Center for Coastal Studies Provincetown

ADMINISTRATIVE OFFICES
115 Bradford Street
Provincetown, MA 02657
tel (508) 487-3622 fax (508) 487-4495

HIEBERT MARINE LABORATORY
5 Holway Avenue
Provincetown, MA 02657
tel (508) 487-3623 fax (508) 487-4695

Assessment of the Century Scale Sediment Budget for the Sandwich and Barnstable Coasts of Cape Cod Bay: Cape Cod Canal to Barnstable Harbor

A Report Submitted to the Towns of Barnstable and Sandwich

Mark Borrelli
Graham S. Giese
Stephen T. Mague
Theresa L. Smith
Bryan Legare
Patrick Barger

Center for Coastal Studies
Provincetown

July 2016

EXECUTIVE SUMMARY

The Center for Coastal Studies (CCS) developed a quantitative, century-scale sediment budget for the Towns of Sandwich and Barnstable along 16.5 miles of shoreline from the Cape Cod Canal to Nobscusset Point in Dennis. Sediment budgets document the direction and volume of sediment movement as well as the sources and sinks of sediment in the nearshore zone. Sediment budgets can be used by coastal mangers to better understand coastal evolution in general and inform decisions about the impacts associated with altering the nearshore zone with coastal engineering structures, beach replenishment projects and other related activities.

Historical and contemporary three-dimensional surface models were developed for this project. Volumetric changes between these surfaces were used to generate the sediment budget and document other phenomena. Data from the 1930-40s and from 2010-11 were used to produce the historical and contemporary surfaces respectively. Preliminary analysis suggested sediment deposition was occurring seaward of ‘wave base’, the depth at which waves begin to interact with the seafloor. Under such a scenario, material deposited beyond wave base would be lost to the nearshore system and of concern along an eroding shoreline such as the Sandwich/Barnstable coast. In order to address this important question vessel-based acoustic data were collected in April/May of 2016 beyond the areas covered by the contemporary data and an older dataset from 1860 was also included in the analysis to provide greater historical context.

The commonly held belief that the jetty is preventing sediment from bypassing the Canal is not true. Ongoing accretion at the shoreline is evidence that some sediment is being captured by the jetty, however bypass is occurring at depth at the seaward end of the jetty. In fact, the jetty was being bypassed as early as 1940 and perhaps earlier. Our findings show that sediment appears to be deposited at depths between 15-20 m in Cape Cod Bay perhaps as a result of rapid, flood tidal currents flowing eastward out of the Canal and into the bay. These currents entrain sediment that has bypassed the jetty west of the Canal and subsequently transported to depths well beyond wave base. If so, this material is effectively lost to the nearshore system, representing a sink for this littoral cell.

Findings of the sediment budget analysis also suggest that the net movement of material in and around Town Neck Beach is westward toward the Canal. This material would also likely be lost to the system after being entrained in the flood tidal flow of the Canal. Although this study was designed to develop a sediment budget for the study area, based upon the work conducted and the unexpected findings additional work should be pursued to address newly identified questions that may have significant implications for the characterization of littoral cells proximate to the Canal.

INTRODUCTION

In 2005 the Center for Coastal Studies (CCS) began developing and evaluating a sediment budget-based geomorphic model to determine long-term volumetric coastal change and longshore sediment transport along outer Cape Cod (Giese, et al., 2011). The methodology developed as part of this work was subsequently applied to the Cape Cod Bay coast, and between 2012 and 2015 CCS completed work on assessments of the coastal sediment budget between Long Point and Macmillan Wharf in Provincetown Harbor; between Macmillan Wharf and Jeremy Point in Wellfleet and between Nobscusset Point in Dennis and Rock Harbor on the Orleans/Eastham town line. These studies demonstrated that comparisons of contemporary bathymetric and terrestrial lidar with high quality 1930s/40s hydrographic and topographic data along evenly spaced cross-shore transects provide an effective means of estimating century-scale sediment budgets along Cape Cod Bay's sandy shores. The results of these assessments were documented in five technical reports funded by the Island Foundation (IF) (Giese et al., 2012; Giese, Borrelli, Mague and Hughes, 2013) the Massachusetts Bays Program (MBP) (Giese et al., 2014);and most recently the Massachusetts Office of Coastal Zone Management (CZM) for the Towns of Provincetown and Brewster (Giese et al., 2015a, b).

As shown in Figure 1, the present study conducted for the Towns of Sandwich and Barnstable, and funded by the Coastal Resiliency Grants Program of the Massachusetts Office of Coastal Zone Management (CZM), extends east from the Cape Cod Canal area of Sandwich to the Nobscusset Point/Chapin Beach area of East Dennis. While the focus of this work is the Sandwich-Barnstable shoreline, it was necessary to extend the analysis slightly to the west of the Canal and east to Nobscusset Point, as denoted by the transects, in order to develop a preliminary sediment budget and link this analysis to that done for the Brewster shoreline.

In addition to this alongshore expansion of the scope, further temporal and spatial expansions were necessary to help understand the potential effects of the Canal on alongshore sediment movement. First, U.S. Coast Survey hydrographic data from 1860 was analyzed to characterize pre-Canal, alongshore sediment movement. Second, as a result of initial transect plots indicating that cross shore sediment movement extended seaward of the 10-meter contour and available bathymetric lidar, three additional days of vessel-based surveys were conducted out to depths of approximately 15 -20 meters in the area of the Canal and the entrance to Barnstable Harbor (Figure 1). Notwithstanding the future need to expand the geographic scope, the results of this study provide a quantitative assessment of sediment transport and budget for 26.5 km (16.5 miles) of the southerly Cape Cod Bay coast. As with previous studies, this information provides the basis for understanding the historical conditions that contributed to the present position, shape and orientation of the coastline and will contribute to understanding and estimating future shoreline changes. Accordingly, these data can be used to reduce the vulnerability of communities and ecological systems to the impacts of a changing climate and rising sea levels.

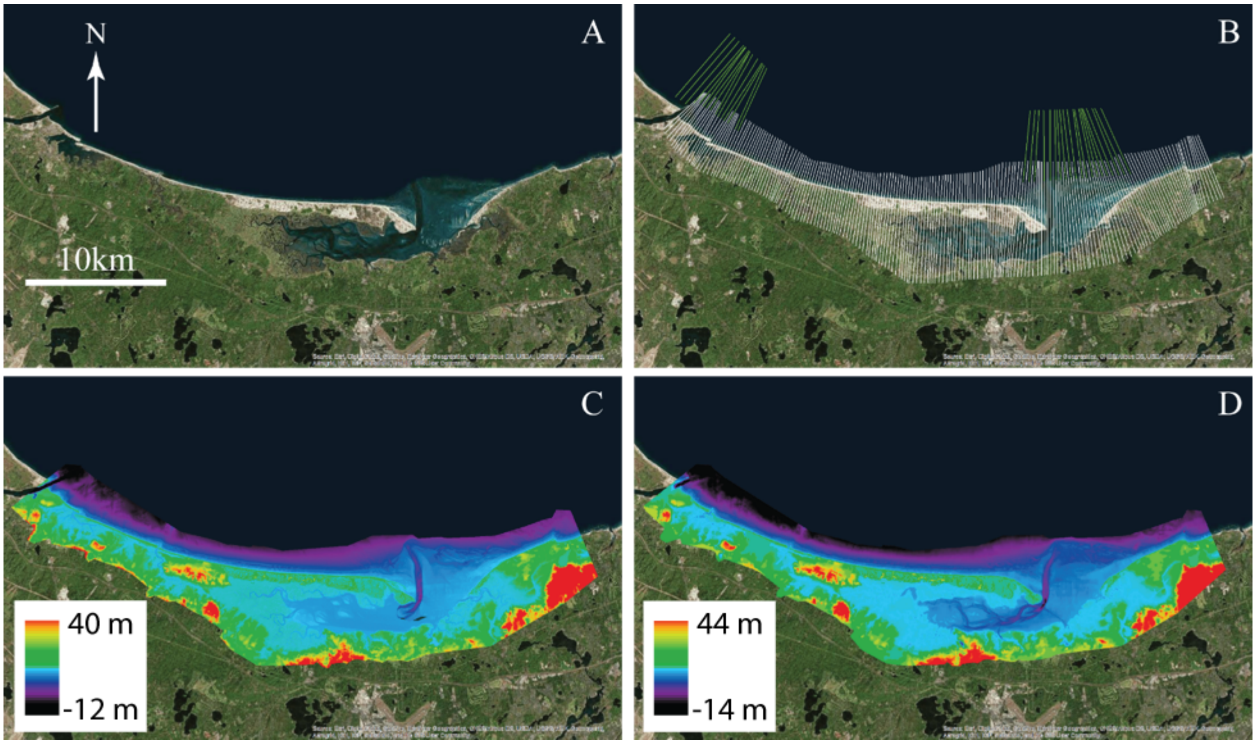

Figure 1: A) Study Area. B) Study area with transects. White transects were developed for this study to extract data from contemporary and historical surfaces. Green transects extending beyond the estimated preliminary wave base were data collected over three vessel-based surveys after initial analysis suggested significant deposition beyond extent of lidar. C) Historical surface (1930-40). D) Contemporary surface (2010-11).

METHODS

As discussed above, the present study represents a continuation of work by CCS to develop a century-scale sediment budget for Cape Cod Bay. The completion of this work represents a significant step towards quantifying the longshore sediment transport processes and "littoral cells" for the entire shore of Cape Cod Bay discussed and described qualitatively by Berman (2011). In addition, it identifies several unanswered questions for further study such as the depth of sediment movement in Cape Cod Bay and the effect of the Cape Cod Canal on the south shore sediment budget. The geomorphic model used in this work has been discussed in Giese et al. (2011) and is repeated here as the framework for presenting the project's historical data compilation and processing.

Theoretical Model Framework

The sediment budget-based geomorphic model applied to the Cape Cod Bay coast is based on the conservation of mass, coastal wave mechanics, and the coastal morphodynamic concept of transport within littoral cells. It can be used to quantify the longshore sediment transport rates and to estimate local sediment sources and sinks and the boundaries between littoral cells. The model depends upon two fundamental principles: 1) the smooth, regular form of most exposed sandy coasts is primarily the product of wave action and 2) waves striking the coast at an angle produce a flow of sediment along the shore in the direction of wave travel.

