RE-ESTABLISHING A HISTORICAL INLET AT EAST HARBOR, CAPE COD, MASSSACHUSETTS

IRENE M WATTS[1], JULIE DEAN ROSATI[2], MARK BORRELLI[3]

1. *U.S. Army Corps of Engineers, New England District, 696 Virginia Road, Concord, MA 01742-2751, USA. Irene.Watts@usace.army.mil.*
2. *U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, USA. Julie.D.Rosati@usace.army.mil.*
3. *Provincetown Center for Coastal Studies, 115 Bradford Street, Provincetown, MA 02657-143,. USA. mborrelli@coastalstudies.org.*

Abstract: East Harbor is a tidally restricted estuary north of Truro, MA, on Cape Cod. The Harbor is connected to Cape Cod Bay by a culvert with 2.2 m^2 cross-sectional area and 200 m length leading to a poorly flushed marsh area which empties into East Harbor. The natural inlet on the north end of the estuary was closed via construction of a dike in 1869, which significantly changed the hydrodynamics of the system. This study examined the benefits of establishing a new inlet within limited property on the southern end of the estuary. The analysis maximized water exchange within East Harbor while minimizing impoundment at inlet structures extending into Cape Cod Bay. Methods include an analysis of the natural and altered channel equilibrium and flow characteristics; a sediment budget for the bay shoreline; and numerical modeling of waves, currents, and sediment transport. Numerical model results agree with channel equilibrium area calculations.

Introduction

Modern coastal engineering continues to contend with the coastal engineering actions of the past century. Many estuaries in New England were modified in the 1800s-1900s to facilitate transportation and reduce flooding (Thelen and Thiet, 2008). Today, many of these estuaries are being restored to reestablish natural hydrologic regimes. East Harbor, MA, is an example of one of these tidally constrained estuaries being studied to partially restore natural tidal flow, increase salinity, and increase tidal range. East Harbor is a 290-hectare site that consists of a poorly flushed marsh area (Moon Pond) which empties into a 26-acre Lake (Pilgrim Lake) which connects to another marsh area (Salt Meadow). The original inlet located at the north end of the estuary (Figure 1a) was closed by the construction of a dike in 1869. The motivation behind this closure was to reduce or eliminate the erosion occurring on the seaward side of East Harbor and later provided railroad access to Provincetown (Headquarters U.S. Army Corps of Engineers (USACE), 1868; National Oceanic and Atmospheric

Administration (NOAA), 2006). Tidal access to the estuary was relocated at the southern end of the estuary with a fixed culvert with dimensions 1.1 m by 2 m (Figure 1b). This closure significantly changed hydrodynamics of the system and sediment transport on Cape Cod Bay and within the estuary.

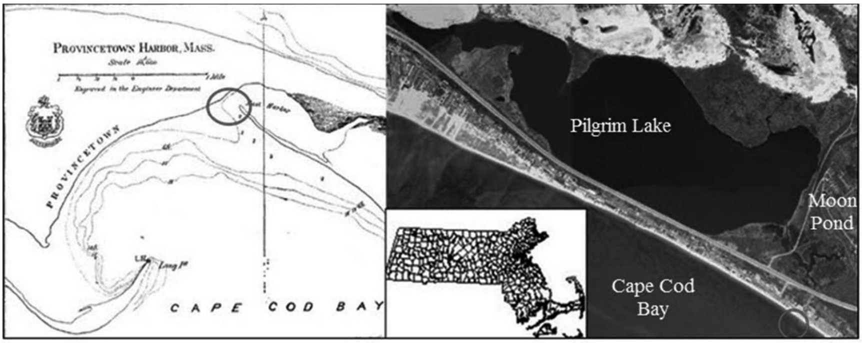

Fig. 1: East Harbor, Massachusetts, historical inlet location (a, left) and present-day culvert opening (b, right) (USACE, 1868; MassGIS, 2003)

