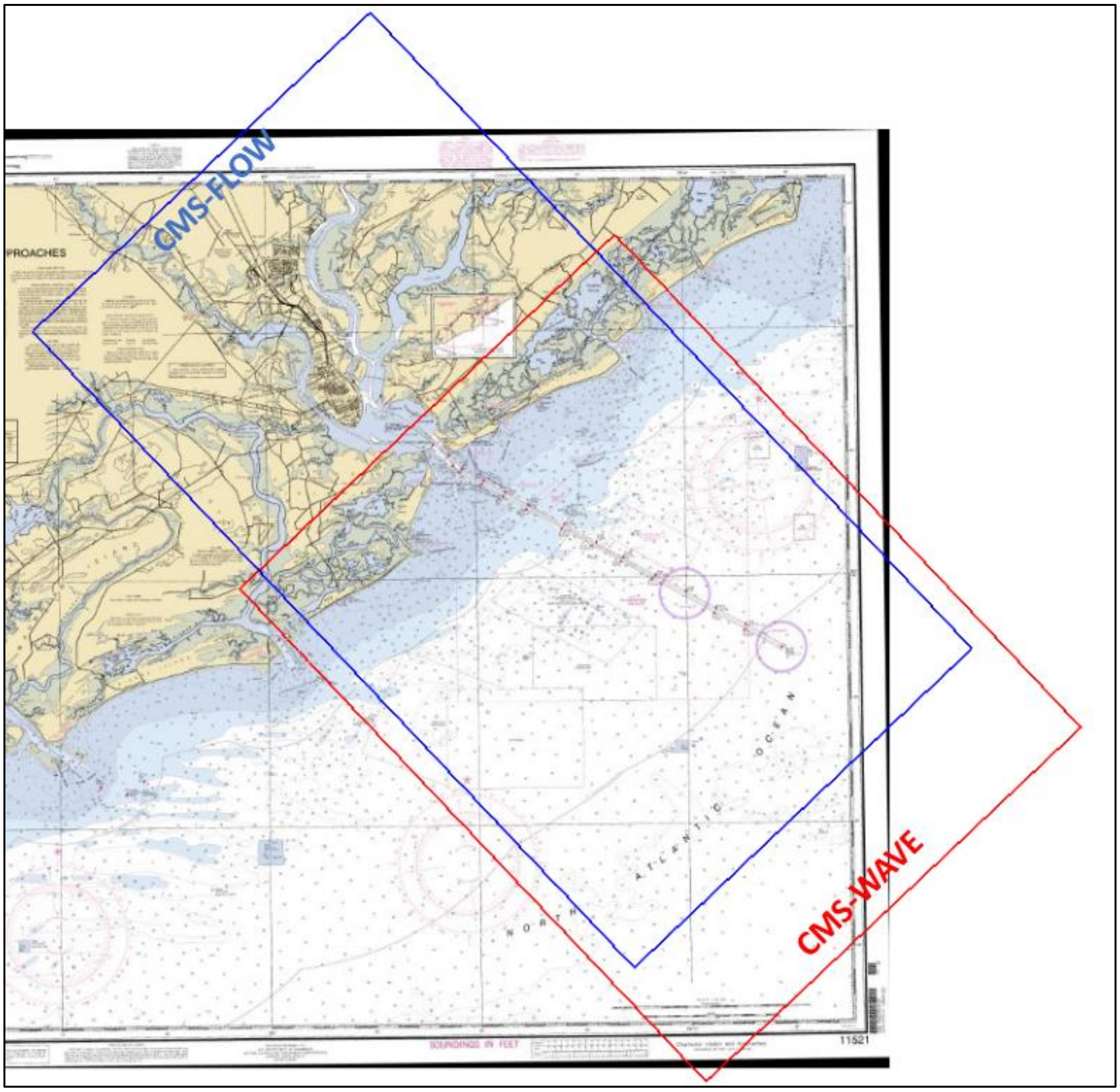

Figure 3- CMS-Flow and CMS-Wave grids domain

3.1 Models Setup

The CMS flow and wave grids resolution was increased in the potential placement sites as shown in figure 4.

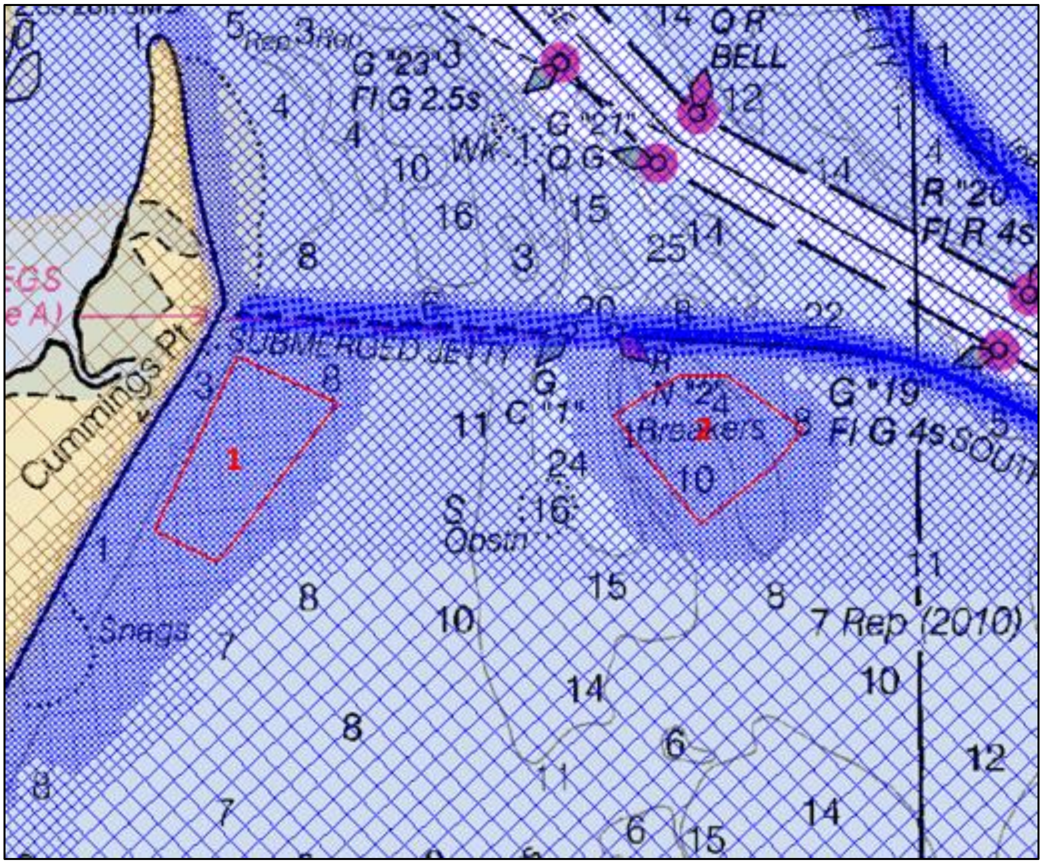

Figure 4- Increased resolution within the potential placement sites

The inline version of CMS-Flow, which includes CMS-Flow and CMS-Wave in one code, was adopted in this study because of its capability to implement the tidal constituent forcing at the ocean boundary for telescoping CMS grids. The surface roller model was also included. It is recommended to always turn on the surface roller model. This model is very fast and represents an insignificant increase in computational costs. The results however, have been shown to significantly improve when simulating nearshore currents and water levels (Sanchez et al. 2011).

3.2 Hydrodynamic and Wave Models Calibration

The CMS models were recalibrated because the original grids were modified. The models were calibrated during the same calibrations period (November, 2012) used in USACE (2013). The CMS-Flow model was forced with:

- Time series of water level extracted from the EC2001 tidal database
- Hourly wind speed and direction at the National Data Buoy Center (NDBC) 41029
- Constant monthly average flow rate of 11.33, 277.5 and 62.3 m^3/sec at Ashley, Cooper and Wando rivers respectively

The U.S. Environmental Protection Agency (EPA) Region 4 conducted a one year study of the currents and waves in the vicinity of a new Charleston Harbor Ocean Dredged Material Disposal

Site (ODMDS) in support of site designation (McArthur, 2012). Figure 5 shows the locations of the five Acoustic Doppler Current Profilers (ADCP) used in the study. Figures 6 and 7 show the comparison between modeled and measured water level and current magnitude at RSM-S ADCP during November 10-30, 2012.
The Index of Agreement (USACE, 2015):

$$1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2}$$

was used to evaluate model performance, where p is the predicted value, o is the observed value and n is the number of data points. The index of agreement is a standardized measure of the degree of simulation error with 1 being a perfect match. The Index of Agreement between measured and modeled water level and current speed was 0.98 and 0.81 respectively.

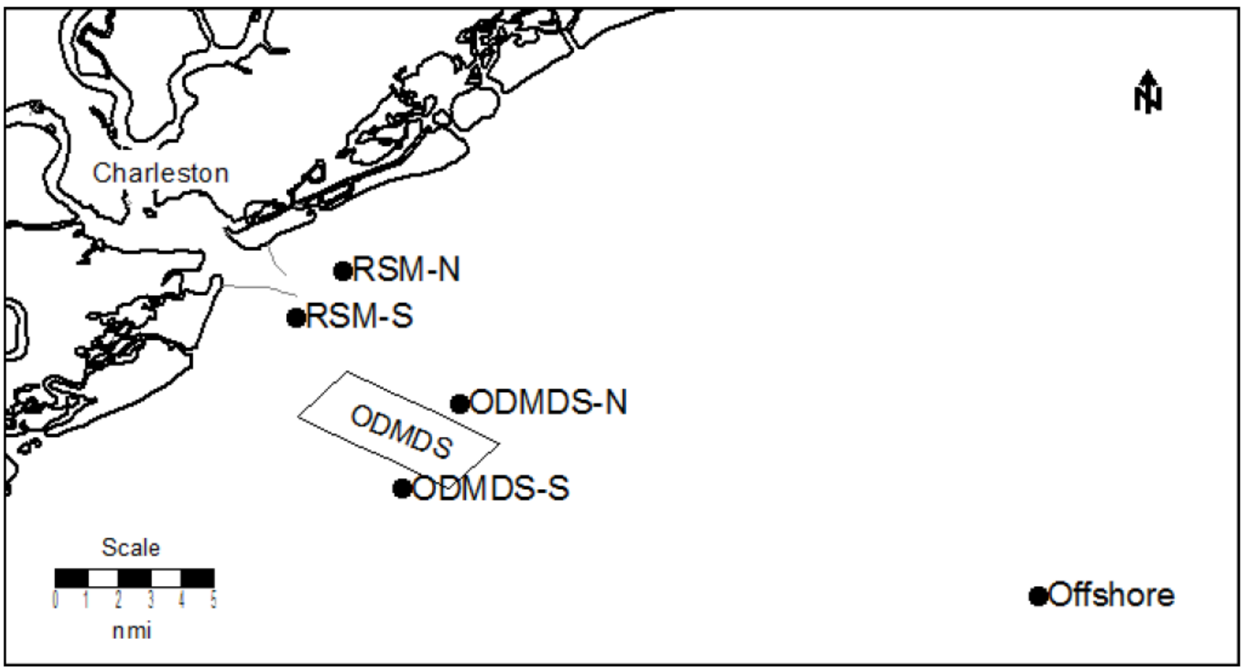

Figure 5- ADCPs locations (EPA, 2014)