The net flow of sediment along the coast over an extended time period, generally annualized, is termed *littoral drift* or (*net*) *longshore sediment transport*. This transport is quantified in the model as a vector, ***Q,*** the volume rate (e.g., cubic meters per year) of sediment crossing a shore-perpendicular transect. ***Q*** has a positive value when sediment flow is along shore to the right (+x direction) when viewed from offshore. Negative Q values indicate flow to the left (-y direction). Transects extend across the active coast from the landward limit of wave-produced sediment transport to a depth representing the assumed offshore limit of sediment movement.

Coastal erosion and deposition do not depend directly on the magnitude of ***Q***, but rather on its rate of change alongshore, $d\boldsymbol{Q}/dy$ (cubic meters per meter per year), that is, the slope of ***Q*** when it is plotted against alongshore distance, "y". Erosion results when transport, ***Q***, increases alongshore (i.e., $d\boldsymbol{Q}/dy$ is positive); deposition results when ***Q*** decreases alongshore (negative $d\boldsymbol{Q}/dy$). This relationship can be expressed explicitly as:

$$dA/dt = - d\boldsymbol{Q}/dy$$

where "dA/dt" (square meters per year) is the time ("t") rate of change in cross-sectional area ("A") between two cross-shore transects for different points in time at a single location.

In addition to the role of sediment transport change along the shore, a shore-perpendicular transect typically loses (or gains) area due to (*net) cross-shore transport* of sediment such as wind-transported sand exchange between a beach and coastal dunes, tidal inlet losses, or offshore transport of very fine sediment by turbulent seas during storms. These gains or losses are designated by ***q***, defined as the net cross-shore transport per unit shoreline distance (square meters per year). The change in cross-sectional area at any point along the shore depends upon the total contributions of longshore and cross-shore sediment transport at that location:

$$dA/dt = - d\boldsymbol{Q}/dy - \boldsymbol{q}.$$

To simplify this relationship, we introduce the symbol, ***E,*** to represent the negative of "dA/dt", the volume rate of coastal change per unit shoreline distance, i.e., erosion. Substituting, this gives

$$\boldsymbol{E} = d\boldsymbol{Q}/dy + \boldsymbol{q}.$$

Application of this expression along a coastal segment enables a volumetric analysis of shoreline change, a 3-dimensional estimate of change as opposed to the more common 2-dimensional view derived from a linear analysis of shoreline advance or retreat. If the segment is sufficiently large to contain an entire littoral cell including all source regions, transportation paths, and sinks, then integration of d***Q***/dy will yield the total values of ***Q*** at each point along the shore. At the updrift and downdrift cell boundaries are points where ***Q*** equals zero; these are termed "null points" (Dean and Dalrymple, 2002), and their location is required for a meaningful evaluation of ***Q*** at other locations.

Cell boundaries, or null points in net longshore sediment transport, can be located by considering the implication of our initial assumption that net longshore sediment transport results from waves striking the coast at an angle, thereby producing a flow of sediment along the shore in the direction of wave travel. When referring to the long-term sediment flow at any particular coastal location (as we are in this study), the actual waves concerned are the composite of all waves that acted on that shore over the entire time period of the study. We replace those "actual" waves with a single "model" wave which, acting continually over that time period, would have produced the same net sediment flow. Thus, the littoral cell boundaries (null points) are located at those locations where the model waves approach onshore in a direction that is at right angles to the shoreline, i.e., the angle, "θ", between wave approach and a line drawn perpendicular to the shore is zero.

This specific relationship between longshore sediment transport, ***Q***, and wave angle, "θ", is consistent with the general expression between the two (e.g., Komar, 1998):

$$\boldsymbol{Q} \sim \sin 2\,\theta.$$

At the null point, "θ = 0". Since the derivative of "sin 2 θ" is proportional to "cos 2 θ", it follows that

$$d\boldsymbol{Q}/dy \sim \cos 2\,\theta.$$

Thus d***Q***/dy is maximum at the null point (θ = 0).

Model Adjustment

Numerical integration of d***Q***/dy to calculate ***Q*** is valid when the transects are approximately perpendicular to the coastline and parallel to each other (Figure 1). For this study, ***Q*** was also calculated by summing Δ***Q*** values derived individually for each pair of transects. Δ***Q***, in turn, is the annualized change in volume between transect pairs - found from (1) the vertical change between profiles along each 1934/40 - 2010/11 transect pair and (2) the horizontal distances separating them - reduced by the volume lost due to cross-shore processes at each transect pair segment of the study area. Details are provided below in "Transect Construction, Volumetric Analysis and Sediment Flow Calculation."

Historical Data Compilation and Processing

Data Sources

Based on previous work of CCS in Cape Cod Bay, the historical base map for the current study was developed from hydrographic and terrestrial data sets compiled for the period 1933 – 1940. For this study, U.S. Coast & Geodetic Survey (USC&GS - predecessor to NOAA's National Ocean Service) survey data consists of three hydrographic surveys conducted in eastern Cape Cod Bay in 1933 and 1934 and three conducted in the western parts of the Bay during 1940 (Figure 2). These surveys were combined with topographic survey information for the same time period to provide a relatively seamless, synoptic coverage of the entire Cape Cod Bay study area.

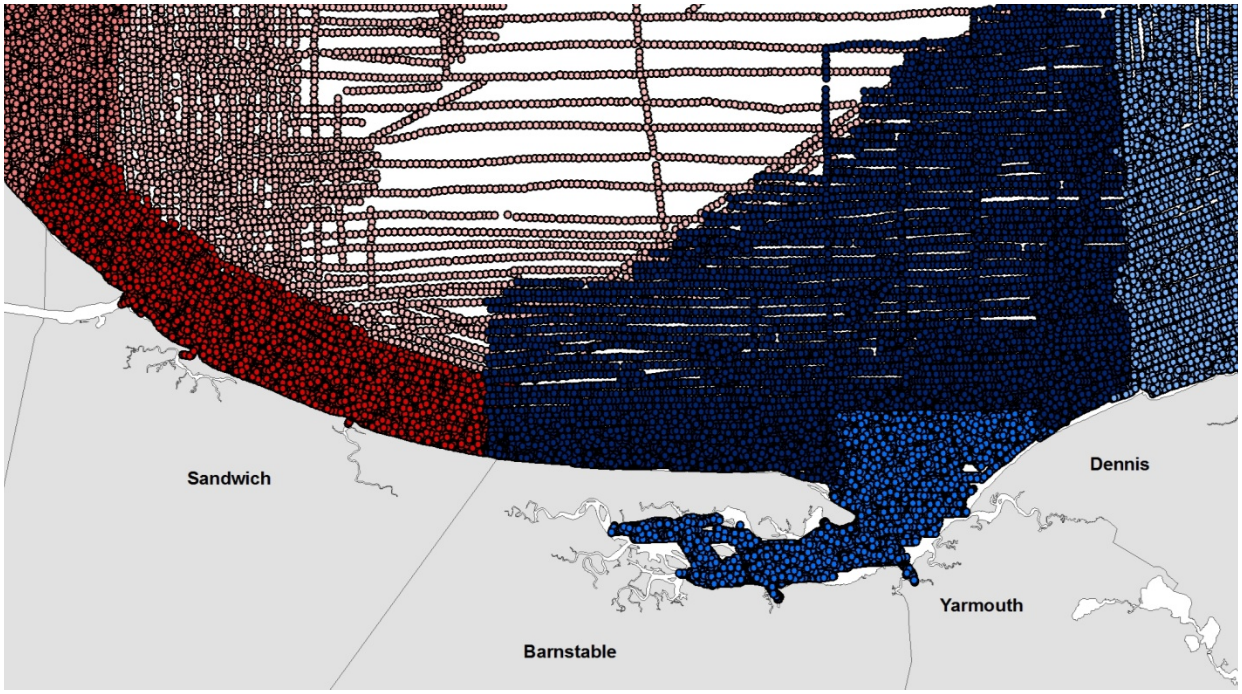

Figure 2: NOAA Hydrographic Survey Point Coverage for Cape Cod Bay, Massachusetts (Red shades denote 1940 surveys. Blue shades denote 1933-34 surveys).

Historical hydrographic survey data were downloaded from the NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html), including Descriptive Reports, color image Hydrographic Smooth Sheets (H-Sheets), digital point data in ASCII XYZ format, and metadata. Original survey data were compiled at scales of 1:10,000 (or in some cases 1:5,000) and related horizontally to the North American Datum of 1927 (NAD27), or its predecessor, the North American Datum (NAD), and vertically to local mean low water (MLW) for the geographic area covered by each survey.

The historical terrestrial data incorporated into the historical base map was limited to the active coast or terrestrial area influenced by marine and coastal processes including wave-produced sediment movement, wind-transported sand exchange between beaches and coastal dunes, tidal inlet losses, etc. This data was derived from USC&GS 1933 and 1938 T-sheets, U.S. Geological

Survey (USGS) quadrangles surveyed between 1932-1940, and 1938 aerial photographs obtained from the U.S. Department of Agriculture – Natural Resources Conservation Service (USDA-NRCS). These photographs were flown on November 21, 1938 after the Hurricane of 1938, near the time of local high water and were used to help identify landforms such as coastal banks and dunes and to verify changes to the terrestrial environment resulting from the recent hurricane.

USC&GS T-sheets for the study area (and accompanying Descriptive Reports) were downloaded as non-georeferenced survey scans from the NOAA NOS Special Project web site at http://nosimagery.noaa.gov/images/shoreline_surveys/survey_scans/NOAA_Shoreline_Survey_Scans.html. Non-georeferenced scans of USGS historical quadrangles were downloaded from the University of New Hampshire at http://docs.unh.edu/nhtopos/nhtopos.html.

The USGS topographic work provides the basis for broad, synoptic coverage of topographic conditions existing at the time of the survey. In addition to limiting the inland extent of the study to the active zone, information derived from each Quadrangle was supplemented with the following data to minimize uncertainties associated primarily with the compilation or mapping scale.