The goal of this study is to evaluate alternatives for increasing the tidal range in East Harbor, which will improve tidal flushing, water quality (salinity), and restoration of marsh habitat. Partial tidal flow was restored to East Harbor in 2002 by opening the flow control structures resulting in a substantial increase in salinity and partial restoration of tidal range. With the control valves open, the salinity in Pilgrim Lake has risen from 4 ppm to 20-25 ppm (Portnoy, et al, 2006). A field effort in 2005 to capture the hydrodynamic characteristics of the system observed the unrestricted tide range in Provincetown Harbor ranged between 2.5-3.5 m was reduced to less than 0.5 m in Moon Pond. A tidal signal was not observed in Pilgrim Lake (Spaulding, 2005). Since the opening of the control valves, native fauna and aquatic species have begun to return to the system (Thelen and Thiet, 2008). Previous 1-dimensional (1D) modeling of the site indicated that the optimum inlet configuration would be greater than 200 m in width with an average depth of 1 m (Spaulding, 2005), similar to the natural inlet. Preliminary analysis indicates the stable equilibrium for a natural inlet at the site is approximately 340 m^2 and the minimum cross-section is 10 m^2. However, present land ownership at the site limits widths to a maximum of 23 m. Relocating the inlet to its natural configuration is not possible due to existing infrastructure and development.

This study consists of different levels of analysis including a channel equilibrium area analysis to develop general inlet characteristics, a beach profile and sediment field analysis for determining initial sand transport characteristics, followed by coastal numerical modeling of waves, currents, and sediment transport to identify sediment pathways and estimate quantities.

Site History and Description

As society continues to interact with the coast, investigating what has occurred historically at a particular site becomes more important to understand the site processes on a macroscale and the site's response to anthropogenic alterations. Investigations into the site history revealed that the natural historical inlet was much larger than the existing culvert opening and was located on the opposite end of the estuary. More than 100 buried groins and a timber-stone dike close off the natural entrance to East Harbor (Figure 2).

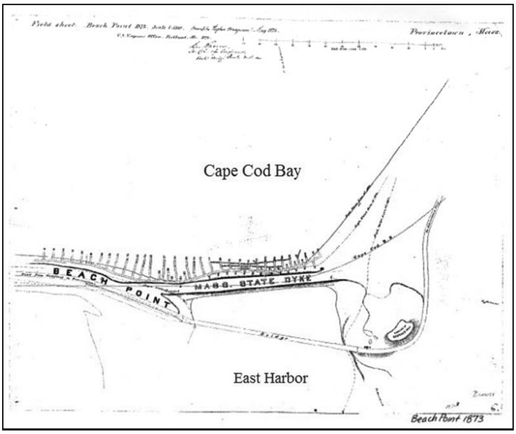

Fig. 2. Dike and buried groins closing off East Harbor Inlet (USACE, 1873)

Unfortunately, not enough data exist in the historical records to determine the natural tidal prism, which would have allowed for a ratio of potential inlet prism to the historical one.

In September 2001, the system suffered oxygen depletion and fish kill which prompted the town of Truro, the Cape Cod National Seashore, and state officials to investigate possibilities to improve water quality (Portnoy et al., 2006). The aim of the opening is to restore tidal exchange, not to open the harbor for navigation. Construction of a new coastal inlet with jetties is rare as stated in Kraus (2006).

Channel Equilibrium Area Program

The Channel Equilibrium Area (CEA) program (Seabergh and Kraus 1997) was applied to provide a desktop level analysis for determining the minimum cross-section channel area for a probable inlet. This tool is based on the Escoffier's Inlet Stability Analysis (Escoffier, 1940) and O'Brien's Tidal Prism - Area relationship (O'Brien, 1976). The program is an analytical 1D model that helps determine the minimum cross-section channel area for a coastal inlet. This exercise was performed to produce a general idea of possible inlet configurations in terms of cross sectional area, depth, and possible range of maximum velocities through the inlet.

CEA Analysis Results

One of the challenges of this type of analysis is simplifying a complex system to align with the calculation procedure. The CEA program is based on the assumption that the bay is connected to the sea via an idealized inlet. The hydrodynamic characteristic for East Harbor is not a straightforward bay-sea configuration. The flow path is not a straight path into Pilgrim Lake, but a sinuous channel through Moon Pond that includes another small culvert and a significant amount of marsh vegetation. To account for this difference in flow path and provide some level of sensitivity, calculations were performed with a variety of channel lengths and Manning's roughness values to evaluate sensitivity. Manning's roughness parameter, *n*, ranged from a typical value to greater values incorporating channel sinuosity and marsh vegetation. Taking into account a variety of channel widths, lengths, and Manning's *n* values, 18 alternatives were developed for the CEA calculations. Table 1 summarizes the output of the CEA analysis and the alternatives for Manning's $n = 0.05$, where various inlet widths are specified to determine equilibrium cross-sectional area, A_c, corresponding depth, and maximum velocity *Vmax*.

