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Effect of Hydrodynamics on Sediment Transport near a Coastal Inlet

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ABSTRACT: Over the years, Plum Island at the Merrimack Estuary has experienced severe erosion around the Merrimack Inlet and along the beach face. A numerical modeling study is required to reduce erosion, increase jetty performance, and develop a sand management strategy. The Coastal Modeling System (CMS) was applied to calculate hydrodynamics, sediment transport, and morphology change. The model calculations are validated by water level and current measurements near the inlet and in the Plum Island Sound. The preliminary CMS results show that the calculated water level and current are in agreement with the measurements. The CMS properly simulates the tidal propagation and the flow pattern in the system, and the general accretion and erosion trends as well as the sand bar formation near the Newburyport Inlet well correspond to strong ebb/flood currents and mean sediment transport direction.

Keywords: Hydrodynamics, Sediment transport, Numerical model, Coastal inlet

1 INTRODUCTION

The Merrimack Estuary, a tidal estuary, is located in northeastern Massachusetts. The estuarine embayment, including the Plum Island Sound, is characterized by tidal marsh, tidal creeks, small islands and ponds. The bay receives freshwater inflows from Merrimack, Mill, Parker, Ipswich Rivers at the west and is connected to the Atlantic Ocean through the Newburyport Inlet at the east (Figure 1). Ebb/flood tidal currents through the inlet erode sediment from Plum Island and transport sand into the navigation channel. Salisbury Beach and Plum Island in the northern and southern sides of the inlet are facing the open ocean. Winter storms (nor'easter) and waves pounding the coast frequently result in severe beach erosion and sand migration in the area.

Figure 1. Merrimack estuary, Massachusetts.

To examine the sediment transport pattern near the inlet and adjacent beaches, a coastal model is developed. The calculations of water surface elevation, current, waves, and sediment transport will be conducted towards the understanding of coastal erosion and ebb/flood shoaling, and will contribute to the evaluation of jetty performance and channel navigability, and the development of a sand management plan.

2 METHODOLOGY AND STUDY DOMAIN

The Coastal Modeling System (CMS), developed by the Coastal Inlets Research Program (CIRP), U. S. Army Corps of Engineers, is selected for this study (http://cirp.usace.army.mil/wiki/CMS). The CMS is an integrated suite of numerical models for simulating water surface elevation, current, waves, sediment transport, and morphology change for coastal and inlet applications. The CMS consists of a hydrodynamic model, CMS-Flow, and a spectral wave model, CMS-Wave. CMS-Flow and CMS-Wave are coupled and operated through a Steering Module developed within the Surface-water Modeling System (SMS).

CMS-Flow is a two-dimensional (2D) finite-volume model that solves the depth-integrated mass conservation and shallow-water momentum equations of water motion on a non-uniform Cartesian grid. Three sediment transport formulations are available in the sediment module: a sediment mass balance, an equilibrium advection-diffusion method, and a non-equilibrium advection-diffusion method. The wave radiation stress and wave field information calculated by CMS-Wave are supplied to CMS-Flow for the flow and sediment transport calculations. Currents, water level, and morphology changes are feeding to CMS-Wave to increase the accuracy of the wave transformation predictions (Sanchez et al., 2011) (Figure 2).

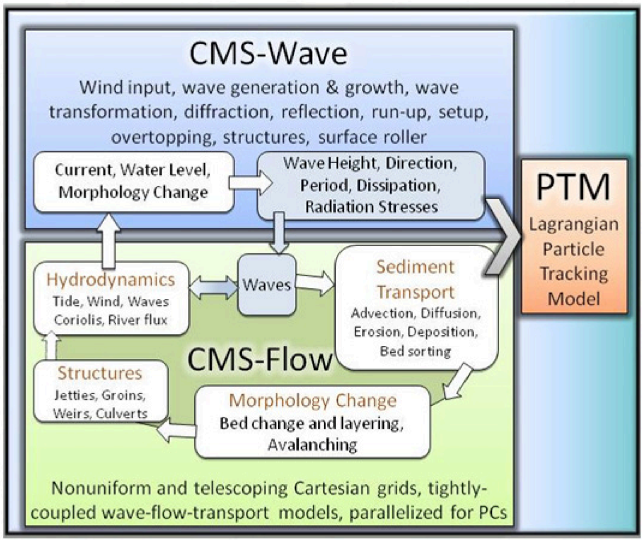

Figure 2. The CMS operational flow chart.