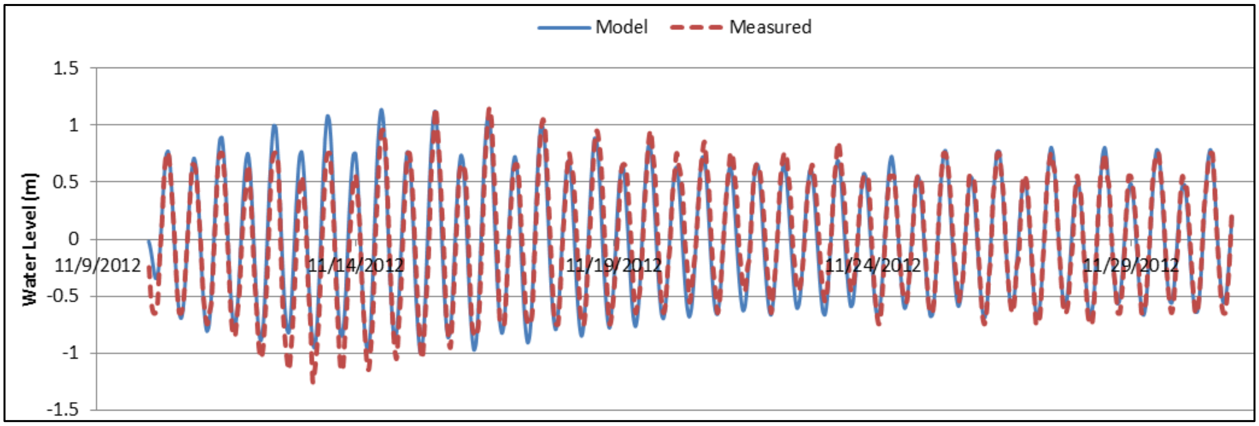

Figure 6 - Comparison of modeled and measured water level at RSM-S

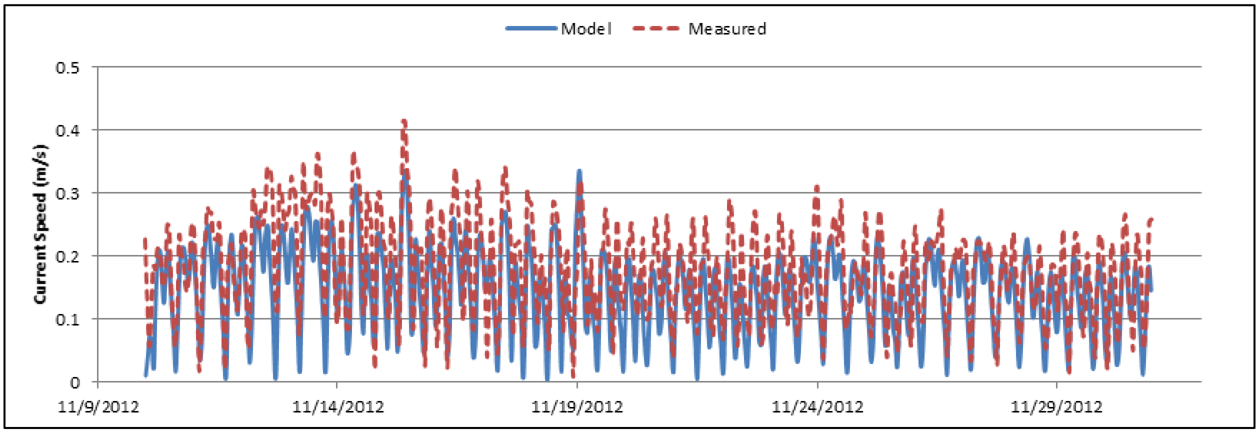

Figure 7- Comparison of modeled and measured current speed at RSM-S

The CMS wave model was forced with wave parameters extracted from the wave data collected every 3 hrs at the offshore ADCP (figure 5) during November 9-30, 2012. Also, the model was forced with wind speed and direction every 3 hrs at NDBC 41029.

Measured wave data, which matched the times of the incident wave conditions, were extracted at RSM-S to compare with modeled data. Figure 8 shows the comparison between modeled and measured wave height at RSM-S ADCP during November, 2012. The agreement between the measured and calculated wave data was evaluated by the Model Performance Index (MPI):

$MPI = 1-Error_{RMS}/Changes_{RMS}.$

$Error_{RMS}$ is the Root Mean Square (RMS) of the model compared to measured data:

$$Error_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} [Y_i - X_i]^2}$$

where N is the number of data points, Y is the modeled parameter and X is the measured parameter, and $Changes_{RMS}$ is the RMS change from the offshore data to the nearshore data:

$$changes_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} [X_{incident} - X_i]^2}$$

Values of MPI near unity indicated good agreement (Smith, 2000). The wave height MPI was 0.82 at RSM-S.

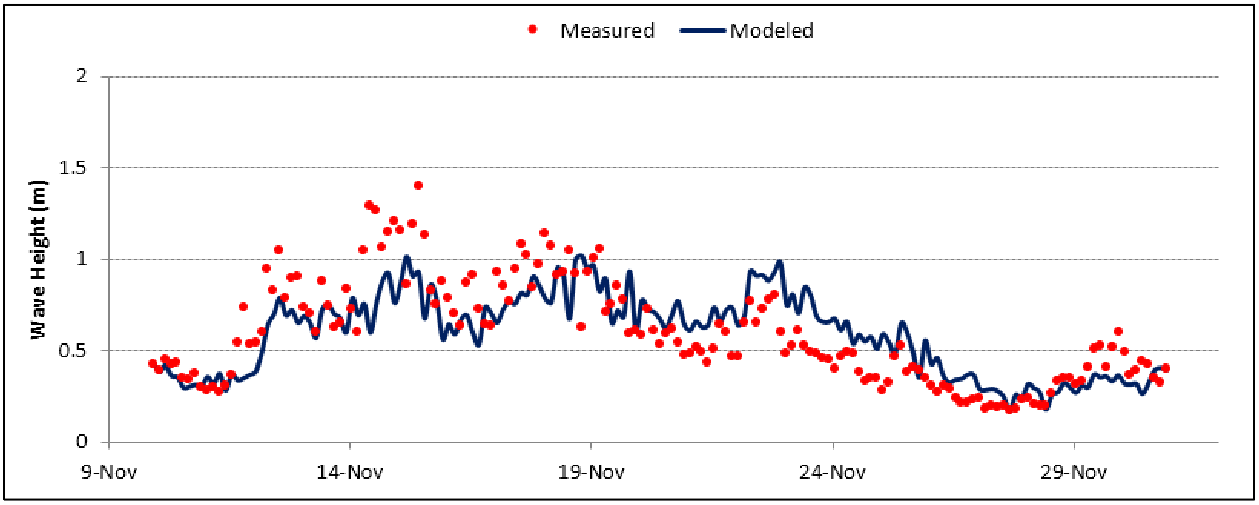

Figure 8- Comparison of modeled and measured wave height at RSM-S

4. MODELING SIMULATION PERIODS

The modeling simulation periods include long-term and extreme short term periods (USACE, 2014). Field data collected during a previous Charleston Harbor numerical modeling study (EPA, 2014) which included nearshore current and wave measurements, were used in the present modeling work (figure 5). The active winter weather month of December of 2012 was selected as the long-term period. Figure 9 shows time series of wave height, at the Offshore ADCP, during December, 2012. The figure also shows wind speed time series during the selected simulation period. Hourly wind data was obtained from NDBC 41029 station.

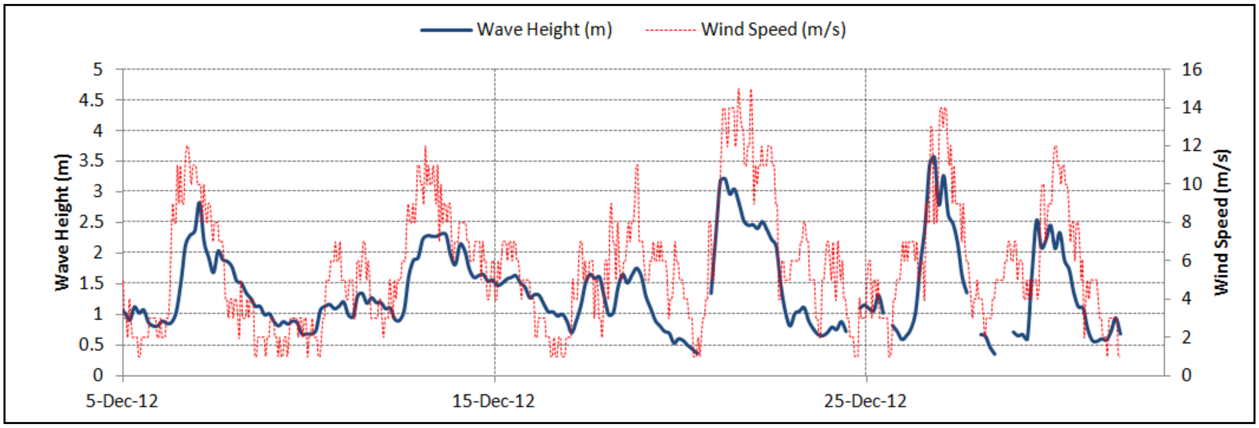

Figure 9- Wave height, at the Offshore ADCP, during the December simulation period

EPA (2015) examined the most intense storms to represent the wave and flow climate at the ODMDS during the EPA ADCPs measurement duration (November 2012-August 2013). Figure 10 shows the wave height, current speed and direction during storm Andrea.