Table 1. CEA Analysis Summary (All depths relative to MSL)

Inlet Width, m											
7.6 m				**15.2 m**				**23 m**			
Length Culvert Only		Length Culvert and Moon Pond		Length Culvert Only		Length Culvert and Moon Pond		Length Culvert Only		Length Culvert and Moon Pond	
Ac, m^2	Depth, m	*Ac*, m^2	Depth, m	*Ac*, m^2	Depth, m	*Ac*, m^2	Depth, m	*Ac*, m^2	Depth, m	*Ac*, m^2	Depth, m
20	2.6	30	3.9	30	1.9	55	3.6	40	1.7	70	3.0
30	3.9	40	5.2	40	2.6	65	4.2	50	2.1	80	3.5
40	5.2	50	6.5	50	3.2	75	4.9	60	2.6	90	4.0
Vmax = 3.5-4.8 m/s		*Vmax* = 2.8 – 3.6 m/s		*Vmax* = 3.0 – 3.8 m/s		*Vmax* = 2.6 – 3.0 m/s		*Vmax* = 2.7 – 3.3 m/s		*Vmax* = 2.3 – 2.5 m/s	

Because the project goal is to restore tidal exchange, thereby increasing salinity through the system and maximizing the total acreage of marsh restored, a larger inlet would logically be assumed to have the maximum benefit. By examining the CEA analysis, this inlet width would also be conducive to minimizing the expected current velocity through the inlet in an effort to mitigate channel scour. Although the CEA tool is somewhat ambiguous in defining the length of the channel for this complex case, it was still capable of providing general inlet configurations and expected velocities to aid in decision making. The stable cross sectional areas ranged from a minimum of 10 m^2 to 380 m^2. These results indicate that the most reasonable inlet width is 23 m, given the anticipated depths and velocities and available property for constructing the inlet.

Sediment Analysis

The purpose of this analysis was to generate a short-term observation of sediment transport quantities near the site. The analysis will give context for the morphology change component of the numerical modeling. Beach profiles were surveyed in January 2010 and repeated in May 2010. Sediment samples were taken at the high, mid, and low water lines along three of the profiles. Sediment is classified as coarse to medium sand D_{50} grain size ranged between 0.56 mm to 0.96 mm. The larger grain sizes were measured at the lower portion of the profile, where fines are concentrated towards the high water mark most likely due to aeolian transport.

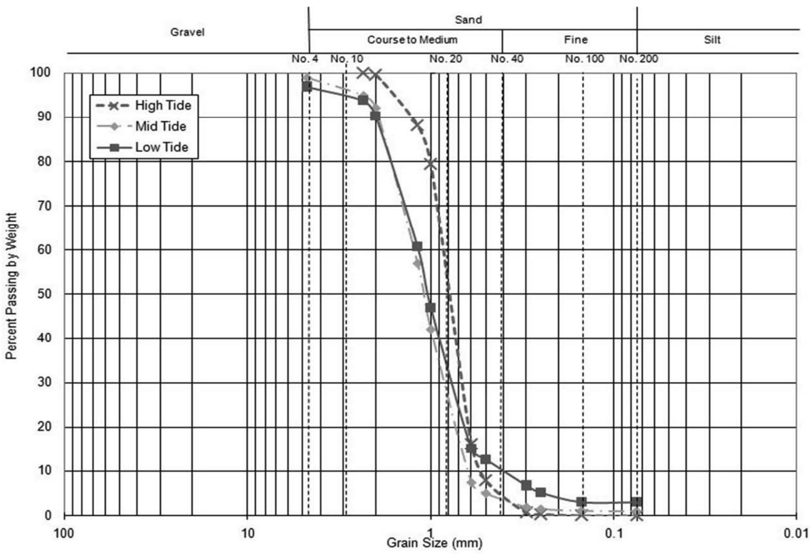

Fig. 3. Grain Size Analysis

A series of low, permeable groins on the updrift and downdrift sides of the culvert exist, but do not seem to interrupt longshore sediment transport because of their deteriorated condition. This observation was corroborated by aerial photography. Net longshore sediment transport is estimated at 11,500 m^3/year in a northerly direction towards the cape hook (personal communication, Dr. Graham Geise, Provincetown Center for Coastal Studies (PCCS), 2009). A post-storm site visit was conducted in January 2009, and the sediment transport had temporarily reversed locally at the culvert. This is typical for Cape Cod Bay as the prevailing winter winds come out of the northwest and the prevailing summer winds are out of the southwest. Since the beach profiles moved from a winter set to a spring set, it was anticipated to observe accretion along the project extent. However, erosion was still observed over the majority of the beach profiles. This observation is limited by the very few number of beach profile survey and the short temporal duration between successive sets. These beach profile surveys should be repeated over a longer period of time before the beach behavior can be captured with greater confidence.