CMS-Wave is a two-dimensional spectral wave transformation model that solves the steady-state wave-action balance and diffraction equation on a non-uniform Cartesian grid (Lin et al., 2011). The model can simulate important wave processes at coastal inlets including diffraction, refraction, reflection, wave breaking and dissipation mechanisms, wave-wave and wave-current interactions, and wave generation and growth. It is a full-plane model with primary waves propagating from open boundaries toward inside domain. If the reflection option is selected from one open boundary, CMS-Wave will perform a backward marching for the boundary reflection after the forwarding-marching calculation is completed. The fundamental wave diffraction process is theoretically developed and calculated in the wave-action balance equation. Additional model features include the grid nesting capability, variable rectangle cells, wave run-up on beach face, wave transmission through structures, wave overtopping, and storm wave generation (Figure 2).

For this estuarine system, a telescoping grid was adopted for the CMS. Figure 3 shows the CMS grid domain that consists of 73,000 ocean cells covering the entire Plum Island Sound and the open ocean region. It extends approximately 20 km alongshore and 3-7 km offshore. The water depth ranges from 1-2 m above the mean sea level at tidal marsh areas in the Plum Island Sound to 13 m at the inlet navigation channel, and further increases to 40 m in the offshore boundary of the CMS domain. The telescoping grid system permits much finer local grid resolution to well resolve hydrodynamic and sediment features in areas of high interest. For this study the cell sizes vary from 6-12 m around the Newburyport Inlet and the creeks/narrow channels linking the north and south Sound to 400 m in the open ocean.

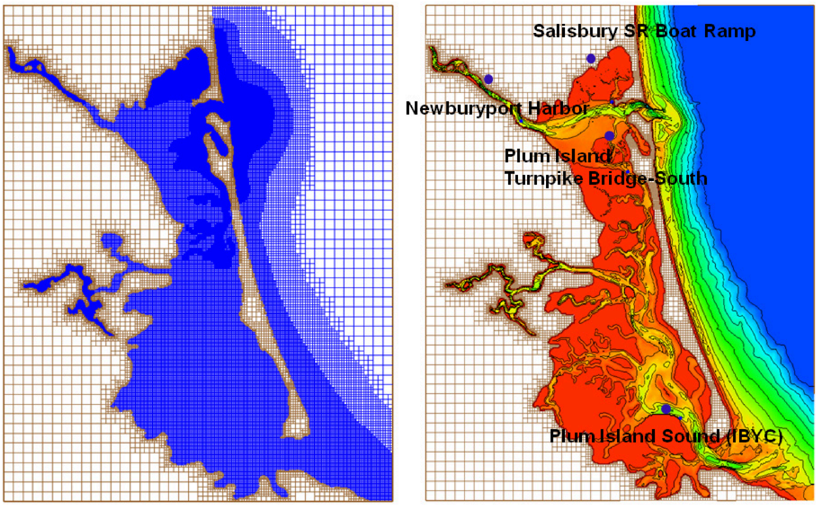

Figure 3. The CMS telescoping grid and tidal gauge locations.

3 DATA

The offshore bathymetric data were obtained from the GEOphysical DAta System (GEODAS) database (NGDC 2009). The U. S. Army Corps of Engineers (USACE), New England District (Daniel Bradley, personal communication) provided dredge survey and topographic data around the Newburyport Inlet and the navigation channel, and the Plum Island Ecosystems. The Long Term Ecological Research Network (PIE-LTER) (NSF Grant 1238212) conducted kinematic bathymetry surveys in the small creeks and tidal marsh areas (Vallino and Hopkinson, 1998). Historical high-resolution LIDAR surveys by USACE and the National Oceanic and Atmospheric Administration (NOAA) cover the Plum Island Sound and near-shore areas.