1) USC&GS T- and H-Sheet Descriptive Reports.
2) The elevations of the mean low water (MLW) and mean high water (MHW) lines obtained from the 1930s/40s Coast Survey T- and H-sheets.
3) Profiles obtained from contemporary survey work to characterize representative beach and bluff profiles.
4) The location of natural features shown on historical T-Sheets, H-sheets, and aerial photographs such as the toe of coastal banks, the edges of salt marshes, and their estimated elevations with respect to MHW and MLW. (Ayers, 1959; Redfield, 1972; Van Heteren & Plassche, 1997; and Giese 2012).
5) The elevations of physical features such as road intersections, railroad centerlines, building corners, etc., common to both historical and contemporary data sets and not likely to have changed over time.

Elevation data from these supplemental sources were incorporated into the historical data set derived from USGS topographic information to increase the reliability and density of the limited landside topography used in the analysis.

Data Compilation

As discussed above, comparisons of historical and contemporary hydrographic and topographic datasets can be important sources of information for quantifying changes in landform volume and net sediment movement. Where the land and sea interact along the sandy shores of Cape Cod, such volumetric comparisons can be used to estimate long-term, regional scale sediment flux and sediment budgets. As discussed further below, to effectively use historical geospatial data, such as those central to the methodology discussed above, however, potential sources of uncertainty inherent in data collection methods must be minimized and accounted for to ensure that quantitative estimates provide reliable information at the scale of the analysis (Byrnes et al., 2002).

For this study, all contemporary data is referenced horizontally to the Massachusetts State Plane Coordinate System (North American Datum of 1983 (NAD83)) and vertically to the North American Vertical Datum of 1988 (NAVD88)). Original historical data were referenced horizontally to the North American Datum of 1927 (NAD27) or its predecessor datum the North American Datum (NAD) and vertically to local tidal datums (either Mean Low Water (MLW) for the hydrographic surveys or Mean Sea level (MSL) for the USGS quadrangles. All datasets must, therefore, be translated to the project datums in order to provide a direct comparison of historical and contemporary points extracted to calculate dA/dt along each transect.

The original horizontal reference system for three USC&GS hydrographic data sets (H5543, H5588, and H5589) used to create the easterly section of the historical base map was the North American Datum of 1927 (NAD27). The mathematical process for translating horizontally from NAD27 to NAD83 is well established (Giese and Adams, 2007). Two additional USC&GS hydrographic surveys (H6561 and H6563) necessary to extend this study west to the Canal were referenced to the North American Datum (NAD). The conversion from this short-lived datum to NAD83 required additional steps, including archival research to identify survey control points and associated coordinate values, the development of a localized mathematical relationship between NAD and NAD83, and finally the conversion of the entire soundings data set to the project's horizontal datum.

The process for developing an accurate vertical translation from multiple local tidal datums used as the plane of reference for the hydrographic surveys to NAVD88 required research to retrace the historical survey office and field work. As discussed more fully below, when recoverable, a significant source of uncertainty associated with historical hydrographic surveys can be minimized by reoccupying reference stations or benchmarks established to memorialize the plane of reference. In the absence of recoverable reference points the short term nature of the tidal observations, inter-annual variations in tidal cycles, rising sea levels, and changing environmental conditions make development of reliable translations of local, historical vertical reference systems to contemporary systems problematic and can greatly increase the uncertainty associated with quantitative comparisons (Jakobsson et al., 2005; Van der Wal and Pye, 2003). This can be particularly true for volumetric change analyses where rising sea levels can introduce a significant bias towards erosion when the original plane of reference must be estimated using general assumptions of relative sea level rise and short-term tidal records.

To minimize this potential source of uncertainty, all historical data points were translated vertically based on research, recovery, and reoccupation of historical tidal benchmarks identified in the 1930s and 1940s Hydrographic Descriptive Reports. Beginning in the late 19th century, the reports were prepared by the USC&GS at the conclusion of each survey mission, and among other things describe the plane of reference and one or more benchmarks to which this plane was referenced. Where benchmarks can be recovered, they can be occupied with high accuracy GPS survey equipment to provide a direct translation to NAVD88. When USC&GS tidal benchmarks have been destroyed, the historical record can be further investigated to establish relationships between other extant benchmarks that can be recovered and occupied. These relationships can be used to determine the elevation of the tidal benchmark and the relationship of the data set to NAVD88 (Mague, 2012).

Benchmarks established in the late 19th century through the mid-20th century have been recovered and occupied to relate historical data sets to NAVD88 for the Center's work along the Outer and Cape Cod Bay shores. (Giese et al., 2012; Giese, Borrelli, Mague and Hughes, 2013; Giese et al., 2015a, b; Giese, Borrelli, Mague, Smith, et al., 2013; Giese et al., 2014). The present study relied on field work conducted on Sandy Neck in May of 2014 to recover Tidal Benchmark 1 set by the United States Coast & Geodetic Survey in 1934 (TBM 1 of 1934). This tidal benchmark was occupied with the Center's Real-Time Kinematic (RTK) GPS equipment and the survey results used to relate hydrographic survey data sets H5543, H5588, and H5589 to NAVD88. Conducted as part of the Brewster project (Giese et al., 2015a), the relationship between local mean low water of 1934 and NAVD88 is shown on Figure 4.

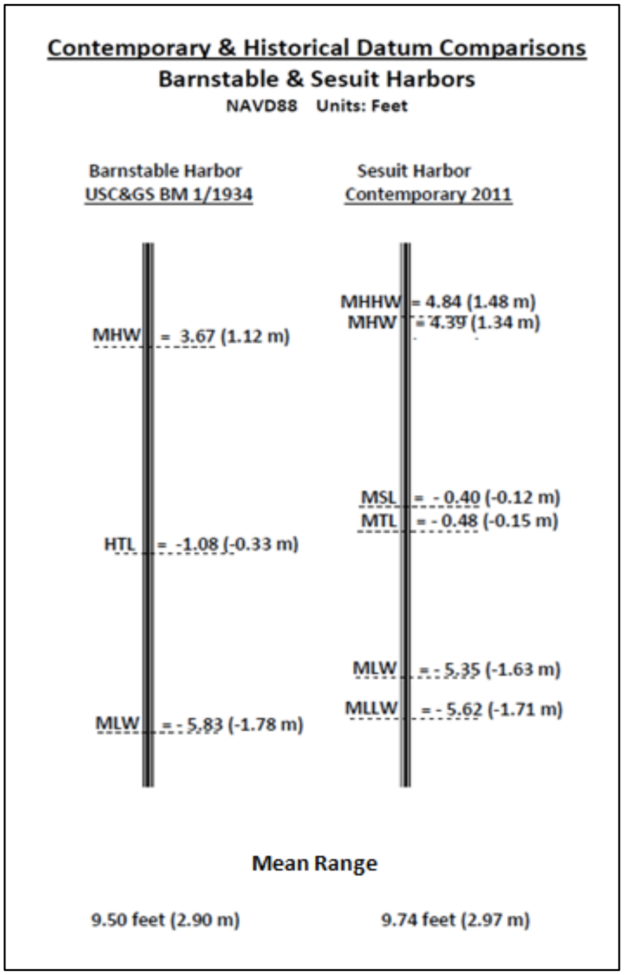

Figure 4. Contemporary and Historical Datum Comparisons for Easterly portions of the study area. Units: Feet (meters)

Descriptive Reports for H6561 and H6563 were reviewed for information about benchmarks used to memorialize the local mean low water datum to which additional 1940s hydrographic work necessary for this study was referenced. These reports noted that the vertical plane of reference for both surveys was:

> …mean low water reading -0.1 feet on [the] tide staff at [the] Cape Cod Canal, East Entrance (gage maintained by U.S. Engineers), 16.7 feet below [tidal] B.M. "Breakwater" [TBM Breakwater]…[The] height of [the] mean high water above [the] plane of reference [the mean range] is 9.4 feet.

A review of various benchmark resources (Cole, 1929; USC&GS, 1938) and conversations with the Survey Division of the US Army Corps of Engineers provided no further description of this benchmark (TBM-Breakwater).

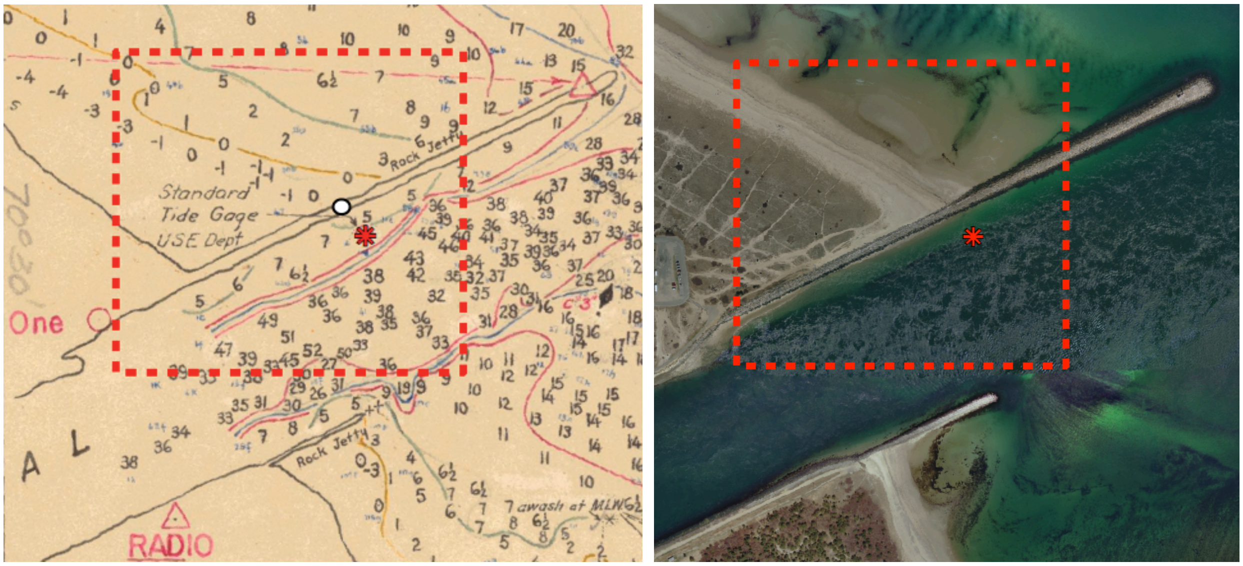

Figure 5. Left image taken from USC&GS, 1940 smooth sheet H-6563 showing location of United States Engineers Tide Gauge (red asterisk) and the initial estimate for the location for the tidal benchmark (white circle). Right image shows 2014 Orthophoto and the likely location of the tide gage.