Coastal Modeling System (CMS)

The CMS was applied to further investigate inlet alternatives shown to be viable from the CEA analysis. Use of the CMS model allowed observations of different inlet configurations under a variety of forcing mechanisms including storms as well as observe the changes in sediment transport in the nearshore in response to a new inlet. The CMS analysis seeks to identify the optimum inlet configuration by examining predicted performance (current velocity through the inlet, inlet stability, scour, and system flushing) as well as estimating the possible inlet maintenance and the amount of sediment needed to bypass the inlet.

The CMS is an integrated two-dimensional numerical modeling system for simulating waves, current, water level, sediment transport and morphology change at coastal inlets and entrances as described by CIRP (2010). The CMS is supported within the Surface Water Modeling System (SMS, 2010) and consists of Flow and Wave components which are linked through a steering module. CMS-Flow is a hydrodynamic and sediment transport model that solves the conservative form of the shallow water wave equations. The CMS-Wave component is a spectral wave transformation model that feeds wave information into the Flow model. Quad tree format used for the Flow model was essential to refine the grid to match the existing culvert size while maintaining model efficiency. Cell size ranged between 1 m in the existing culvert and marsh areas to 256 m in the offshore. The grid configuration for both models covers an area of 852 km^2 oriented to match the existing culvert and to minimize possible model instabilities. The quadtree approach to grid generation allows for simultaneously optimizing grid refinement and computational time. Figure 4 shows the grid domain (a, left), and magnified view of the additional grid refinement (b, right) representing the culvert sections of Moon Pond.

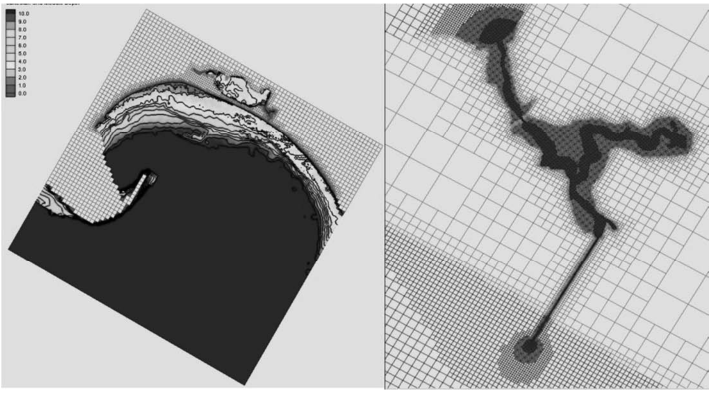

Fig. 4. CMS Grid Doman (a, left), and Moon Pond Quadtree grid (b, right)

CMS Set Up

Field data for the site includes water elevation measurements from Provincetown Harbor, Moon Pond, and Pilgrim Lake, and current speeds at the Moon Pond end of the culvert. Because of lack of wave data, the wave model was forced with wind data from Provincetown. This section of the cape is sheltered and the majority of waves are wind generated. The flow model was driven with tidal constituents developed from the Boston tide gauge. Model duration was one month to include a spring tide over March 2004 to corresponding with available field data.

CMS Model Calibration

To demonstrate that the CMS set up represented the existing conditions before making major changes for different inlet alternatives, the CMS was calibrated to near present-condition field data. A previous study performed in 2005 collected water surface elevations at Provincetown Harbor for approximately 3 months. This data set served for hydrodynamic model calibration, and the relative error is used to express goodness of fit quantitatively. The relative error was computed to be approximately 6%. A degree of error can be attributed to the Boston tidal constituents since the forcing boundary in the grid is located approximately 75 km from the Boston tide gauge location. The depth of the Provincetown gauge was also not available.