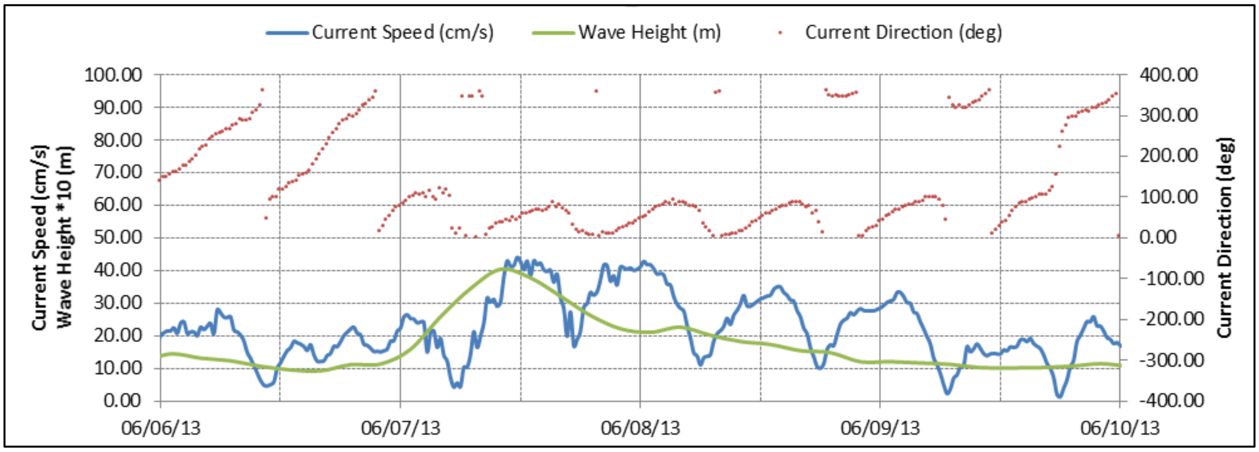

Figure 10- Wave height, current speed and direction during storm Andrea

5. EVALUATION OF PLACEMENT AREA 1

SAC suggested placing the material at Area 1 shown in figure 4. Placing the sediment close to the jetty will most probably result in sediment moving back into the jetties area and eventually into the Navigation Channel. A previous study (USACE, 2014) showed that placing the material in front of the southern portion of Morris Island resulted in deposition along the Morris Island southern shorelines and least deposition inside the jetties area. Therefore three scenarios, two of them outside SAC delineated area, were examined to place the dredged material in the nearshore area in order to keep the sediments in the littoral zone and benefit Morris Island. Figure 11 shows the three proposed placement sites: Berm1, Berm2 and Berm3. Each placement site was delineated to accommodate 400,000 cubic meters with depth of 1.0 m MTL (0.15 below MLLW).

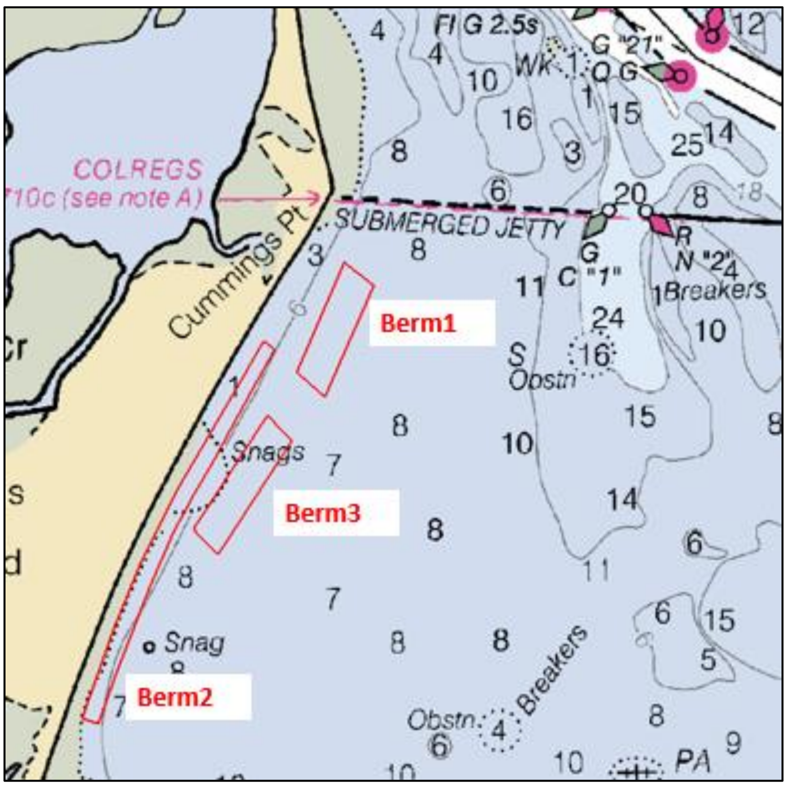

Figure 11- Proposed three potential placement sites within Area 1

CMS flow and wave models were used to estimate sediment transport patterns in the area before and after material has been dredged and placed within the selected sites. Modeled morphology change was calculated at the end of the long December simulation period for the existing and each placement site grid configuration. Morphology change differences between the existing and with placement at the three proposed sites was examined. Sediment deposition due to placing dredged sediment at the three proposed sites as compared to the existing configuration, without the dredge material placement, at the end of the long December simulation period is shown in figures 12 thru 14. The placement areas are delineated in red colors in the figures. In general, sediment deposition was mainly observed around the boundaries of the placement sites. Sediments moved toward the shorelines in front of Morris Island from the three sites. Placing the dredged material at Berm1 site resulted in maximum sediment movement into the area between the jetties.

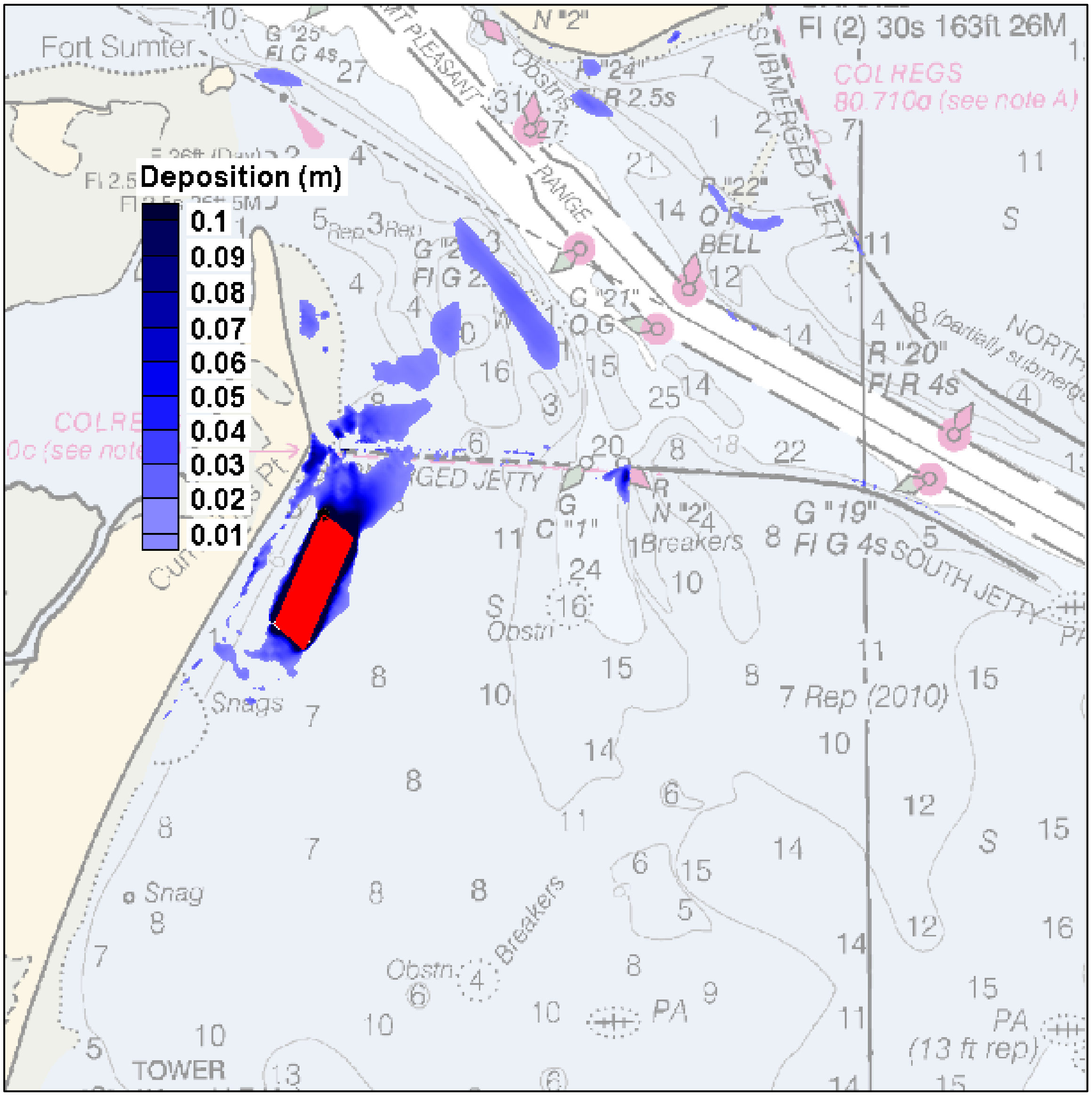

Figure 12 - Morphology change difference between the existing and with placement at Berm1at the end of the December simulation period