Figure 5 shows a portion of smooth sheet H6563 showing the location of the tide gage used to establish the plane of reference and tidal reductions for the 1940s surveys. Based on past experience most tide gages or stations used in hydrographic surveys have been observed to be referenced to at least one benchmark (usually a minimum of three), within sight of the tide station. Based on this assumption, and observing the location of the tide station shown on H6563, TBM-Breakwater was assumed to be located on northerly jetty, near the gauge (Figure 5). Using the project GIS to obtain the

Figure 6: Left: US Engineering Department disk found in granite boulder located at the westerly end of the Cape Cod Canal north jetty. Right: Disk shaft and lead plug inserted into granite boulder in the jetty opposite the location of the 1940s US Engineering Department tide gauge.

coordinates of the former tide station, field reconnaissance was conducted on October 11, 2015 to recover TBM-Breakwater. During the site visit, a U.S. Engineering (USE) survey disk (Figure 6) was recovered at the westerly end of the north jetty. Using a handheld GPS, the reconnaissance proceeded east along the top of the jetty to a point opposite the location of the former tide station. While no disk, such as that discovered at the westerly end was present, a lead plug and disk shaft were observed in one of the granite stones of the breakwater. As shown in Figure 6, a circle worn into the stone from a former disk is clearly visible surrounding the shaft.

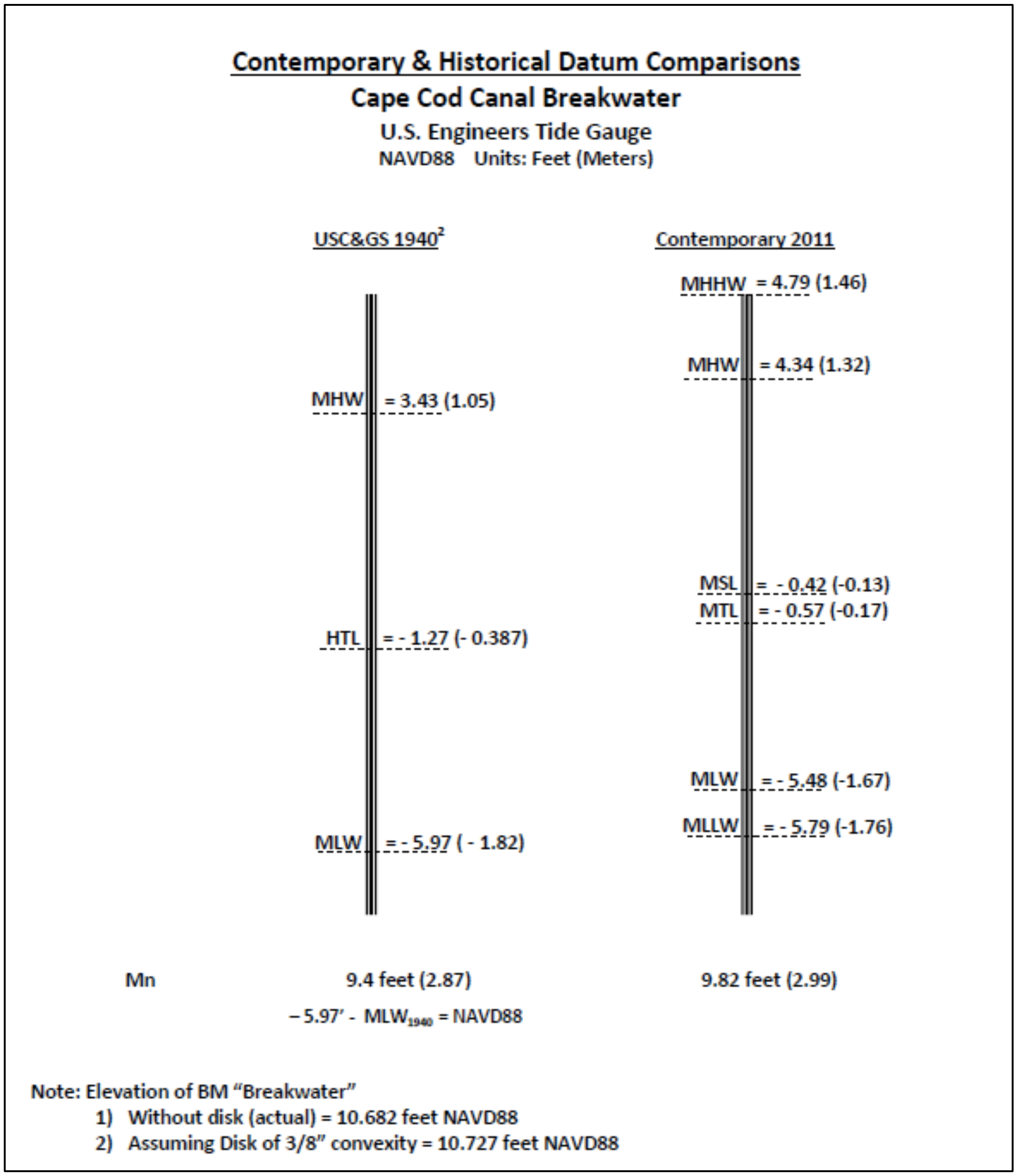

Figure 7: Contemporary and Historical Datum Comparisons for Westerly portions of the study area. Units: Feet (meters).

The potential benchmark was occupied with the RTK-GPS and the results of this fieldwork, when compared with the tidal elevations of previous recovery surveys for the Provincetown and

Brewster studies strongly support the conclusion that this was the location of TBM-Breakwater. The elevation of this point (10.682' NAVD88) was used to develop the relationship between the vertical plane of reference for surveys H6561 and H6563 and NAVD88 (Figure 7) and to convert the soundings data of hydrographic surveys H6561 and H6563.

Over 80,000 soundings from the five survey missions were translated horizontally to NAD83 and vertically to NAVD88. When compiled into one commonly referenced data set, the information provided by the soundings results in quantitative 80-year old data that covers an area of Cape Cod Bay in excess of 1800 km^2 (420 mi^2). Significantly, half of these soundings (42,305) were located in the 303 km^2 (117 mi^2) nearshore area of this study, providing a valuable and reliable record upon which to apply this sediment budget-based geomorphic model approach of this study.

After establishing the 1930s/40s vertical datum relationships, historical terrestrial contours from the USGS Quadrangles were digitized and supplemented with physiographic data derived from USC&GS T- and H-sheets. All data points were translated horizontally (NAD27 to NAD83) and vertically (ca. 1940 local MSL to NAVD88) and combined into the comprehensive point file used to create the 1930s/40s three-dimensional surface, or surface model. This surface model formed the basis for quantitative comparisons with a similar surface derived from U.S. Army Corps of Engineers 2010 bathymetric lidar data, 2011 USDA-NRCS terrestrial lidar data and CCS's 2016 vessel-based acoustic surveys.

Historical 1930s/40s Surface Model

With the conversion of the historical data to the project datums, a 3-dimensional model of the historical surface was developed from the comprehensive, digital point database used to create a point shapefile within the ArcGIS v10.x software suite. These points were then converted into a Triangulated Irregular Network (TIN) using the 3-D analyst extension within ArcGIS. These triangles are formed using 3D data from three points to create a plane that represents a real-world surface. The TIN was then converted into a raster with latitude (y), longitude(x), and elevation (z) attributes. A krigging method was chosen as the best interpolation method for this study and utilized to represent changes in natural topography and/or bathymetry. Before finalizing the surface model, CCS coastal geologists reviewed the surface to identify potential data issues as well as to remove outliers from the final transects used to develop the sediment budget. This was found to be a critical step in previous studies to ensure that a processes-based assessment is conducted prior to accepting or rejecting points within the surface and proceeding with the analysis.

Contemporary Data and Surface Models

Contemporary surface models for the study area were compiled from two data sets of terrestrial and bathymetric lidar. The terrestrial lidar was flown in the spring of 2011 by the U.S.

Department of Agriculture's Natural Resources Conservation Services. The bathymetric survey was flown in May of 2010 by the U.S. Army Corps of Engineers. As part of its QA/QC program, representative areas of terrestrial lidar data were tested and confirmed with values using data collected with the Center's GPS equipment. The 2010 had horizontal and vertical uncertainties of 0.5 m and 0.15 m, respectively. The 2011 lidar had horizontal and vertical uncertainties of 0.5 m and 0.07 m, respectively.

Acoustic data were acquired by CCS in areas without bathymetric lidar coverage (Figure 1) using a Tritech PA500/6-S altimeter side-mounted to the R/V Shackleton in late April and early May 2016. The data were processed using Hypack 2014 software and appended to the transect data set within ArcGIS. The acoustic data were also collected in areas that overlapped the bathymetric lidar. QA/QC included the comparison of the overlapping 2016 acoustic data with the 2010 lidar data in order to test for gross offsets. The RTK-GPS unit was mounted onto the same pole as the altimeter to reduce offsets and sources of uncertainty. The altimeter has a resolution of 1 mm and is accurate to ~0.5% of water depth.

Accounting for Uncertainty

Comparisons of historical and contemporary data can form the basis for assessing and quantifying changes to a variety of terrestrial and coastal landforms. To discuss the significance of these changes, however, the results of such comparisons must be considered in the context of the uncertainties of the underlying historical spatial data (Mague, 2012). For this reason, when spatial data from different time periods is compared to quantify coastal change, estimates of the uncertainty associated with the acquisition and processing of the underlying data ensure that study conclusions are considered at appropriate scales - e.g., regional v. site-specific (Byrnes et al., 2002).