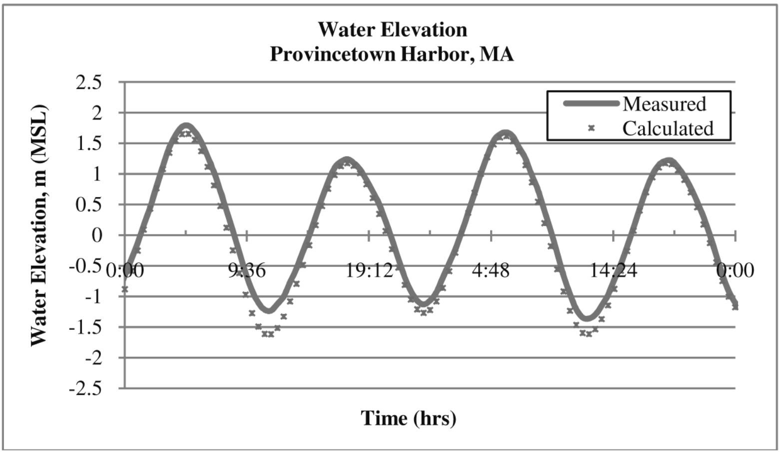

Fig. 5. Water elevation calibration curve, 12 hour snapshot

CMS Modeling Results

The CMS was run for inlet widths of 7.6, 15.2 and 23 m to compare with the CEA analysis. The grid was altered for inlets with jetties whose length corresponds to the existing culvert. An initial depth of 2.5 - 3 m defined the inlet thawleg, which corresponds to the existing depth at the end of the culvert. Sediment transport capabilities were included in the model which allowed the inlet to scour. A Manning's *n* value of 0.05 was used to follow the CEA analysis. Three points along the inlet were used to develop a range of velocities. One output location at the Moon Pond end of the inlet, one at the midpoint and the third at the outlet into Cape Cod Bay. Table 2 details the velocity ranges, depths and cross sectional areas of the inlets at the conclusion of one month model duration.

Table 2. CMS Model Results Summary, One Month Duration (All depths relative to MSL)

Inlet Width, m					
7.6 m		**15.2 m**		**23 m**	
Ac, m^2	Depth, m	Ac, m^2	Depth, m	Ac, m^2	Depth, m
30-68	4-9	46-167	3-11	46 -207	2-9
$Vmax$ = 2.5 – 2.7 m/s		$Vmax$ = 2.3 -2.5 m/s		$Vmax$ = 1.9 – 2.1 m/s	

Current speeds from the CMS are lower than the CEA analysis, but show reasonable correlation. As CEA is a 1D analysis tool, the analysis still provided a baseline for possible inlet configurations given the tide environment. The inputs to the analysis are limited to the tide range, M2 amplitude and the tidal period. The CMS provided more refinement of the analysis to include a broader range of tidal constituents, wave processes, and sediment transport. The inlet depth was determined by specifying a series of cross sections along the length of the inlet. The cross sectional areas of the inlets fall within the stable range provided by the CEA analysis.

Morphology and Sediment Transport

Sediment was allowed to move within the CMS model set up in order to develop preliminary inlet cross sections. A D_{50} of 0.78 mm was used in the model which was determined from sediment samples. As anticipated, all the inlet alternatives scoured along the length of the inlet channel. A horseshoe-shaped ebb shoal formed during the month run, which is skewed towards the northern side of the inlet which corresponds to the observed direction of sediment transport. Volume of this shoal after the one-month simulation is approximately 14,500 m^3. Sediment is also observed to move through Moon Pond to develop a small flood shoal within Pilgrim Lake, which has a volume of 870 m^3. Modeled sediment transport rates and direction compare well with observed, which indicates that wind-generated waves are being generated correctly within the wave model.