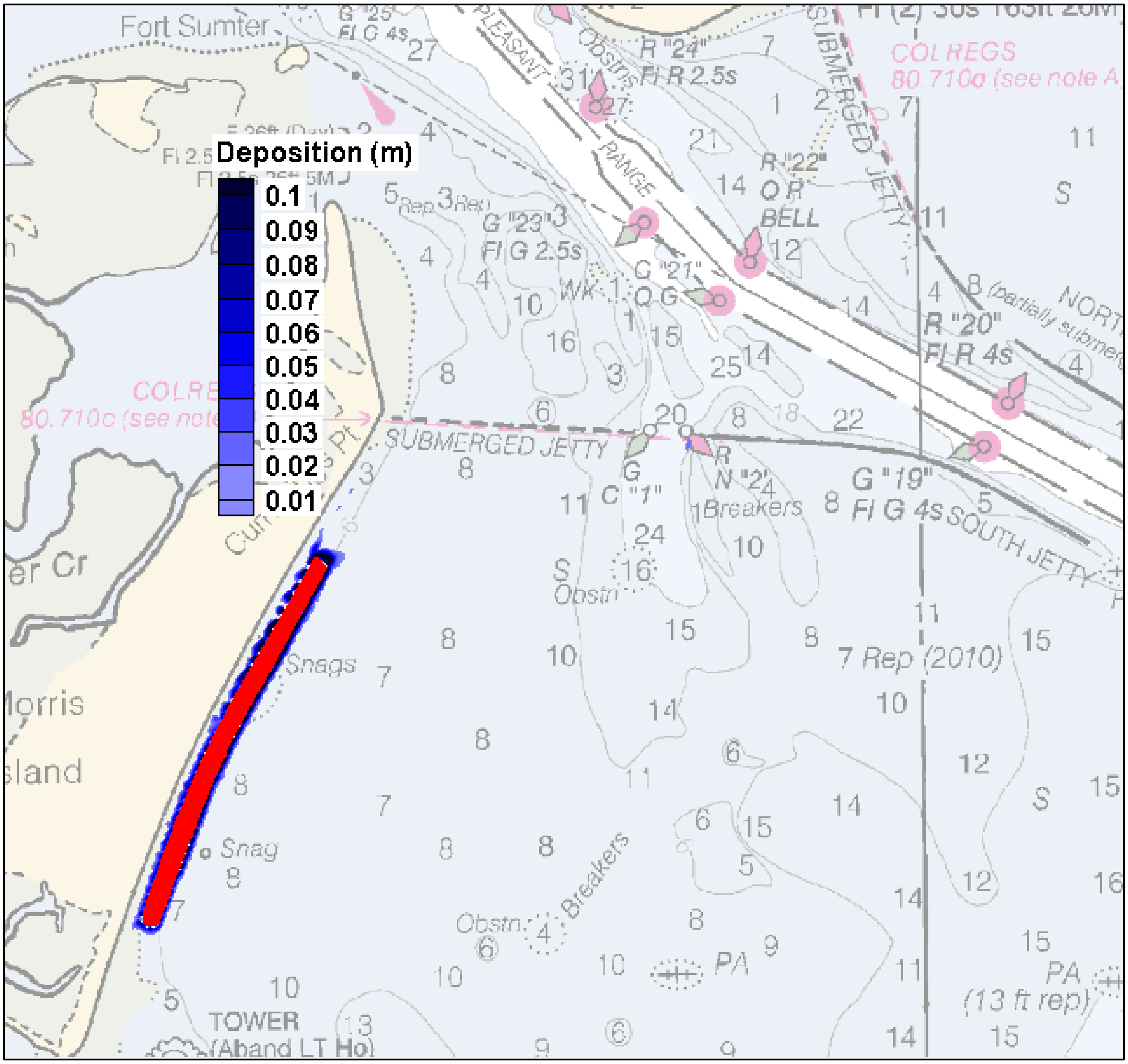

Figure 13 - Morphology change difference between the existing and with placement at Berm2 at the end of the December simulation period

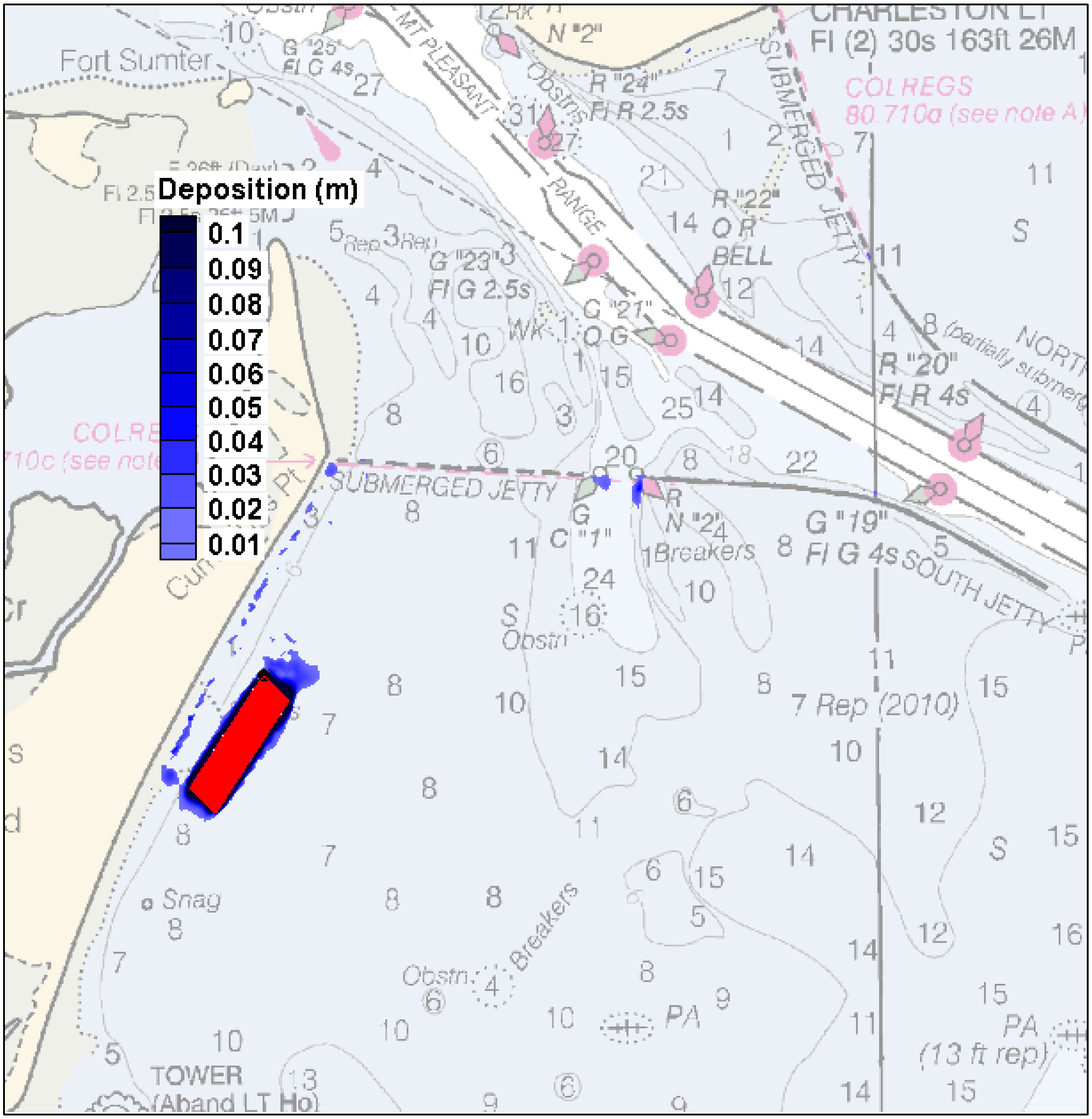

Figure 14 - Morphology change difference between the existing and with placement at Berm3 at the end of the December simulation period

Net volume change is calculated as the volume of material lost or gained in the placement area and is calculated using initial and ending depth at grid cells regardless of whether a cell has become shallower or deeper. Net volume change provides complimentary information for understanding the overall movement of material (USACE, 2011). Table 2 shows the calculated net volume change over the long December simulation period for the cells within the placement sites areas and the Navigation Channel. Figure 15 shows delineated portions of Fort Sumter Reaches EC1 and EC2. Positive values indicate deposition while negative values indicate erosion. Table 2 shows minimal volume change in Fort Sumter Reach EC1 for placement of dredged material in the three sites. Minimum sediment deposition in Fort Sumter Reach EC2 occurred with placing the dredged material at Berm2. Maximum berm erosion occurred at placement site Berm1. Berm2 site was considered the optimal placement location because it resulted in minimum sediment movement into the navigation channel. Also, sediment is kept around the berm in the littoral zone.

Table 2- Net Volume Change

Placement Area	**Net Volume Change (m³)**		
	Fort Sumter Reach EC1	**Fort Sumter Reach EC1**	**Placement Area**
Berm1	-62	2222	-34,442
Berm2	-25	427	-22,022
Berm3	-91	1074	-21,789

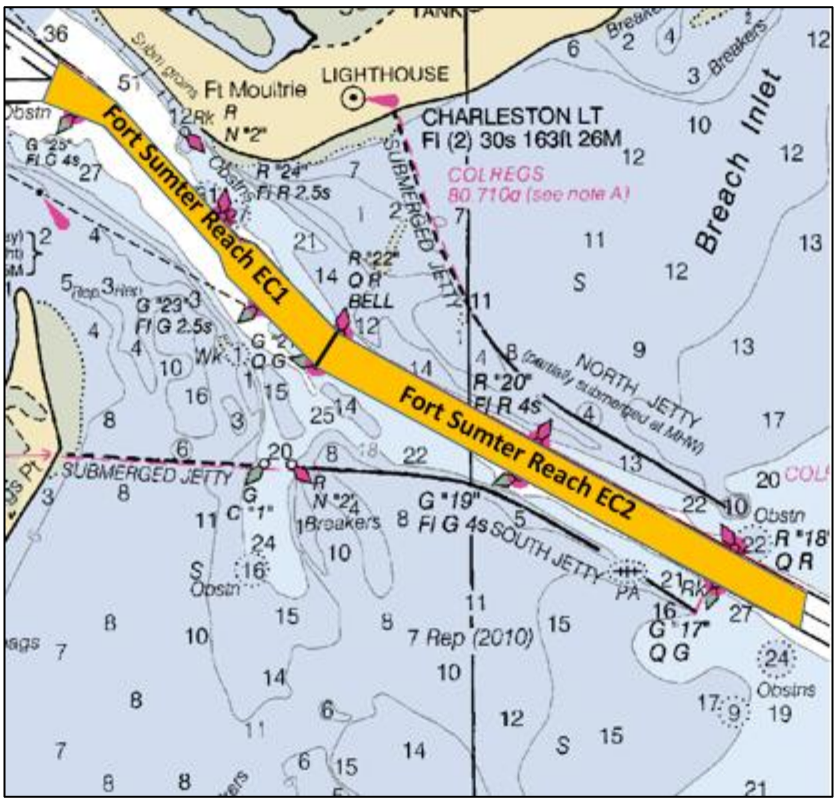

Figure 15- Delineated areas of the Navigation Channel used for morphology change estimation

CMS flow and wave models were used to estimate sediment transport patterns before and after material has been dredged and placed within the optimum site, Berm2 during storm. Figure 16 shows sediment deposition due to placing dredged sediment at Berm2 site as compared to the existing configuration, without the dredge material placement, at the end of the 5-days storm simulation period. Similar deposition patterns were observed at the end of the storm simulation, compared to December simulation, but with less extent.