For both contemporary and historical hydrographic surveys, the accuracy of the final data product is related directly to the error associated with obtaining measurements. Measurement error, defined as the difference between the measured value and the true value, can be blatant (human error), systematic, and/or random (Byrnes & Hiland, 1994a; Jakobsson et al., 2005). Recognizing that the true value (and, therefore, the true error) can never be known, accuracy is increasingly being characterized in terms of uncertainty or error budgets based on an analysis of residuals (IHO, 2008). When considering hydrographic or bathymetric surveys these budgets must consider not only the uncertainty associated with horizontal (*x, y*) positioning but that associated with measurement of elevations (*z*).

The primary sources of potential error associated with two-dimensional analyses, such as shoreline change, where highly accurate contemporary data is compared with historical surveys are well-documented (e.g., Anders and Byrnes, 1991; Byrnes and Hiland, 1994a and b; BSC, 2007; Crowell et al., 1991; Ruggerio et al., 2003; and Shallowitz, 1964). These uncertainties typically derive from the random and systematic error associated with equipment and measurement methods used in the field survey, the plotting of data to produce a cartographic product, the registration of historical work to a contemporary datum, and the process of digitizing historical data. For the U.S. Coast Survey (and its successor agencies the U.S. Coast and Geodetic Survey (USC&GS) and NOAA's National Ocean Service) horizontal positioning errors associated with archived topographic surveys (T-sheets) have been found to range between 8 and 10 meters with accuracy limited largely by mapping scale and not based on the document age or surveying techniques used. (BSC, 2007; Crowell et al., 1991; and Daniels & Huxford, 2001). This has been demonstrated with several post-compilation accuracy assessments of Atlantic and Pacific Coast T-sheets and H-sheets (US Coast Survey hydrographic smooth sheets), including Massachusetts, where horizontal positioning error was found to be less than 8 meters and typically met or exceeded National Map Accuracy Standards at the published scale (BSC, 2007; Crowell et al., 1991; and Daniels & Huxford, 2001**).**

Where study objectives involve vertical positioning, such as comparisons of historical and contemporary bathymetric data, estimates of uncertainty must also consider the methods and equipment used to determine elevations (referred to as soundings) measured from a dynamic plane of reference (Byrnes et al., 2002; Higgins et al*.,* 2007; NOAA, 2007). In addition to the horizontal positioning errors associated with topographic work, factors contributing to the uncertainty of hydrographic surveys include the method used measure depth (e.g., lead line v. echo sounder); the units and rounding protocol used to record depth measurements; the density of soundings and interpolation between data points; tidal reductions (i.e., corrections representing equipment calibration and the stage of the tide above or below the plane of reference); the evenness of the seafloor (i.e. whether it is irregular (i.e. high rugosity) or smooth and gradually sloping); and the plane of reference (historically for the Atlantic Coast a mean low water (MLW) tidal datum) from which depths were measured (see e.g., Byrnes et al., 2002; Byrnes and Li, 1999; Byrnes and Hiland, 1994b; Calder, 2006; Gibbs and Gelfenbaum, 1999; Gorman et al., 1998; Hare, 2011; Hawley, 1931, Wong et al, 2007;). For the comparison of historical and contemporary bathymetric datasets, the most significant source of error is frequently that associated with the historical plane of reference and the ability to relate it accurately to a contemporary vertical datum (Byrnes, et al, 2002; Gorman et al., 1998; Jakobsson et al., 2005; and Van der Wal & Pye, 2003).

For historical surveys conducted in the mid-1930s, horizontal uncertainties for work performed within sight of shore (v. offshore and beyond the sight of land), in relatively shallow water (10 – 12 m), and on relatively regularly contoured seafloors contribute approximately 0.3- 0.5m to the vertical uncertainty (Adams, 1942). Tidal reductions for work in these types of coastal areas can be expected to introduce additional vertical error on the order of 0.1 to 0.3 m (Byrnes and Li, 1999) while lead line measurements can be expected to contribute an additional 0.1 to 0.2 m to the vertical uncertainty budget (Adams, 1942; and Hawley, 1931).

Elevations reported in early surveys, were routinely referenced to a local tidal datum, such as local mean low water. Derived from tide gauges installed in the survey area and based on a relatively short time frame (typically on the order of several months) these tidal observations were used to calculate the mean for the plane of reference and to reduce soundings. Due to the dynamic and local nature of tidal datums (e.g., changes in relative sea level, and fluctuation of water surface elevations in response to long-term astronomical and short term meteorological conditions) high uncertainty can be associated with the conversion of historical local datums to contemporary datums. Significantly, in the absence of additional information such as recoverable benchmarks, conversion to a common or contemporary vertical datum must be based on numerous assumptions that can contribute a systematic bias approaching two feet (~0.6 m), limiting the use of historical and contemporary data comparisons (Gibbs and Gelfenbaum, 1999; Van der Wal & Pye, 2003). Where reliable relationships between historical and contemporary vertical datums can be established by reproducing original survey stations, however, a significant component of the uncertainty associated with the comparisons of elevation data can, however, be eliminated or minimized (Mague, 2012).

As discussed above, to develop reliable conversions of historical sounding data to NAVD88 for CCS's Cape Cod Bay sediment budget work, geospatial descriptions of the benchmarks used by the USC&GS to memorialize low water planes of references for the mid-1900s hydrographic survey work were developed through research in various archives including the those of the Coast Survey, the Army Corps of Engineers, the American Society of Civil Engineers (ASCE), and the Massachusetts Geodetic Survey. These descriptions were then used to conduct field reconnaissance in an effort to recover those benchmarks that have not been damaged or destroyed. Those benchmarks that were recovered were occupied and with the use of RTK-GPS the relationship between the historical plane of reference and NAVD88 established to facilitate volumetric comparisons with contemporary bathymetric data.

The Hydrographic Descriptive Reports and accompanying Hydrographic Smooth Sheets (H-Sheets) prepared by the USC&GS to describe its mid-1900s work are listed in the Reference section of this report. A review of this information reveals that the historical hydrographic survey data used this study was collected using lead lines and reduced daily to the plane of reference. While covering all of Cape Cod Bay, as described above, the focus of this study is on a subset of depth measurements from 0 m to 12 m obtained within 2.5 nautical miles of the shore. As shown on the H-sheets, in shore soundings are closely spaced with depths recorded along shore-parallel lines spaced at 50 meter intervals with line spacing increasing to about 100 meters at depths of 10 meters. Depth curves drawn on the H-sheets depict a gradually sloping, sandy bottom and, as supported by contemporary data, minimal bathymetric irregularities from the shoreline out to the seaward extent of the study. In areas where shoals, bars, and other subsurface features (e.g., Scorton Ledge) were discovered the density of the soundings was increased to define the irregularity.

From its inception, the U.S. Coast Survey topographic and hydrographic surveys have been conducted subject to detailed quality-control instructions describing requirements and survey procedures for both horizontal positioning and depth measurements. While these instructions did not necessarily result in more accurate survey information over time, they do provide a means of estimating potential error associated with the work of different epochs (Sallenger, 1975). Using the information provided in these instructions, a reasonable potential error for water depth measurements obtained in the mid-1900s has been estimated to be between ±2 and ±3 feet (0.6 to 0.9 m) (Byrnes et al., 2002). For surveys conducted close to shore in shallow water (< 20 m) along regular seafloors such as the study area, the potential error associated with the use of lead lines in areas of adequate survey control is estimated to be ± 1.5 feet (± 0.5 m) (Sallenger, 1975). This estimate compares favorably with the standards and accompanying commentary on the methods and quality control procedures required for USC&GS hydrographic surveys in the mid-1900s (Hawley, 1931; Adams, 1942).

Although more detailed analysis is required, this initial estimate of uncertainty can be used to inform the quantitative conclusions of this study and in particular to identify areas of no significant change in comparisons between mid-1900s and contemporary bathymetric surfaces. Based on current hydrographic standards for survey work in less than 100 feet (30 meters), the potential positioning and depth measurement error allowed for surveys in less than 100 feet (30 meters) of water is ± 0.5 to ± 1 feet (± 0.1 to ± 0.3 m) (Byrnes et al., 2002; IHO, 2008). These values have been used in several studies to quantify change resulting in an estimate of the combined RMS error for bathymetric surface comparisons between mid-1900s and late-1900s on the order of 1.5 to 2.0 feet (~0.5 to 0.6 m) to denote areas of no significant change on surface comparison maps (Byrnes and Li, 1999; Byrnes & Hiland, 1994a and b).

The historical bathymetric data depicted on the H-sheets of the U.S. Coast Survey and its successor agencies can be an important source of information for assessing and quantifying changes in coastal landforms. In order to achieve meaningful results from comparative analyses, however, among other things historical data must be translated accurately to common, contemporary horizontal and vertical datums. Further, detailed analyses of potential errors and uncertainties associated with the comparisons must be conducted to evaluate the significance of the comparative analysis and the resulting sediment volumes. With horizontal and vertical uncertainties accounted for, these calculations may be used to quantify the net movement of sediment into and out of a study area and associated long-term net transport rates, to assess changes to sediment volumes, to evaluate changes in nearshore bathymetry, and to predict geomorphological changes (Byrnes et al., 2002; Van der Wal & Pye, 2003).

Transect Construction, Volumetric Analysis and Sediment Flow Calculation

While the historical and contemporary surface models were being developed, a shore-parallel baseline and shore-perpendicular transects were constructed along the 18 km shoreline of the study area. These transects were combined with transects of previous studies, as shown in Figure 1. Transects were spaced at 150-meter intervals (approx. 120 transects) and extended initially out to a depth of 10 meters.

A review of initial transect plots indicated that cross-shore sediment movement extended seaward of the 10-meter contour and the seaward extent of bathymetric lidar. As a result, 35 transects were extended offshore to depths of approximately 15 -20 meters in the area of the Canal and the entrance to Barnstable Harbor (Figure 1) using the CCS survey vessel and the side-mounted altimeter. As discussed below, the extension of these transects was necessary as the available data indicated that offshore sediment deposition may be occurring at depths greater than the normally expected 10 meters.