Wave data were available from the National Data Buoy Center (NDBC) (www.ndbc.noaa.gov). The NDBC buoy #44098 is located about 50 km offshore of the CMS open boundary (Figure 4). Directional wave spectra were retrieved for CMS simulations in a 3-hour interval and transformed to the model seaward boundary. The wave data analysis shows that the predominant waves are from the east to southeast (90-180 deg azimuth) in the summer and the northwest (270-360 deg azimuth) to northeast (0-90 deg azimuth) directions during the winter months. Large waves occur during the winter with extreme wave heights between 4 and 8 m. The summer wave height is small, usually less than 2 m.

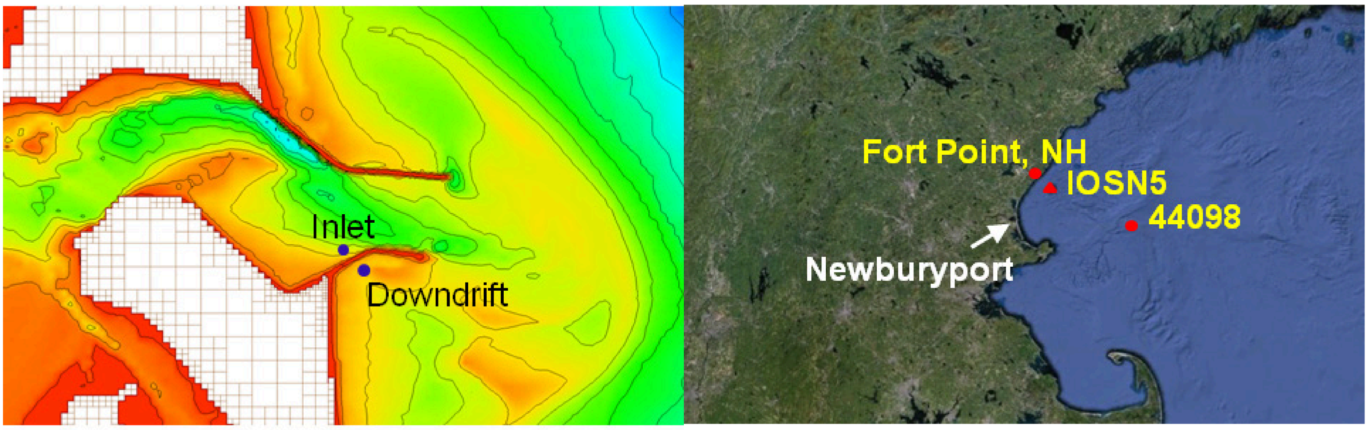

Figure 4. ADCP gauge, NOAA tide gauge, and NOAA buoy locations.

Wind observations were provided by another NDBC buoy IOSN3 (Figure 4), which is located about 17 km northeast of the CMS domain. At this offshore buoy location, dominant winds are south-southeasterly during the summer and west-northwesterly during the winter. The summer months are relatively calm and the frequency of storm occurrences starts to increase in October and it decreases in April. The maximum and minimum monthly mean wind speeds are 9.1 m/s and 6.3 m/s in December and September, respectively.

Water surface elevation (WSE) data were downloaded from NOAA tide gage #8423898 at Fort Point, NH (http://tidesandcurrents.noaa.gov) (Figure 4). A semi-diurnal tidal regime is surrounding the study area. The mean tidal range (mean high water – mean low water) is 2.63 m and the maximum tidal range (mean higher high water - mean lower low water) is 2.87 m.

River flow data were obtained from the USGS gages at the Merrimack, Mill, Parker, and Ipswich Rivers. The flow discharge in summer is 1 to 2 orders of magnitude smaller than the winter. The flow discharge at the Merrimack River can be more than 1000 m^3/s during the high flow season and is 1 to 2 orders of magnitude larger than the other rivers.