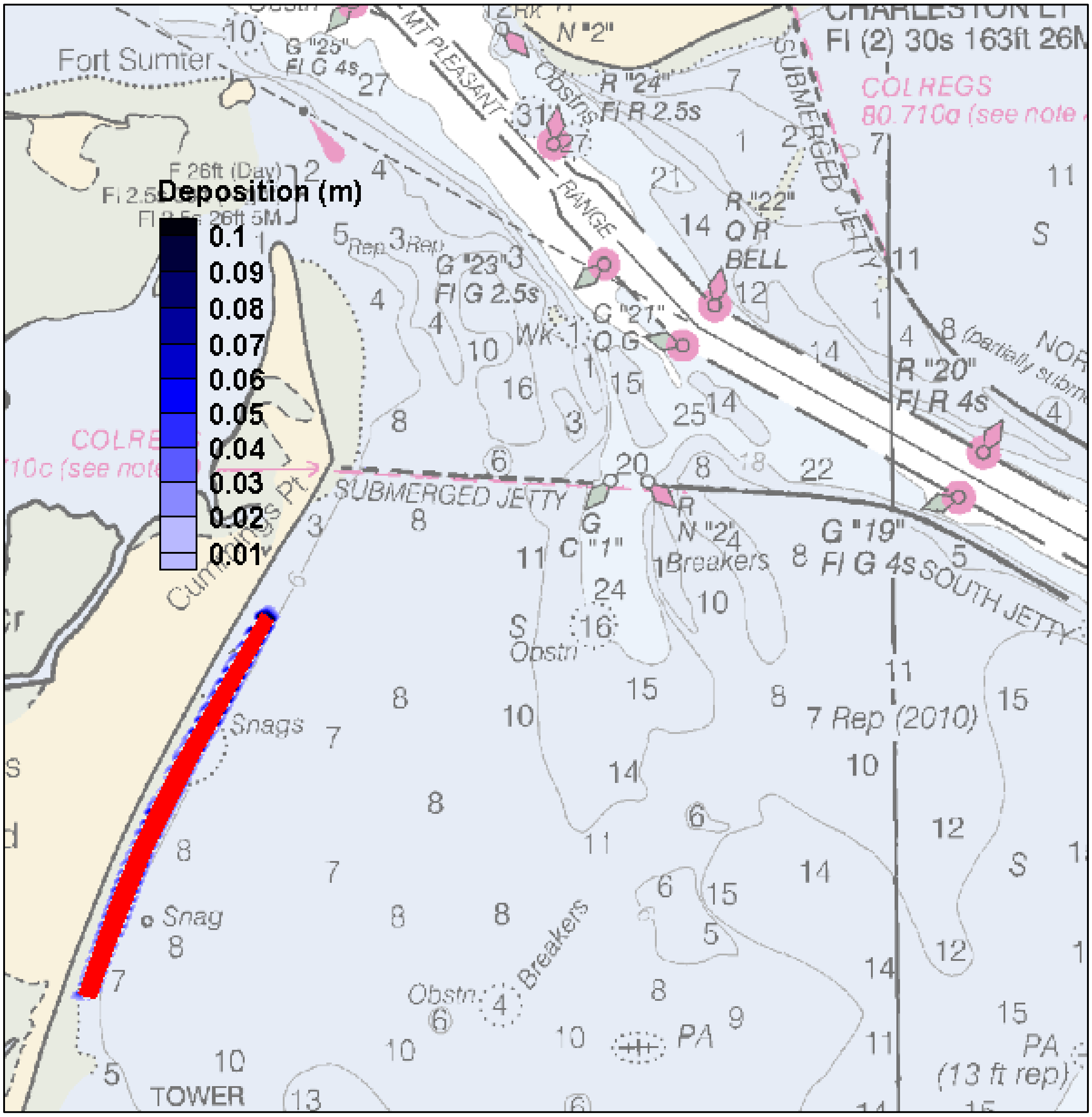

Figure 16 - Morphology change difference between the existing and with placement at Berm2 at the end of the storm simulation period

6. EVALUATION OF PLACEMENT AREA 2

Three scenarios were examined within Area 2 (figure 17). Each placement site was delineated to accommodate 400,000 cubic meters with elevation of 0.0 MTL (0.85 above MLLW). Island1 was delineated in the area with low residual current, identified in previous modeling simulations, to minimize the Island erosion. Island2 was delineated within the depositional area identified in previous modeling simulations. Island3 was delineated as an optimization of Island1 and Island2 footprints.

CMS flow and wave models were used to estimate sediment transport patterns in the area before and after material has been dredged and placed within the selected sites. Modeled morphology change was calculated at the end of the long December simulation period for the existing and each placement site grid configuration. Morphology change differences between the existing and with placement at the three proposed sites was examined. Sediment deposition due to placing dredged sediment at the three proposed sites as compared to the existing configuration, without the dredge material placement, at the end of the long December simulation period is shown in figures 18 thru 20. The placement areas are delineated in red colors in the figures. In general, sediment deposition was mainly observed around the boundaries of the placement sites and moving into the area between the jetties.

Table 3 shows the calculated net volume change over the long December simulation period for the cells within the placement sites areas and within portions of Fort Sumter Reaches EC1 and EC2 (figure 15). Positive values indicate deposition while negative values indicate erosion. Table 3 shows that the net erosion for Fort Sumter Reach EC1 was similar for the three sites. Minimum sediment deposition in Fort Sumter Reach EC2 occurred with placing the dredged material at Island3. Also, least material loss was observed at placement site Island3. Therefore, Island3 site was considered the optimal placement location within Area 2 and accordingly Island3 was examined during storm condition.

Table 3- Net Volume Change

Placement Area	**Net Volume Change (m^3)**		
	Fort Sumter Reach EC1	**Fort Sumter Reach EC1**	**Placement Area**
Island1	-67,398	175,475	-30,781
Island2	-67,616	176,787	-35,082
Island3	-67,539	174,781	-25,374