Using the historical surface model and the contemporary lidar data sets, 20th and 21st century elevations were extracted at 2 meter intervals along each transect. Using MATLAB software, elevations and cross-shore and longshore distances derived from the historical and contemporary data sets were plotted together to determine the local change in sediment volume, ΔV, between adjacent pairs of transects over the intervening time period. These, annualized, provided $\Delta V/\Delta t$ rates for each segment. Subsequent analysis based on profile comparisons of historical and contemporary data, documented changes in sediment volume and form permitting estimates of cross-shore gain and loss rates, $\boldsymbol{q}$, for each segment. The local rate of change in net longshore transport, $\Delta \boldsymbol{Q}$, was determined from $\Delta V/\Delta t$ and $\boldsymbol{q}$ at each transect-pair segment, i.e.,

$$\Delta \boldsymbol{Q} = -\Delta V/\Delta t - \boldsymbol{q}.$$

Finally, estimates of the volume, rate and direction of sediment movement along each segment of the shoreline, $\boldsymbol{Q}$, were determined by summing $\Delta \boldsymbol{Q}$, both east and west of the source “null points”.

RESULTS

The comparison of the historical and contemporary surfaces provides valuable information. A 2-value surface (erosion or deposition) provides for an initial assessment of the study area and highlights potential areas of interest (Figure 8A). For example, deposition in the offshore area near the Canal was somewhat unexpected and after further analysis additional vessel-based data collection was conducted to validate this observation. Similarly, many of the tidal channels near the entrance to Barnstable Harbor show deposition while the channels further away from the entrance show erosion, in contrast to the presence of nearby depositional salt marsh over this time period. Refining the data range of elevation differences provides additional information for characterizing the magnitude of change, while accounting for the estimated uncertainty associated with the data sets as discussed above.

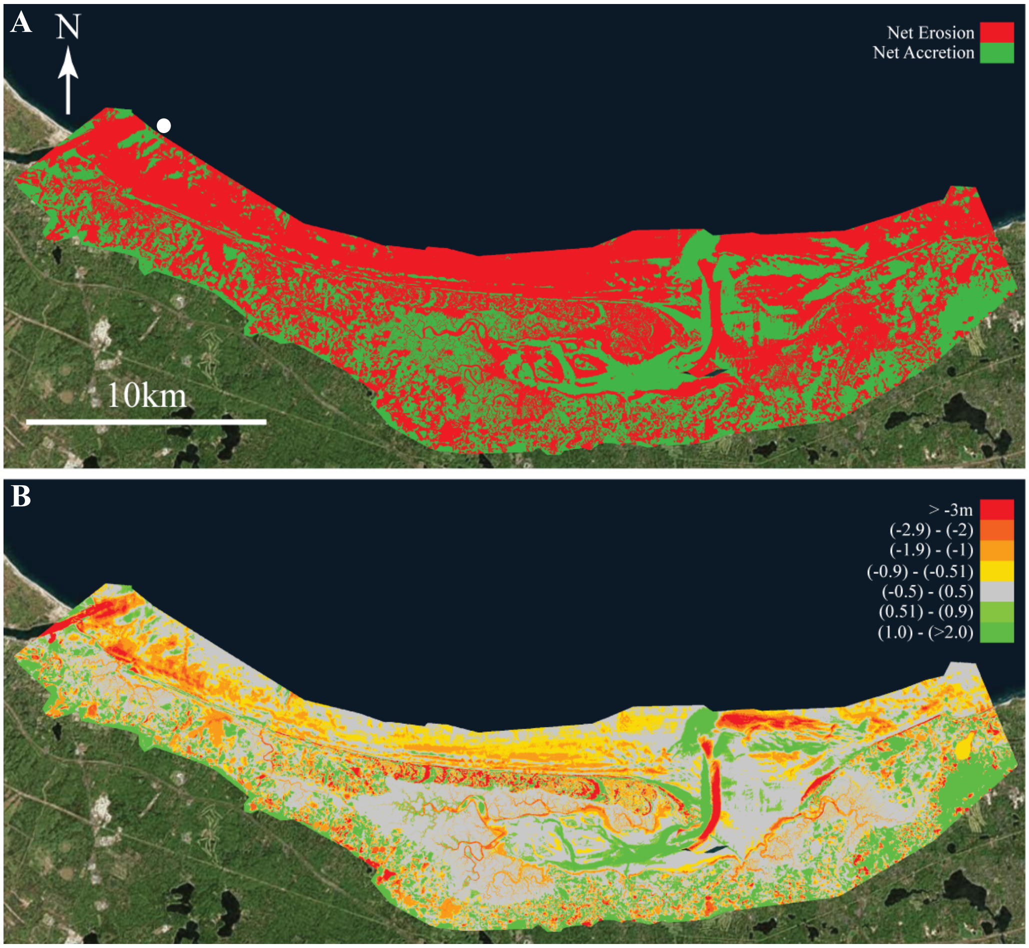

Figure 8. Elevation difference between 1933 and 2010-11. A) 2-value surface where red represents erosion and green deposition. B) 7-value surface with warmer colors representing erosion and cooler colors deposition. Values between +/- 0.5 m are depicted in gray to characterize areas of no significant change.

Another example of a preliminary geomorphological assessment change is illustrated by the eastward movement and straightening of the main tidal channel in Barnstable Harbor. As shown in Figure 8B, the channel has migrated eastward approximately one channel width from 1933 to the present day. Represented by the nearly vertical green area located directly to the east of Beach Point, the 1933 channel and adjacent areas experienced significant deposition as it migrated eastward to its present location represented by the red area.

Based on a review of records and available bathymetric data, it is clear that the jetty immediately updrift (to the west) of the Canal has and continues to minimize the amount of sediment from entering and shoaling the east end of the Canal. This is partially illustrated by the amount of deposition and accretion updrift of the jetty (Figure 9). In spite of the effectiveness of the jetty, however, as evidenced by dredging records some sediment bypasses the jetty and is deposited within the Canal. This is supported by the 2010 bathymetric lidar data, which illustrates clearly that sediment is readily bypassing the updrift jetty (Figure 9). Although the Canal was only constructed a decade and half earlier (ca. 1917), looking at this historical surface it would appear that bypass was also occurring by 1940 (Figure 9). Based on this observation, a profile from an 1860 dataset (datum referenced by CCS as part of on-going work) was drawn to represent nearshore conditions prior to the construction of the Canal. Comparison of the profiles from each time period (1860, 1940, and 2010) updrift of the Canal show ongoing shoreline accretion above depths 3-4 m (NAVD88), but little to no deposition below depths 4-5 m (NAVD 88).

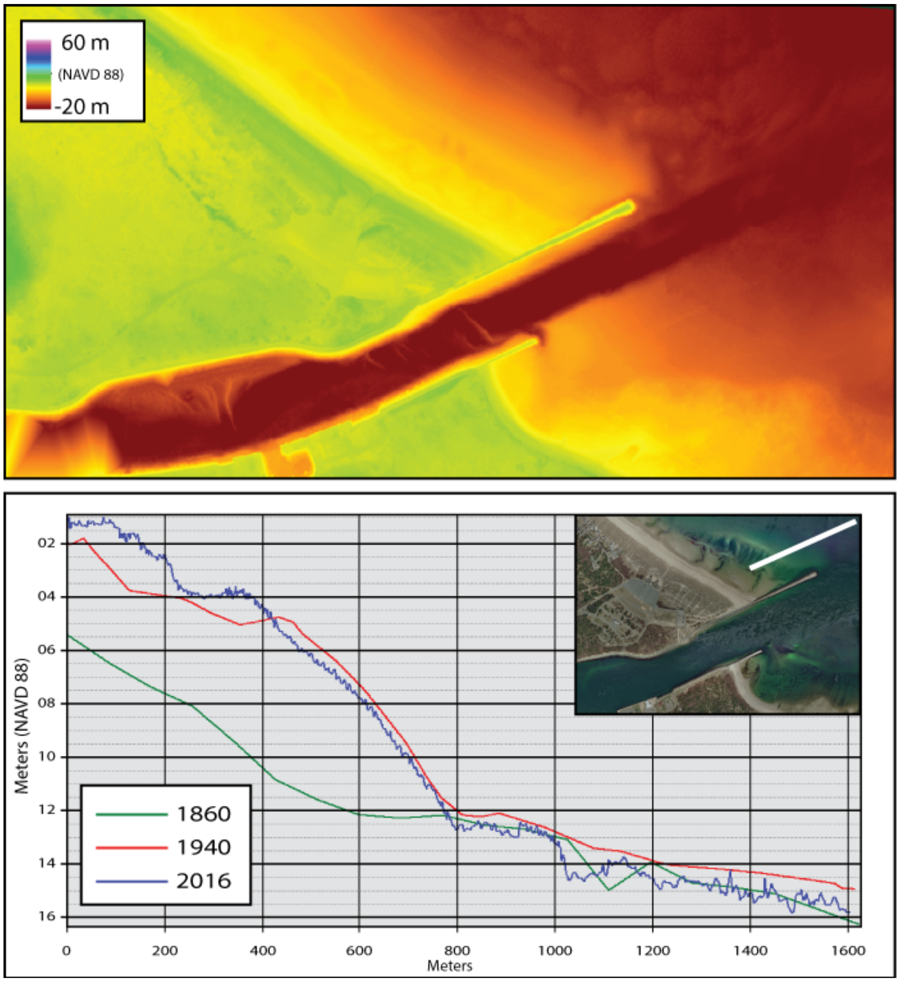

Figure 9. Top: bathymetry from the 2010 lidar. Bottom: Shore-normal profiles from three time periods (1860, 1940, 2016) inset 2014 aerial photograph with location of profile in white.

While it is clear that material has been actively moving around the jetty, given the erosional nature of the shoreface immediately downdrift of the Canal it is not clear where this material is being deposited. Based on initial observations, however, it appears likely that sediment is being deposited beyond the extent of lidar (~10 m water depth) and the commonly accepted wave base for a moderately energetic shoreline.