A field data survey was conducted by Woods Hole Group. Two ADCPs were deployed around the south jetty from September through October 2012 and four water level gages in the Plum Island Sound from September through December 2012 (Figures 3 and 4). Current and water surface elevation data were collected at those gauges. Besides the hydrographic data, sediment grab samples were collected in north Plum Island Sound (Figure 5). Based on 17 samples, D_{50} of 0.32 mm was calculated

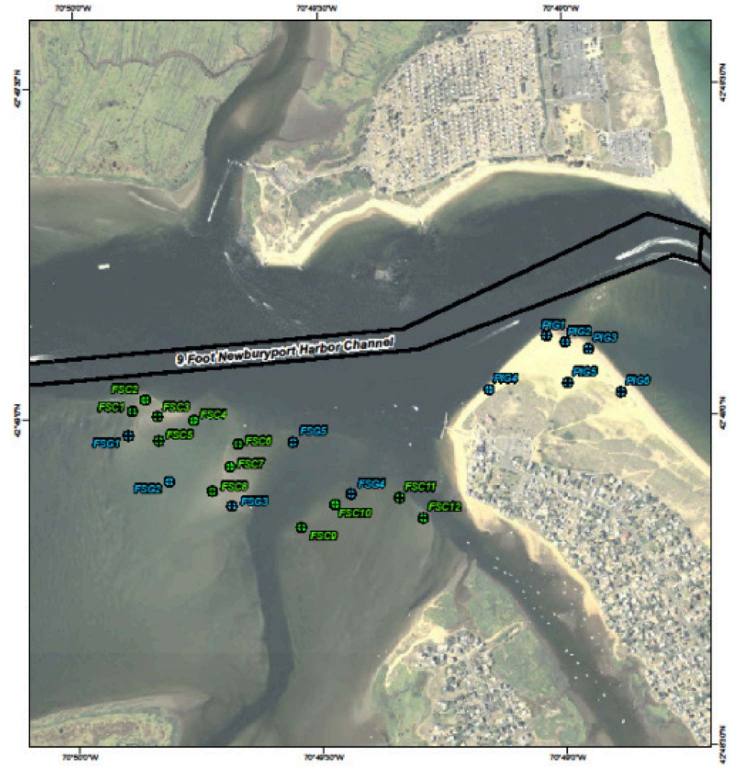

Figure 5. Sediment grab sampling locations in north Plum Island Sound.

The bathymetry data were interpolated to configure the numerical model grid. Waves, wind, water surface elevation, and river flow data were assembled to provide forcing terms to the CMS at the offshore and estuary boundaries. The field measurements were analyzed and the model performance was evaluated by conducting hydrodynamic calibration/validation against the data.

4 RESULTS AND DISCUSSION

The CMS simulations were conducted for September, 2012 (regular condition) and January 2010 (winter condition). Figure 6 shows the comparison of calculated and measured WSEs at the 4 tidal gauges in the estuarine system (Figure 3). Both the measurements and calculations show that the spring tidal amplitude is close to 3.5 - 4 m in the area. A small surge occurred near the end of the 30-day simulations. The goodness of fit statistics shown in Table 1 indicates that the CMS results well reproduce the tidal signals displayed in the WSE survey.

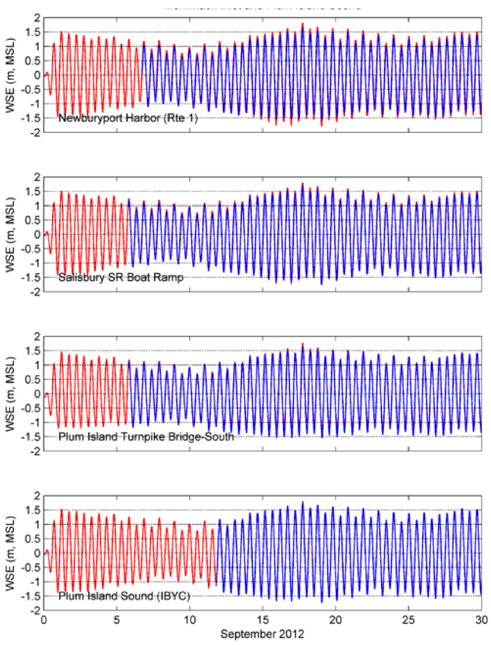

Figure 6. Calculated and measured water surface elevations in Plum Island Sound.

Table 1. Water level goodness of fit statistics: September 2012 field data.