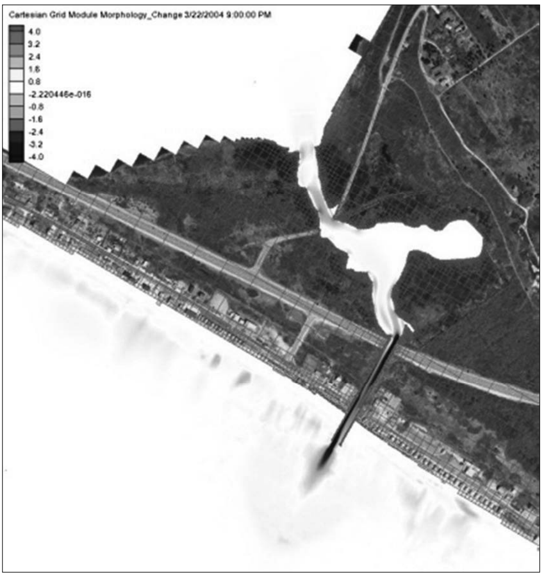

Fig. 6. Morphology change for 15.2 m wide inlet alternative

Conclusions

The CEA analysis indicated that a 23-m wide inlet with an approximate depth of 2 m is the most reasonable inlet for the area as judged by the velocity through the inlet and practicality of construction. This inlet configuration was determined by iteratively examination of a variety of inlet widths, lengths, and roughness parameters in response to the tide range. However, it should be noted that as the velocity of current through the inlet increases, the depth of the channel could scour to as much as 9-m depth for the 23-m inlet width. The CMS model added to this analysis by refining current speeds in the different inlet alternatives taking into account additional forcing mechanisms as well as observing morphologic responses to inlet alternatives. The CMS modeling further refined and reinforced the assessment that the 23-m wide inlet is the most reasonable inlet dimension given the available property in which to site the inlet.

Future Analysis

Next steps in this study include a more thorough quantification of the shoreline response to the different inlet configurations, addressing scour concerns, and observations of shoreline response to storms. The CMS will also be run for longer durations to observe seasonality changes and longer term morphologic response.

Acknowledgements

We would like to acknowledge the data contributions of the Provincetown Center for Coastal Studies (PCCS) and Graham Giese, National Park Service and local sponsors. The authors would also like to thank Dr. Nicholas Kraus who provided insightful review and continues to inspire. The second author was supported by the Dredging Operations Technical Support (DOTS) and Coastal Inlets Research Programs at the U.S. Army Corps of Engineers, Engineer Research and Development Center. Permission was granted by Headquarters, USACE, to publish this information.

References

Escoffier, F. F. (1940) "The Stability of Tidal Inlets," *Shore and Beac*h,Vol. VIII, No. 4, 114-115.

Headquarters, U.S. Army Corps of Engineers (USACE). (1868). "*Provincetown Harbor, Massachusetts,"* Annual Report of the Secretary of War: Appendix RS. 828-829 p.

Coastal Inlets Research Program (CIRP) USACE. (2010) CMS Wiki. Last accessed on 11 November 2010. http://cirp.usace.army.mil/wiki/CMS

Dean, R. G., and Dalrymple, R. A., (2002) "Coastal Processes with Engineering Applications," Cambridge University Press, 475 p.

Kraus, N. C. (1998). "Inlet cross-sectional area calculated by process-based model."*Proceedings 26th Coastal Engineering Conference*, ASCE, Vol. 3, 3,265-3,278.

Kraus, N.C. (2006). "Coastal inlet functional design: anticipating morphologic response," *Proceedings Coastal Dynamics '05*, ASCE Press, 13 pp.

NOAA Fisheries Office of Habitat Conservation. (2006). "East Harbor Estuarine Restoration Project." http://seahorse2.nmfs.noaa.gov/hcrcdb_app/class/rcdb_abstracts.jsp? PROJECT_ID=1162. Last updated 31 July 2006, accessed 26 January 2010.

O'Brien, M. P., (1976)"*Notes on Tidal Inlets on Sandy Shores,*" U.S. Army Coastal Engineering Research Center, GITI Report 5, 27 p.

Office of Geographic and Environmental Information (MassGIS) (2003). Commonwealth of Massachusetts Executive Office of Environmental Affairs.

Portnoy, J., Smith, S., Gwilliam, E., and Chapman, K. (2006). "Annual Report on Estuarine Restoration at East Harbor (Truro, MA), Cape Cod National Seashore," *Cape Cod National Seashore*, 48 p.

Thelen, B. A., Thiet, R.K. (2008). "Molluscan Community Recovery Following Partial Tidal Restoration of a New England Estuary, U.S.A," *Restoration Ecology* 17(5): 695-703.

Seabergh, W.C., and Kraus, N.C. (1997). "PC program for coastal inlet stability analysis using Escoffier method," Coastal Engineering Technical Note CETN IV-11, U.S. Army Engineer Research and Development Center, Vicksburg, MS, 7 p.

Surface Water Modeling System (SMS) USACE (2010) http://chl.erdc.usace.army.mil/sms Last Accessed on 3 December 2010.

Spaulding, M. (2005). "*Hydrodynamic Assessment of Estuarine Restoration of Pilgrim Lake, Moon Pond and Salt Meadow, Truro, Massachusetts*." University of Rhode Island, Ocean Engineering Department, Narragansett, RI.