Recognizing the significance of this observation, 2016 altimeter data was collected and compared to the 1933 surface. These data further demonstrate deposition in water depths well beyond wave base. As shown on Figure 10, several areas experienced deposition between 0.3 – 0.9 m as well as some deposition >1m in water depths ranging from 15-18 m, and in some areas >20m. At these depths this material is effectively lost to the nearshore littoral cell and

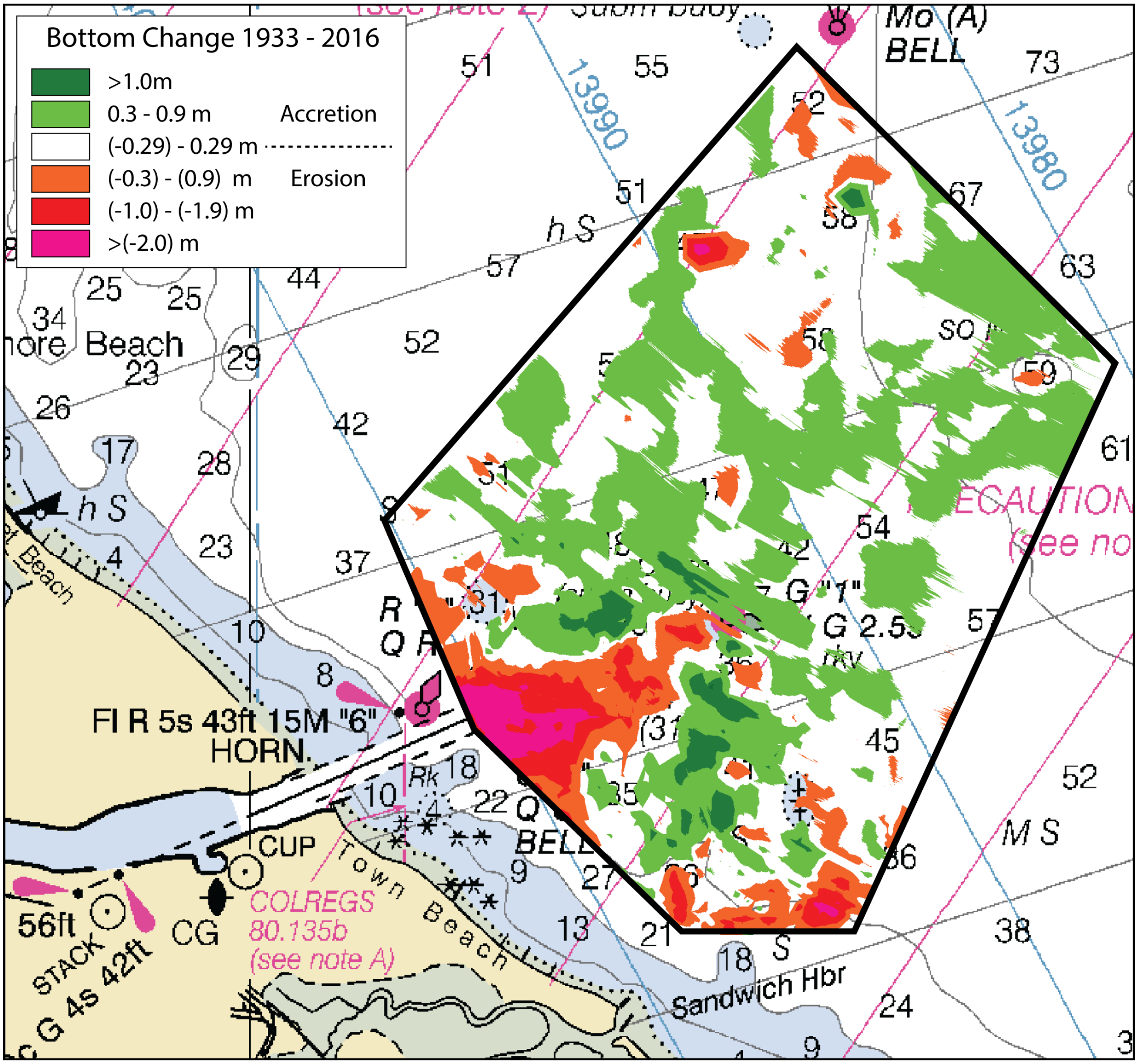

Figure 10. Change along the seafloor from 1933 to 2016. Note: change is expressed in meters and the underlying nautical chart shows depths in feet.

fairweather waves cannot move that material back onshore; information that was critical in developing a more representative sediment budget.

Sediment Budget

Net cross-sectional erosion/accretion (E) rates at each transect within the study area are presented in Figure 11. Strikingly, appreciable accretion was found only in the vicinity of Beach Point at the eastern extremity of Sandy Neck. The estimated location of the null points (***Q*** = 0) separating littoral cells are indicated by the vertical red lines on the figure. There are two null points marking centers of sediment source zones, one at transect 2526 and one at transect 2976. The null point of the sediment sink zone is marked by lines at transect 2628 and transect 2634 which flank Barnstable Harbor channel – the tidal conduit to and from Barnstable Marsh.

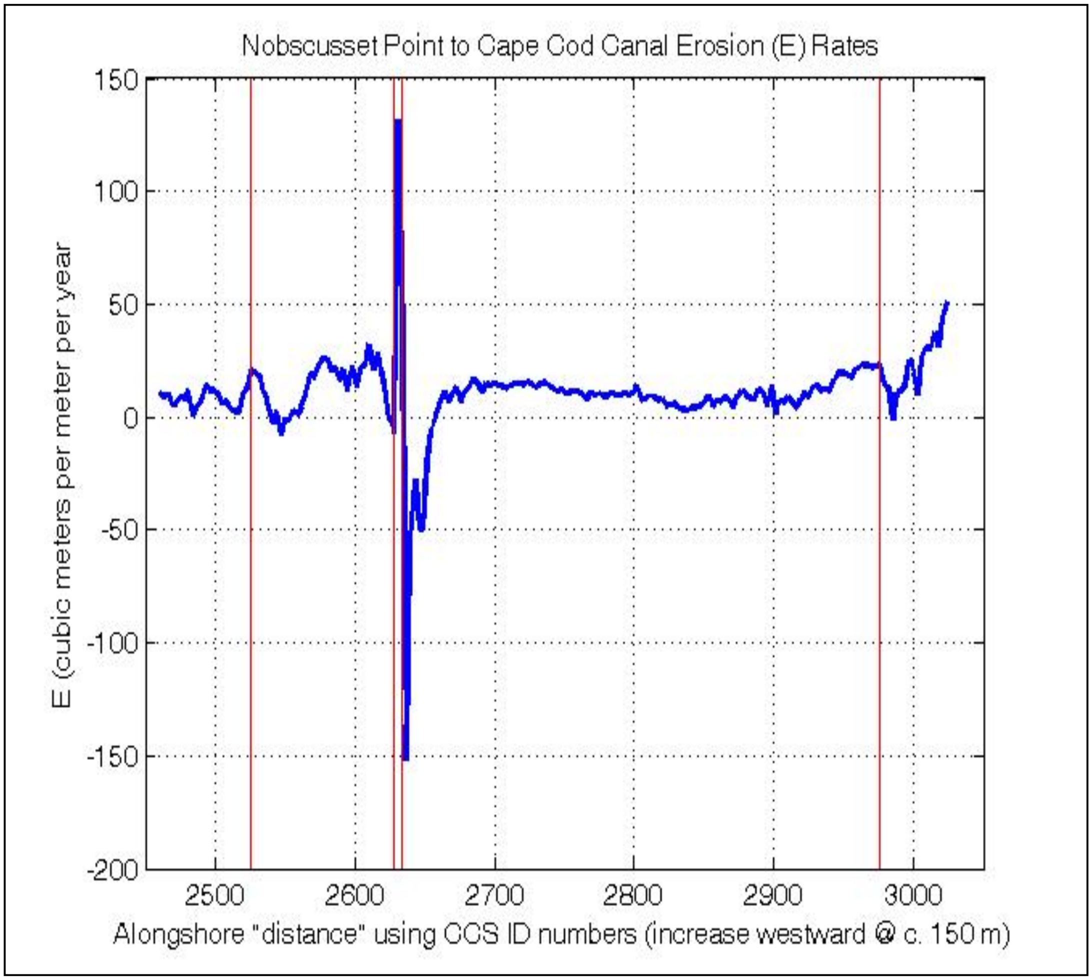

Figure 11: Distribution of *E* for all transects (net cross-sectional erosion/accretion rate) within the study area. Vertical red lines represent the estimated location of the null points (Q = 0) separating littoral cells. Negative *E* values indicate accretion. The extreme accretion near transect 2634 resulted from fill of the former channel.

Figure 12 presents the direction and rate of net alongshore sediment transport, ***Q,*** from Nobscusset Point to the Cape Cod Canal. Calculated from the information illustrated in Figure 11 together with estimated cross-shore losses (***q***), Figure 12 shows the results for all transects. Geographic points-of-interest are superimposed to assist interpretation and application to management issues. Negative "***Q***" values indicate eastward transport; positive values, westward transport. As presented in the Discussion below, red lines indicate shoreline conditions that are characterized primarily by increasing "***Q***" values. These are areas of erosion – source areas for the littoral drift in the region. Similarly, the green lines (decreasing "***Q***") indicate primarily areas of accretion, while black denotes fairly constant net transport with little total erosion or accretion. Black dots designate the "null points" determined as explained in "Methodology".