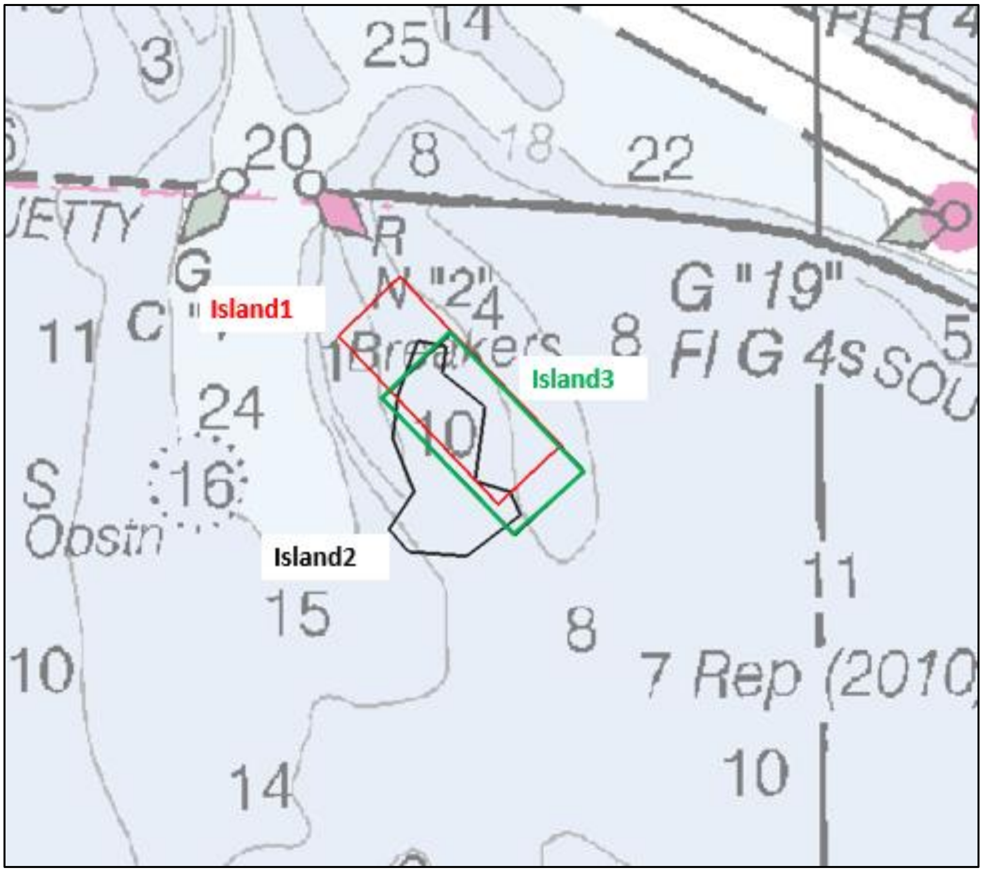

Figure 17- Proposed three potential placement sites within Area 2

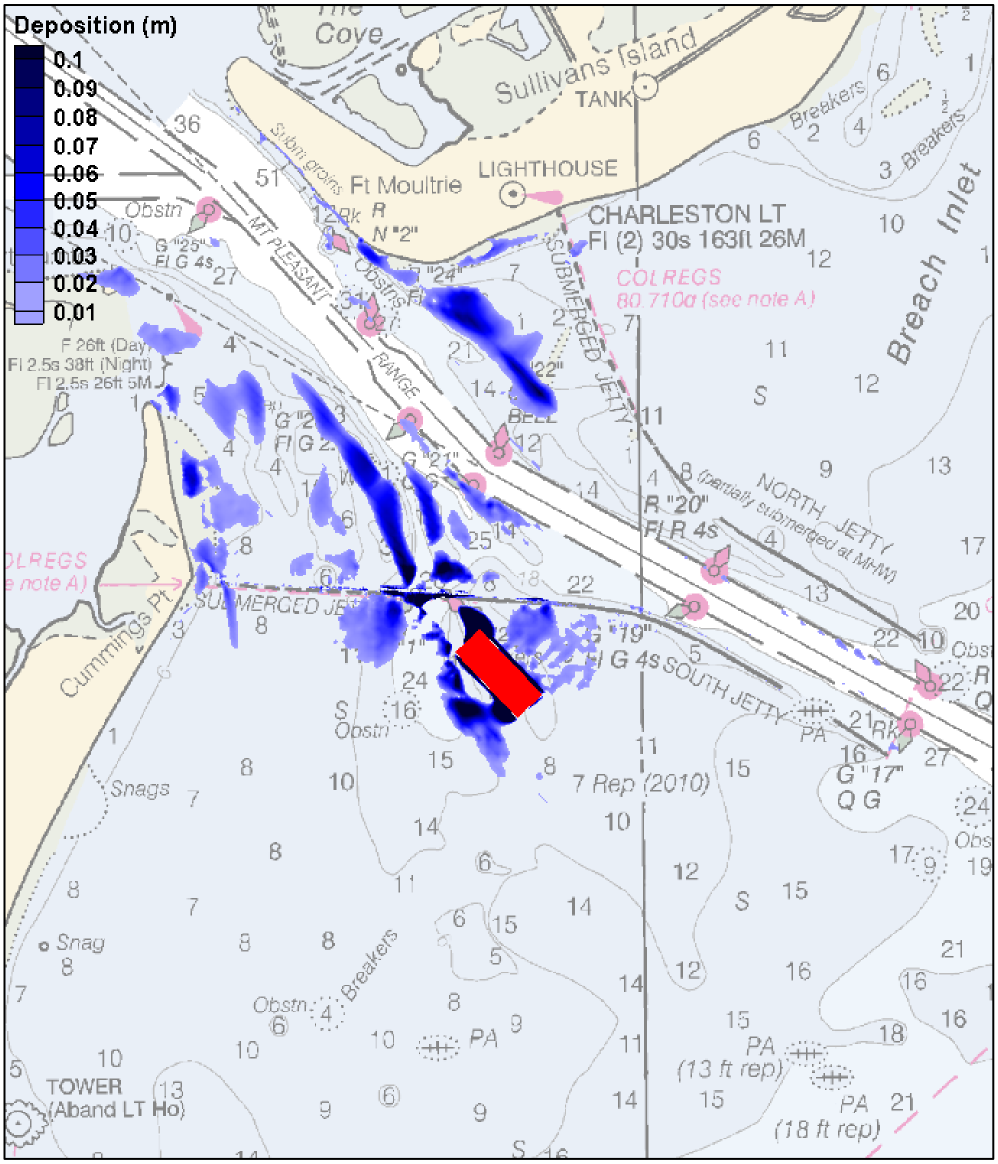

Figure 18 - Morphology change difference between the existing and with placement at Island1 at the end of the December simulation period

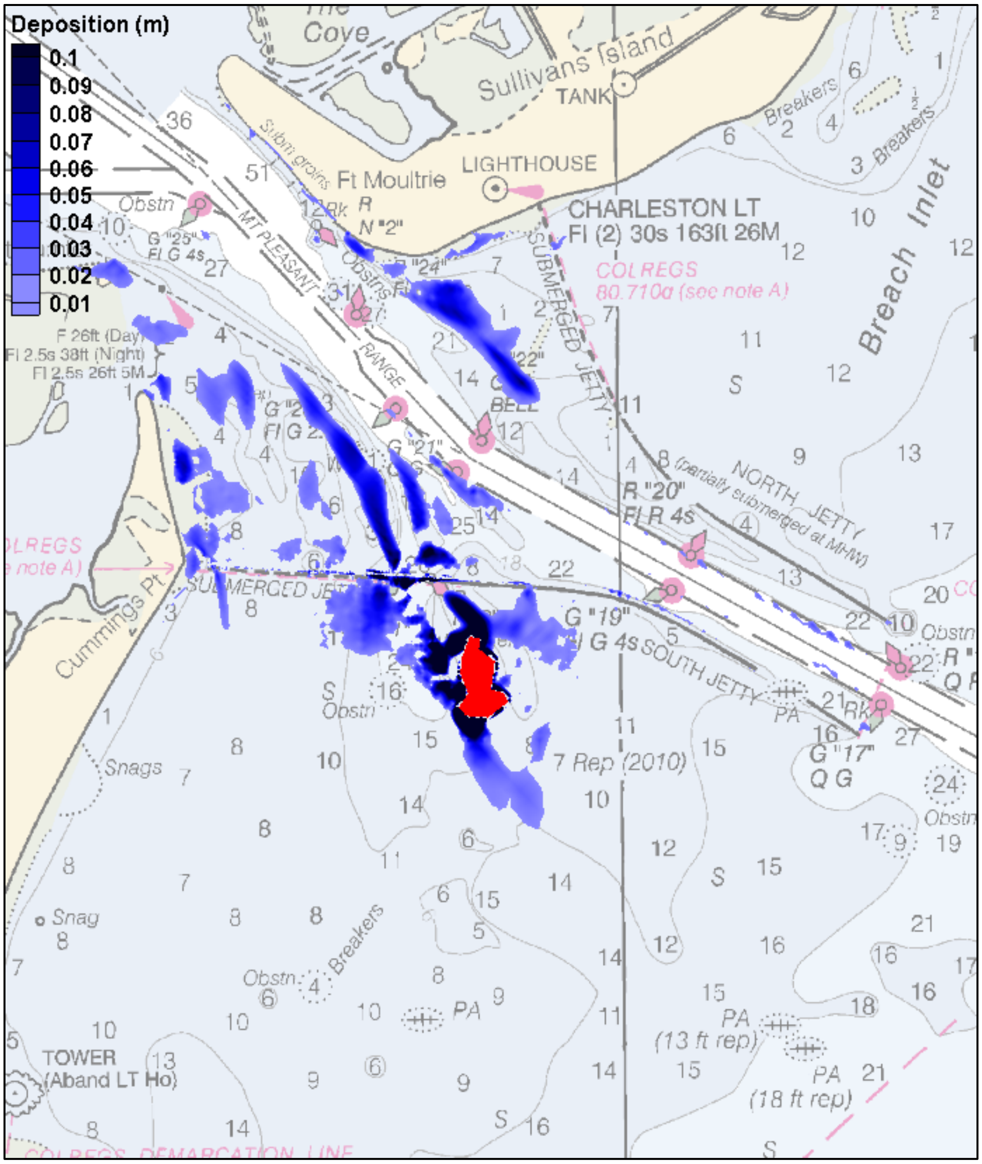

Figure 19 - Morphology change difference between the existing and with placement at Island2 at the end of the December simulation period

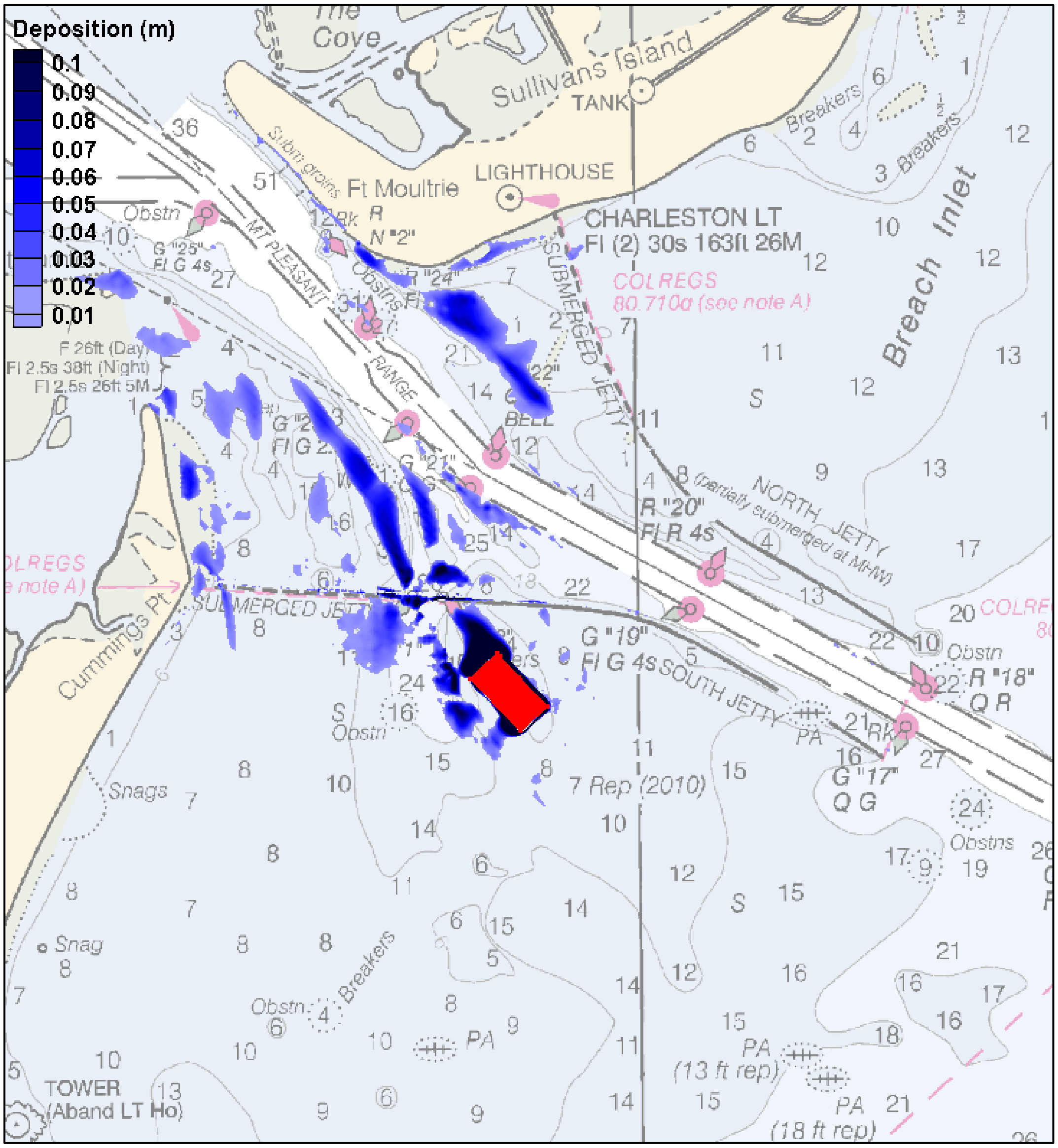

Figure 20 - Morphology change difference between the existing and with placement at Island3 at the end of the December simulation period