Gauge	CC[*]	RMSE[**] (m)	RRMSE[***] (%)
Newburyport Harbor	0.982	0.209	5.9
Salisbury SR Boat Ramp	0.994	0.127	3.6
Plum Island Turnpike Bridge	0.993	0.128	3.7
Plum Island Sound (IBYC)	0.999	0.069	2.0

[*] Correlation coefficient
[**] Root mean square error
[***] Relative root mean square error

Figure 7 shows a snapshot of the depth-averaged flood and ebb current fields on 17 September 2012 at 14:00 and 20:00 GMT, relatively, during a spring tidal period (Figure 6). Strong currents occurred at the inlet. The maximum current speed is approximately 1.3-1.4 m/sec in the navigation channel. At the two ADCP locations in the vicinity of the south jetty, currents are relatively weak with a maximum speed of 20-30 cm/sec. A small eddy formed close to the Inlet ADCP station during the ebb tide.

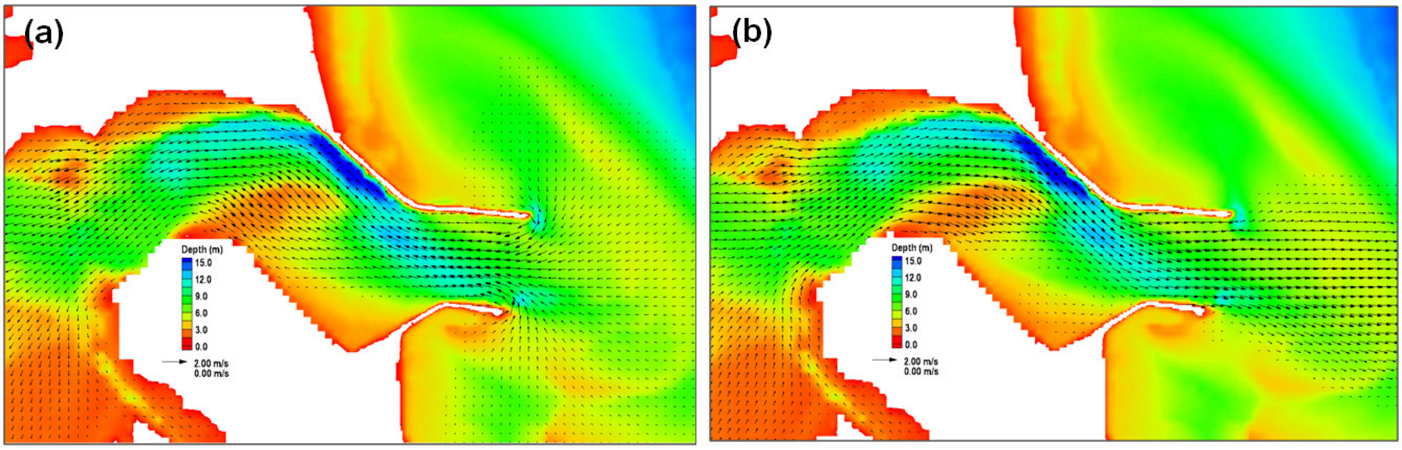

Figure 7. Calculated depth-averaged (a) flood and (b) ebb currents on 17 September 2012 at 14:00 and 20:00 GMT, respectively.

The calculated current components (u: east-west; v: north-south) are compared with the measurements at the two ADCP stations (Figure 8). The current measurements show weak but clear tidal signals. The current speed at the Inlet location is larger than that at the Downdrift location. Table 2 details the goodness of fit statistics for the gauges.

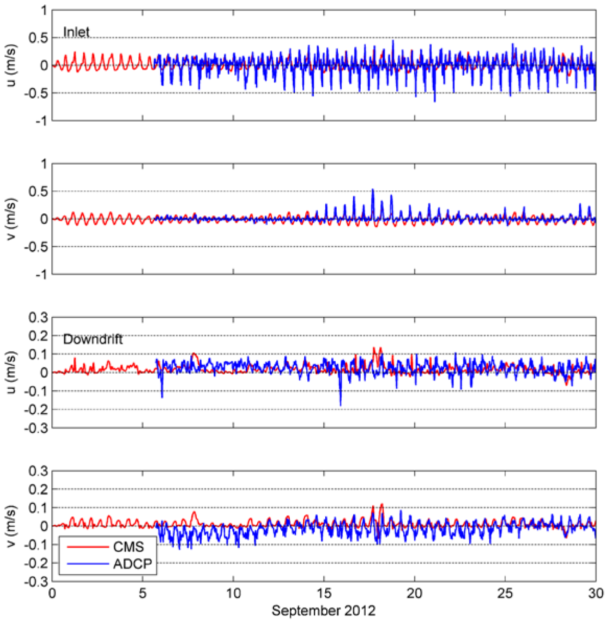

Figure 8. Calculated and measured currents in Merrimack Inlet.

Table 2. Current goodness of fit statistics: September 2012 field data.

Gauge	CC[*]		RMSE (m/s)[**]		RRMSE (%)[***]	
	u	v	u	v	u	v
Inlet	0.479	0.475	0.143	0.067	13.0	11.2
Downdrift	0.009	0.391	0.039	0.042	13.0	16.8

[*] Correlation coefficient
[**] Root mean square error
[***] Relative root mean square error

The closer correlation was for the Inlet ADCP while the Downdrift ADCP showed the weak model validation. This performance is most likely due to a combination of the proper representation of the structure in the model and the location of the Downdrift ADCP which is sheltered from direct wave action. Inspection of the measured data also reveals the vertical structure of current profiles and it is difficult for a 2D model to generate good model and data comparisons at those locations.

Residual current and corresponding sediment transport were obtained by averaging monthly simulation results. As shown in Figure 9, the net flow and sediment transport are towards the open ocean and the morphology change at the end of simulations shows the sediment accumulation and sand bar formation around the ebb shoal for September 2012 and January 2010. The mean current speeds in the winter month are stronger than the fall month, especially the long-shore components, due to storms and waves. Corresponding to that, the net sediment transport is much stronger and the morphology change larger during the winter time.

The calculated morphology change results are validated by latest dredging data at the inlet entrance channel. Figure 10(a) shows the morphology change based on channel surveys between February 2009 and September 2010 and Figure 10(b) is the calculated morphology change at the end of a winter month simulation in January 2011. Warmer colors indicate sediment deposition while cooler colors represent erosion. The major morphologic features are represented although the magnitude and location of the bed change may vary. For example, the model properly simulated the growth of bars near the inlet entrance and erosion hot spot around the tip of the south jetty although the distribution pattern does not have an exact match.