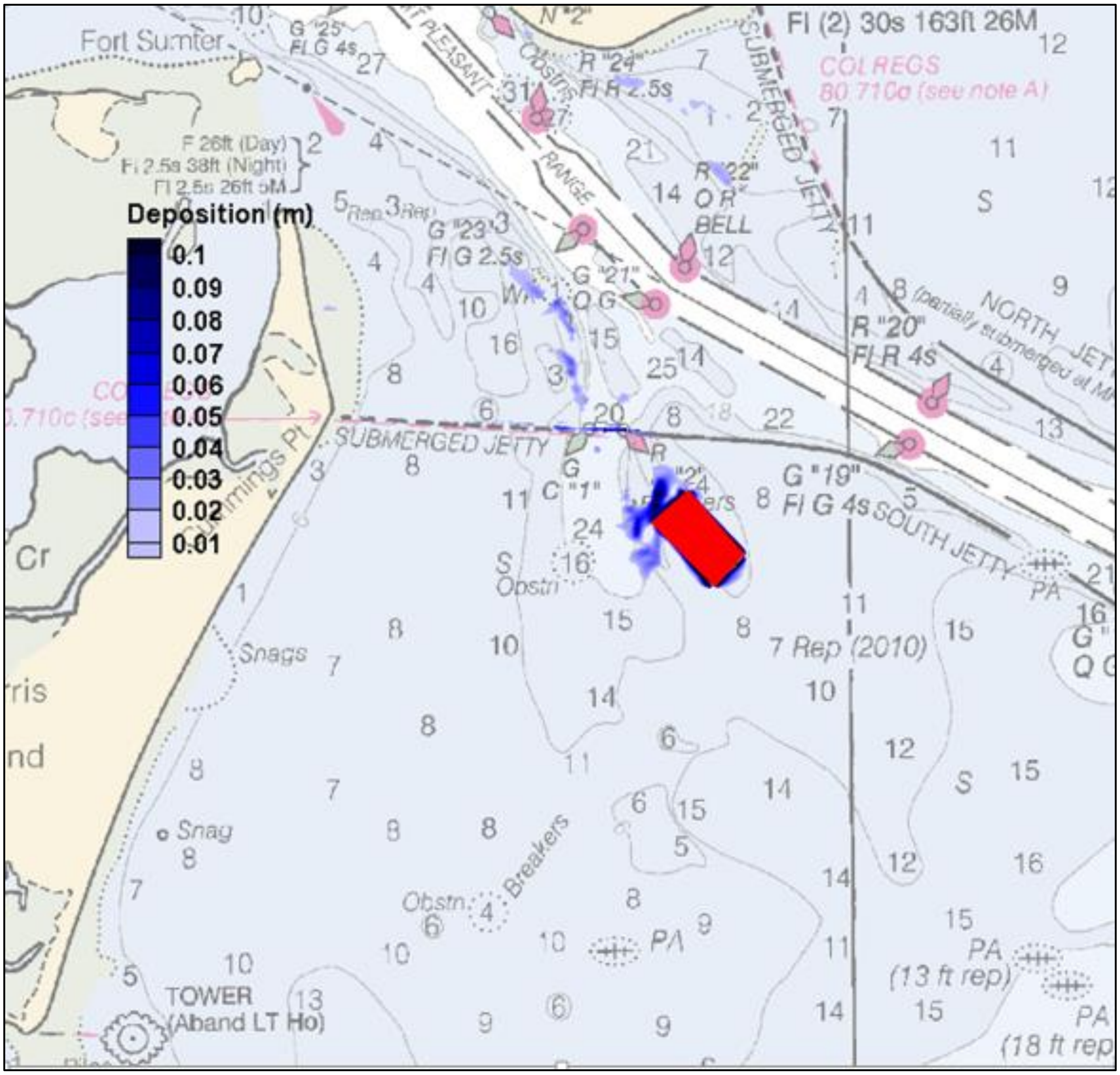

Figure 21 - Morphology change difference between the existing and with placement at Island3 at the end of the storm simulation period

CMS flow and wave models were used to estimate sediment transport patterns before and after material has been dredged and placed within the optimum site, Island3 during storm. Figure 21 shows sediment deposition due to placing dredged sediment at Island3 site as compared to the existing configuration, without the dredge material placement, at the end of the storm simulation period. Similar deposition patterns were observed at the end of the storm simulation, compared to December simulation, but with less extent.

7. PTM SIMULATIONS

PTM is capable of introducing and following the trajectory of discrete particles in the flow field (Demirbilek et al., 2008). It computes the paths of sediment particles using the Lagrangian method through a geometric domain as the particles interact with the environmental forcing. The computational environment includes the hydrodynamic flow, wave conditions, sediment property, and land boundary. Therefore, water surface elevations and currents calculated by CMS-Flow and wave information by CMS-Wave drive the PTM computations in the same CMS domain. The SMS includes tools to generate the necessary information to define the PTM environment, such as sediment release method and sediment properties (Lin et al., 2012). The hydrodynamic simulation is separate from PTM simulations. Therefore, multiple dredging and sediment scenarios can be simulated using one hydrodynamic simulation.

New work dredged material from a deepening project removed from the Charleston Entrance Channel, based on limited sampling, was identified to be composed of approximately 80 percent sand with small percent of gravel, silt and clay. Sand is expected to settle close to the placement area while fine material would be transported further inland and offshore away from the placement area. Native bed sediment was defined by D35, D50, and D90 for each cell, where D35 is the thirty-fifth-percentile grain size and D90 is the ninetieth-percentile grain size. Grain size distribution was investigated by examining available borehole database. The values of D35, D50 and D90 used in the simulation were estimated at 0.15 mm, 0.18 mm and 0.3 mm respectively (USACE, 2013).

Details of the dredging operations, such as specific location, equipment, and the length of the operation were not specified in this study because the main objective is to address the feasibility of the nearshore placement in the study area. Particles can be released from different source options (points, lines, or areas). The source specified was a point mass rate source which produces particles at a specific rate over time. Charleston Entrance Channel dredging window is during winter (December-March). Therefore, the PTM simulation was conducted during a 7- day period (December 5-12 of 2012) to evaluate sediment pathways during the release of the dredged material. A hypothetical placement operation of particles release for 24 hrs was adopted.

Sediment pathways during the release of dredged material at the optimal placement sites were examined. PTM was applied to assess the transport patterns and pathways of sediment from Berm2 and Island3 placement sites. Figures 22 and 23 show the pathway of sediment material from the source at the end of the 7-day simulation period for Berm2 and Island3 respectively. The release points were selected within placement areas of Berm2 and Island3. Figure 22 shows a large portion of the sediments placed at Berm2 deposited along the shorelines of Morris Island. Sediments were also observed offshore of Berm2 placement area. Some sediment moved inside the area within the jetties close to the Navigation Channel. Also, some fine sediments moved toward the Lighthouse inlet and in front of Folly Island. Figure 23 shows that considerable portion of the sediments placed at Island3 is going back into the Navigation Channel. Some coarse sediment deposited along the outside of the southern jetty and some fine sediment moved offshore in front of Morris Island shorelines.

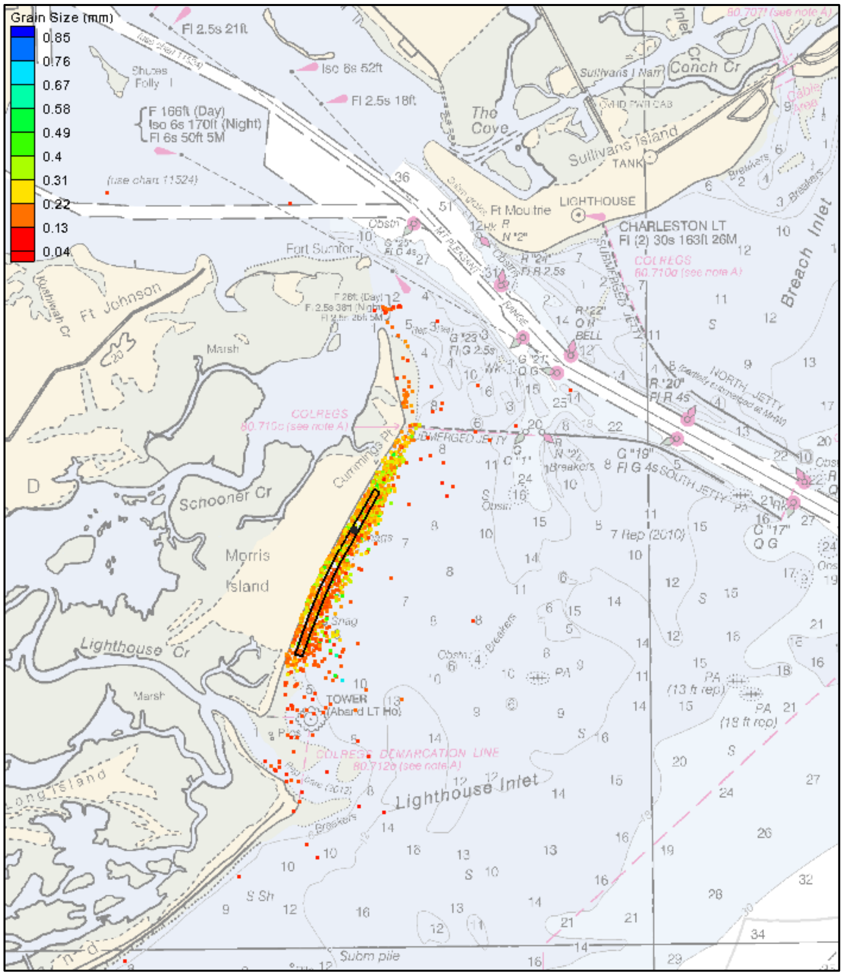

Figure 22- Sediment particles distribution at the end of the 7-day PTM simulation for Berm2

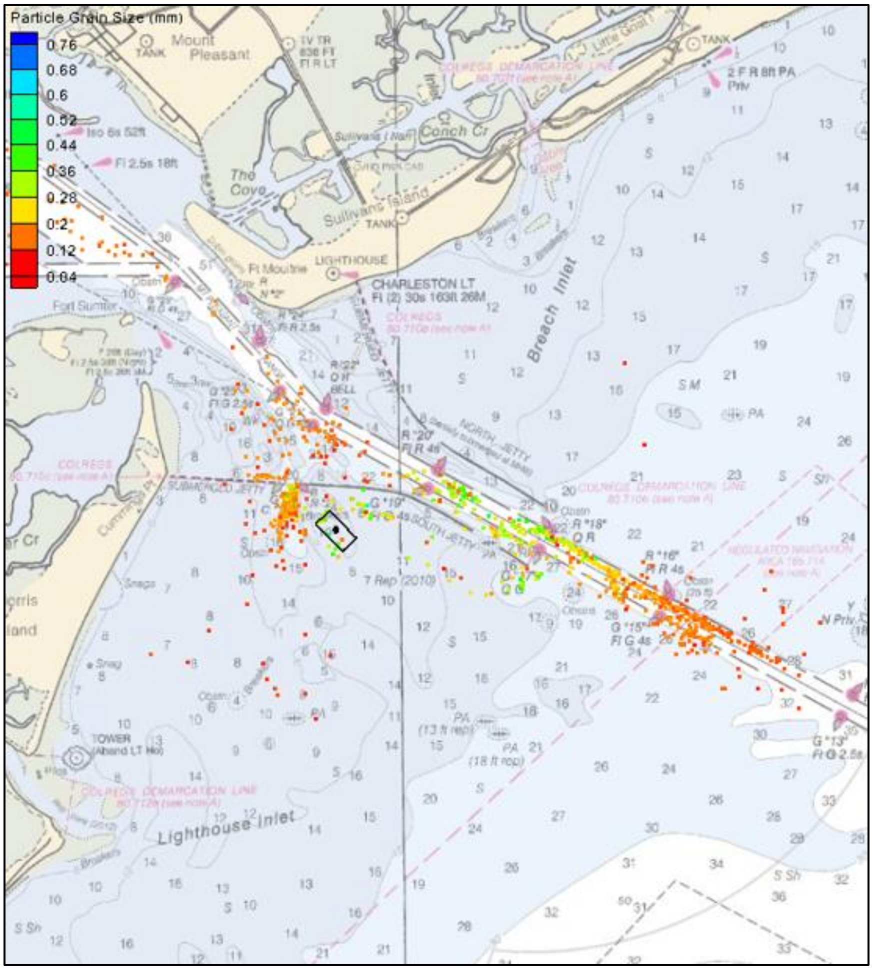

Figure 23- Sediment particles distribution at the end of the 7-day PTM simulation for Island3

8. CONCLUSIONS

Dredged material to be removed from Charleston Entrance Channel under the deepening project is composed of approximately 80 percent sand and it does not meet general guidelines for direct beach placement. Therefore, nearshore placement of the sand is considered a beneficial use of the dredged material because it will keep the sand in the littoral system.

CMS flow and wave models were conducted to calculate sediment transport benefits associated with nearshore placement of 400,000 m^3 of the Charleston Entrance Channel new work dredged material in the areas south of the Charleston Harbor south jetty. Area 1 is located in front of Morris Island which is an erosional area and its main benefit is to feed sediment back into the littoral system and feed sediment toward Morris Island and Folly Island shorelines. Area 2 is proposed to be depositional area, an "island" with elevation of 0.0 MTL (0.85 above MLLW)and can erode over time. Water level, wind and river flow data was used to force the CMS-Flow model. CMS-Wave model was forced with measured wave data that was collected by EPA at the Offshore ADCP. The inline version of CMS-Flow, which includes CMS-Flow and CMS-Wave in one code, was adopted in this study due to its capability to implement the tidal constituent forcing at the ocean boundary for telescoping CMS grids.

Berm1, Berm2 and Berm3 scenarios, within placement Area1, and Island1, Island2 and Island3 scenarios, within placement Area2, were investigated. Sediment transport and morphology change at the proposed dredged material placement sites were examined during selected representative periods. CMS models were used to estimate sediment transport patterns before and after material has been dredged and placed in the littoral zone, within the selected sites at the south of the jetties.

Morphology change in the Charleston Harbor area was estimated at the end of the month of December for the existing condition and the three placement sites conditions within each proposed area. Berm2 site was considered the optimal placement location, within Area 1, because it resulted in minimum sediment movement into the navigation channel. Also, sediment is kept around the berm in the littoral zone. Island3 site was considered the optimal placement location, within Area 2, because it resulted in minimum sediment deposition in the Navigation Channel. Also, least material loss was observed at placement site Island3. Morphology change was estimated before and after material has been dredged and placed within the optimum sites during storm. Similar deposition patterns were observed at the end of the storm simulation, compared to December simulation, but with less extent for both sites.

PTM was applied to assess the transport patterns and pathways of sediment from Berm2 and Island3 sites. The dredged material obtained from the entrance channel was composed of small percent of gravel, silt and clay. A large portion of the sediments placed at Berm2 deposited along the shorelines of Morris Island. Sediments were also observed offshore of the Berm2 placement area. Some sediment moved inside the area within the jetties close to the Navigation Channel. Also, some fine sediments moved toward the Lighthouse inlet and in front of Folly Island. For Island3, considerable portion of the sediments is going back into the Navigation Channel. Some coarse sediment deposited along the outside of the southern jetty and some fine sediment moved offshore in front of Morris Island shorelines.

In general, placing the dredged material close to the southern jetty is economical but it will result in sediment moving back into the Navigation Channel. It is recommended to place the dredged material further away from the southern jetty.

9. REFERENCES

ANAMAR Environmental Consulting, Inc., 2013. Draft Report, Charleston Harbor Navigation Improvement Project (Post 45) Dredging MPRSA Section 103, Sediment Testing and Analysis, Charleston, South Carolina. Contract No. W912EP-09-D-0013-DW01.

Buttolph, A. M., Reed, C. W., Kraus, N. C., Ono, N., Larson, M., Camenen, B., Hanson, H., Wamsley, T. and Zundel, A., 2006. Two-Dimensional Depth-Averaged Circulation Model CMS-M2D: Version 3.0: Report 2, Sediment Transport and Morphology Change. Coastal and

Hydraulics Laboratory Technical Report ERDC/CHL TR-06-9. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Demirbilek, Z., Connell, K. J., MacDonald, N. J. and Zundel, A. K., 2008. Particle Tracking Model in the SMS10: IV. Link to Coastal Modeling System. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-IV-71. Army Engineer Research and Development Center, Vicksburg, MS.

Gailani, J. Z., Lackey, T. C. and Smith, S. J., 2008. Application of the Particle Tracking Model to Predict Far-Field Fate of Sediment Suspended by Nearshore Dredging and Placement, Brunswick Ga.

Lin, L., Demirbilek, Z., Mase, H., Zheng, J. and Yamada, F. A., 2008. Nearshore Spectral Wave Processes Model for Coastal Inlets and Navigation Projects. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL TR-08-13. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Lin, L., Li, L., Brown, M., Wu, F., and Andes, L., 2012. Pilot Study Evaluating Nearshore Sediment Placement Sites, Noyo Harbor, CA. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL TR-12. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

McArthur, C., 2012. Quality Assurance Project Plan, Charleston Harbor ODMDS Current and Wave Measurements, Inshore Regional Sediment Management (RSM) Current and Wave Measurements, United States Environmental Protection Agency, Region 4.

Mukai, A. Y., Westerink, J. J., Luettich, R. A., and Mark, D. J., 2002. Eastcoast 2001, A Tidal Constituent Database for the Western North Atlantic, Gulf of Mexico and Caribbean Sea, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Sanchez, A., W. Wu, T. M. Beck, H. Li, J. D. Rosati, Z. Demirbilek, and M. Brown. 2011b. Verification and Validation of the Coastal Modeling System, Report 4: Sediment Transport and Morphology Change. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-11-10. Vicksburg, MS: US Army Engineer Research and Development Center.

Smith, J. M., 2000. Benchmark Tests of STWAVE. Proceedings, 6th International Workshop on Wave. Hindcasting and Forecasting, Environment Canada, 369-379.

U.S. Army Corps of Engineers (USACE), 2010. Section 905(B) (WRDA 86) Analysis Charleston Harbor Navigation Improvement Project, Charleston, South Carolina.

U.S. Army Corps of Engineers (USACE), 2011. Regional Sediment Management, East Rockaway Inlet, New York, Utilizing the USACE Coastal Modeling System. Draft Final Report, Numerical Modeling supported by Offshore & Coastal Technologies, Inc.

U.S. Army Corps of Engineers (USACE), 2013.Numerical Modeling Study, Charleston Harbor Coastal Area, SC.

U.S. Army Corps of Engineers (USACE), 2015. Charleston Harbor Post 45 Final Feasibility, Final Integrated Feasibility Report and Environmental Impact Statement, Army Corps of Engineers Charleston District, Charleston, SC.

U.S. Army Corps of Engineers (USACE), 2015. Charleston Harbor Morphology Evaluations, Charleston Harbor Coastal Area, SC.

U.S. Environmental Protection Agency Region 4 (EPA), 2014. Charleston Harbor ODMDS Current and Wave Measurements (DRAFT), Regional Sediment Management Current and Wave Measurements. Under EPA Interagency Agreement #RW-96-95822401-0

U.S. Environmental Protection Agency Region 4 (EPA), 2015. Draft Environmental Assessment For Modification of The Charleston Ocean Dredged Material Disposal Site (ODMDS), Charleston, South Carolina.

U.S. Army Corps of Engineers (USACE), 2014. Charleston Harbor Regional Sediment Management: Dredged Material Beneficial Nearshore Placement**.** Charleston District, South Carolina.