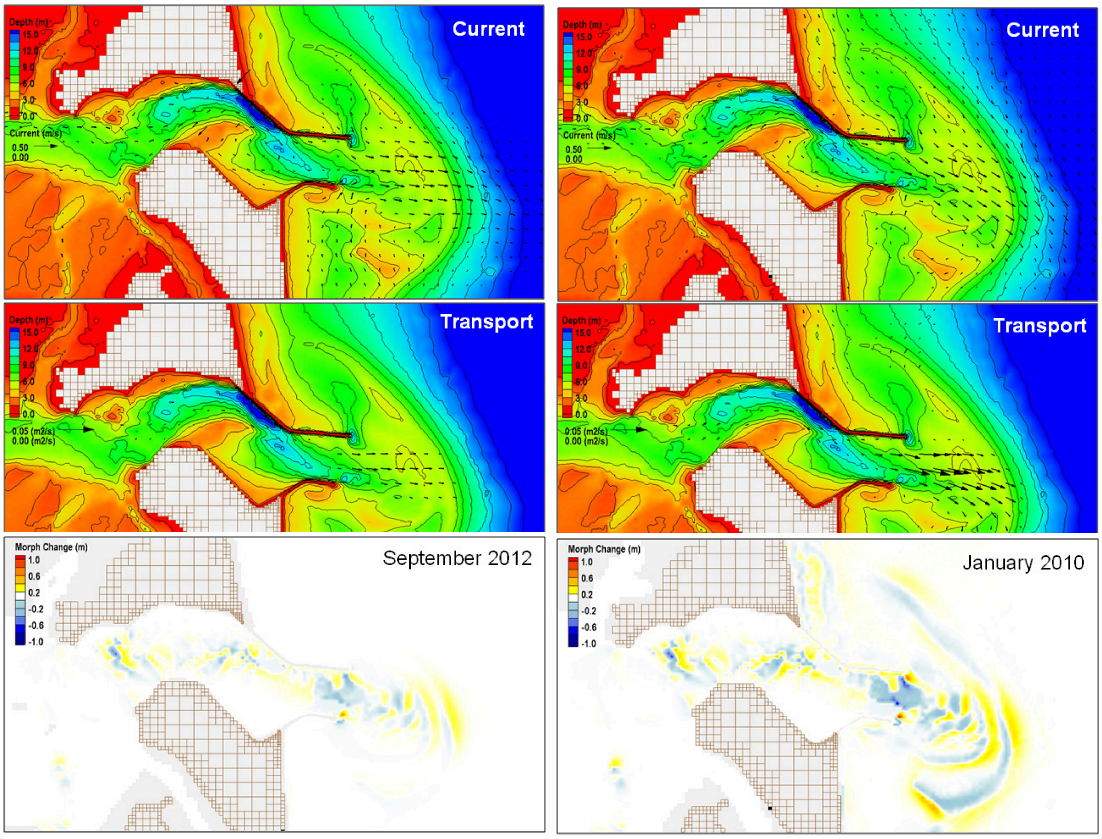

Figure 9. Residual current, sediment transport and morphology change for September 2012 and January 2010.

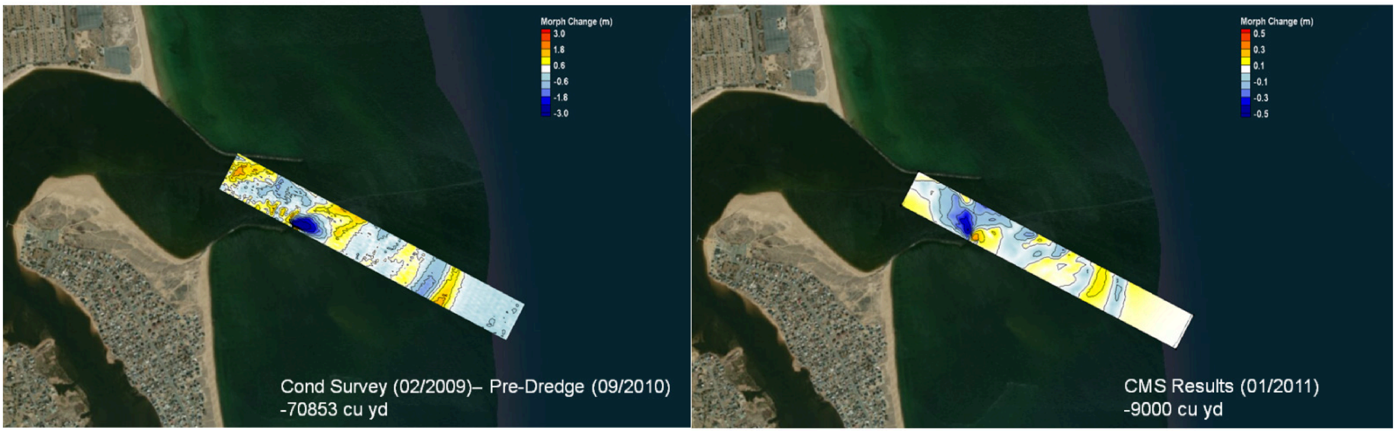

Figure 10. Morphology change along the 15-foot channel.

5 CONCLUSIONS

Hydrodynamics and sediment transport were simulated by the CMS, an integrated wave, flow and sediment transport modeling system. The model performance was investigated by comparing to the measured water surface elevation and current at four tide and two ADCP gauges in Plum Island Sound and at the Merrimack Inlet, respectively. The calculated morphology change was validated by channel condition surveys along the inlet entrance channel.

Comparisons of the CMS results and measured data indicate that tide is the dominated forcing around the inlet and in the estuarine system. The depth average current has a maximum flood or ebb speed of greater than 1.3 m/sec at the inlet channel. The net current indicates that water flows towards the open ocean, and the net sediment transport direction and the morphology change correspond to potential shoal formation at the estuarine entrance. The winter storm and wave conditions induce stronger longshore currents and larger sediment transport and morphology change.

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