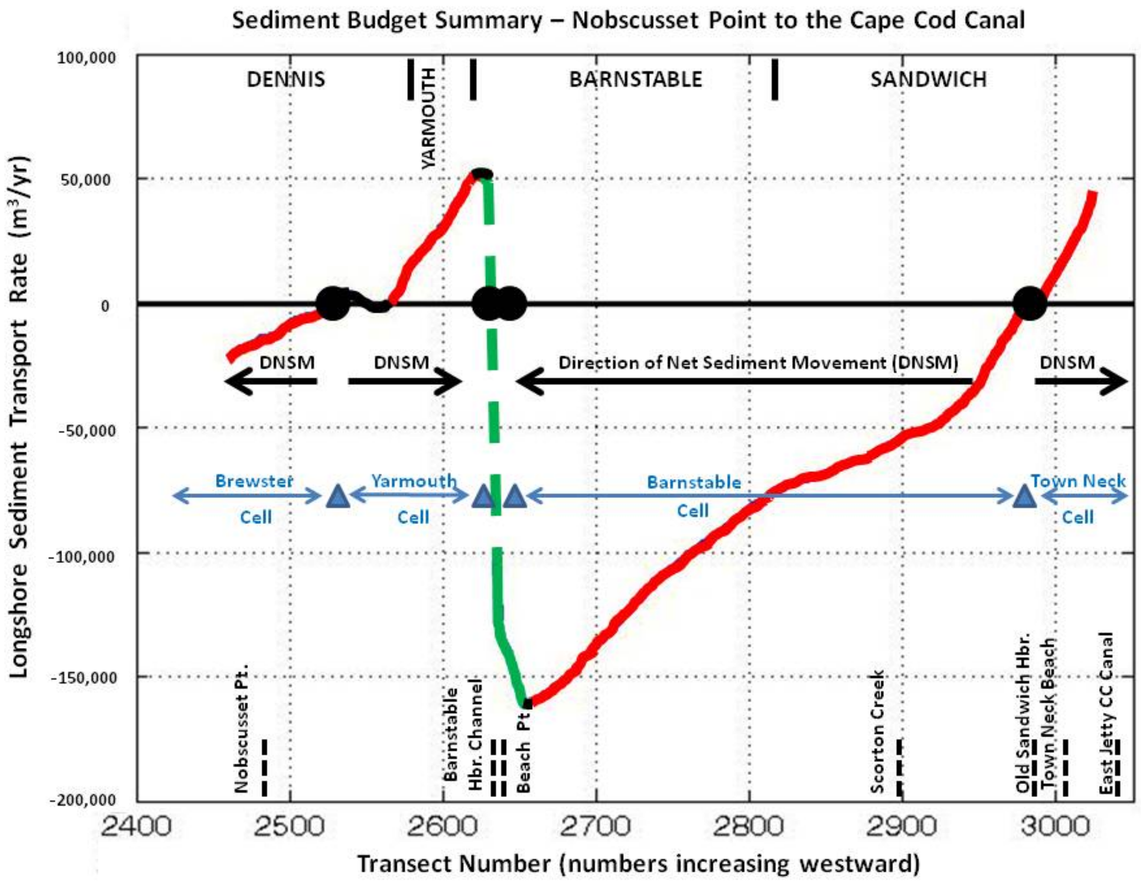

Figure 12: Preliminary distribution of *Q* for all transects. Solid blue dots denotes null point; red Line denotes eroding (source); green line denotes accretion (sink); and blue triangle denotes approximate boundary of littoral cell.

Viewed from east to west (increasing "distance" using transect numbers), sections of four littoral cells are apparent: the western section of the Brewster cell, ending at transect 2526; the Yarmouth cell, ending at Barnstable Harbor channel which is centered at transect 2631; the Barnstable cell, ending at transect 2976; and the Town Neck cell. Three significant estuarine areas are located within the Barnstable cell along the project shoreline from the Cape Cod Canal east to Barnstable Harbor (Figure 13).

These results indicate eastward transport in the Brewster cell and, in the Yarmouth cell, westward transport toward Barnstable Harbor, increasing in intensity to a maximum of some 50,000 cubic meters/year at the harbor channel. West of Barnstable Harbor, transport is eastward toward the harbor in the Barnstable cell with a rate of approximately 100,000 cubic meters/year at the channel. Westward transport, up to about 40,000 cubic meters per year, toward the Cape Cod Canal, is indicated in the Town Neck cell.

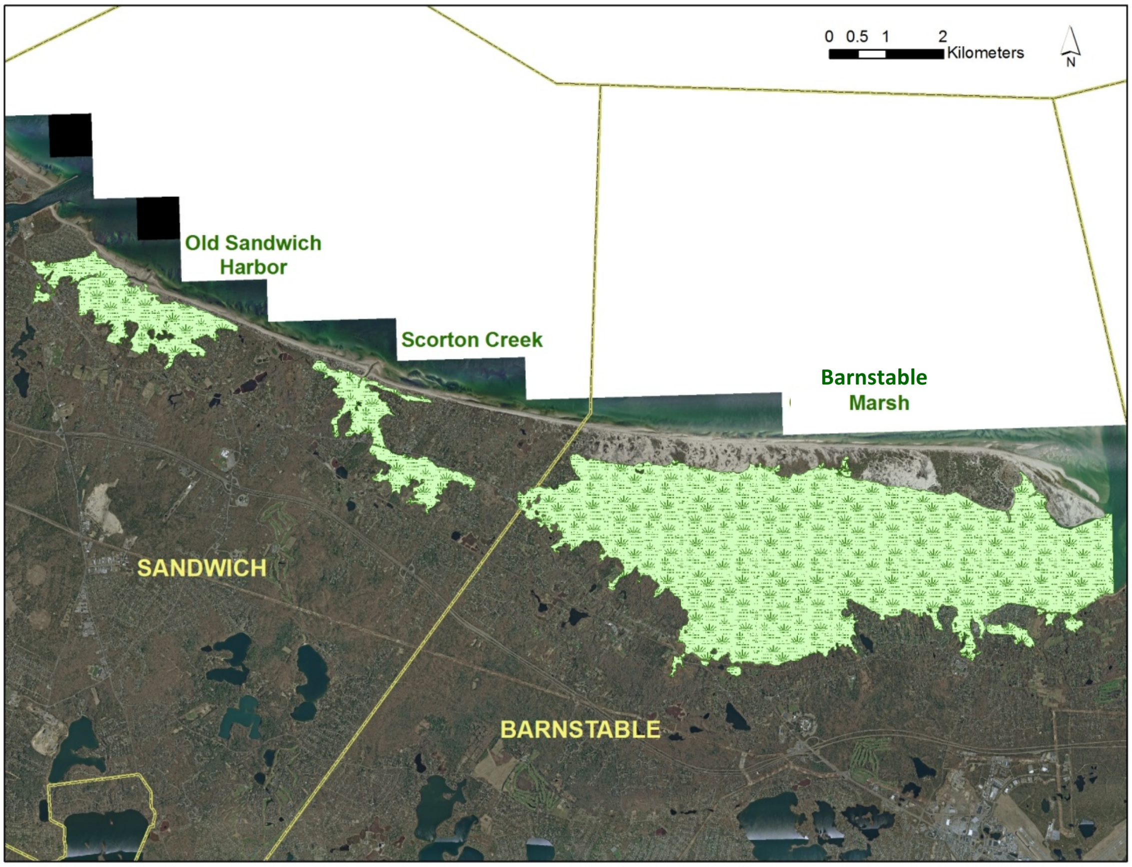

Figure 13: Three significant estuarine areas are located along the project shoreline from the Cape Cod Canal east to Barnstable Harbor. These include; Old Sandwich Harbor (254 ha (630 acres)); Scorton Creek (169 ha (417 acres)); and the Barnstable Marsh (2342 ha (5,787 acres)).

DISCUSSION

The results of this study provide further insight into, and questions about, the sedimentary conditions and processes associated with the southerly shore of Cape Cod Bay. At first glance the sediment transport patterns shown in Figure 12 are not surprising. Eastward transport in the Brewster cell has been described by Giese et al. (2015), and Redfield (1972), summarizing many sources, has described the patterns of sediment movement into Barnstable Marsh. Wave transported sediment (of the Barnstable cell), moving eastward along Sandy Neck, is carried into the marsh by strong tidal currents in the Barnstable Harbor channel. Sand that bypasses the channel is carried to the broad tidal flats to the eastward where it is joined by sediment from the east (Yarmouth cell). Net transport over the flats is southwestward, into the marshes. It is interesting to note the linking of the two littoral cells (Barnstable and Yarmouth) in this instance. It is believed that the three marshes in the system are sediment sinks and changes seen in those areas were taken into account when developing the sediment budget.

Altogether, Figure 12 indicates that some 150,000 cubic meters of sand is deposited in Barnstable Marsh each year; about two-thirds of this arrives from the west and about one-third from the east. This rate is understandable in consideration of the fact that some 60,000 cubic meters per year are required to prevent marsh submergence due to relative sea level rise (c. 3 mm/yr), while observations indicate that the entire marsh system is growing and channels shoaling.

What *is* surprising, however, is that all (or most, see below) of the material moving eastward past Sandy Neck, some 100,000 cubic meters per year, is supplied by coastal erosion east of Sandwich Harbor, while historically (i.e., prior to construction of the Cape Cod Canal) the major source of that sediment was “erosion of the sea cliffs which extend from Manomet Point to the Cape Cod Canal” (Redfield, 1972). Where once one large littoral cell extended from Manomet Point to Sandy Neck/Barnstable Harbor, there now appear to be three cells, one west of the Canal, and two (Town Neck and Barnstable) east of the Canal. If so, these three cells are certainly “linked” as are the Barnstable and Yarmouth cells, but net sediment transport between them appears to be limited. On the other hand, perhaps the Town Neck cell is in fact a “nested” cell lying within a single and much larger littoral cell extending from Manomet Point to Sandy Neck/Barnstable Harbor (e.g., Berman, 2011). It is clear that further study is required to resolve this question and to provide a satisfactory determination of sediment transport patterns in the vicinity of the Cape Cod Canal.

Town Neck Cell

The structures, channels and tidal hydraulics associated with Cape Cod Canal severely interrupt alongshore sediment transport patterns in the study area. The Town Neck region of Sandwich shows the effects of this disturbance (Figure 14). This region lies just east of the Canal, and while its coast is directly exposed to the impacts of easterly storm waves which transport sediment westward, toward the Canal, there appears to be much less return, i.e., easterly, transport. We suggest that Canal-associated structures and tidal flows cause this imbalance by (1) sheltering the Town Neck area from northerly and westerly wave action, and (2) deflecting offshore the eastward-directed littoral drift at the Canal mouth. There is evidence that the strong (~ 4 knot) flood tidal currents entrain and carry out to deep water sediment that arrives from both east and west of the Canal.

It should be noted that an ongoing, but unrelated project conducted by the USGS mapped the thickness and distribution of sand deposits in the area of the Canal that are consistent with findings in this report (pers. comm. D. Foster).

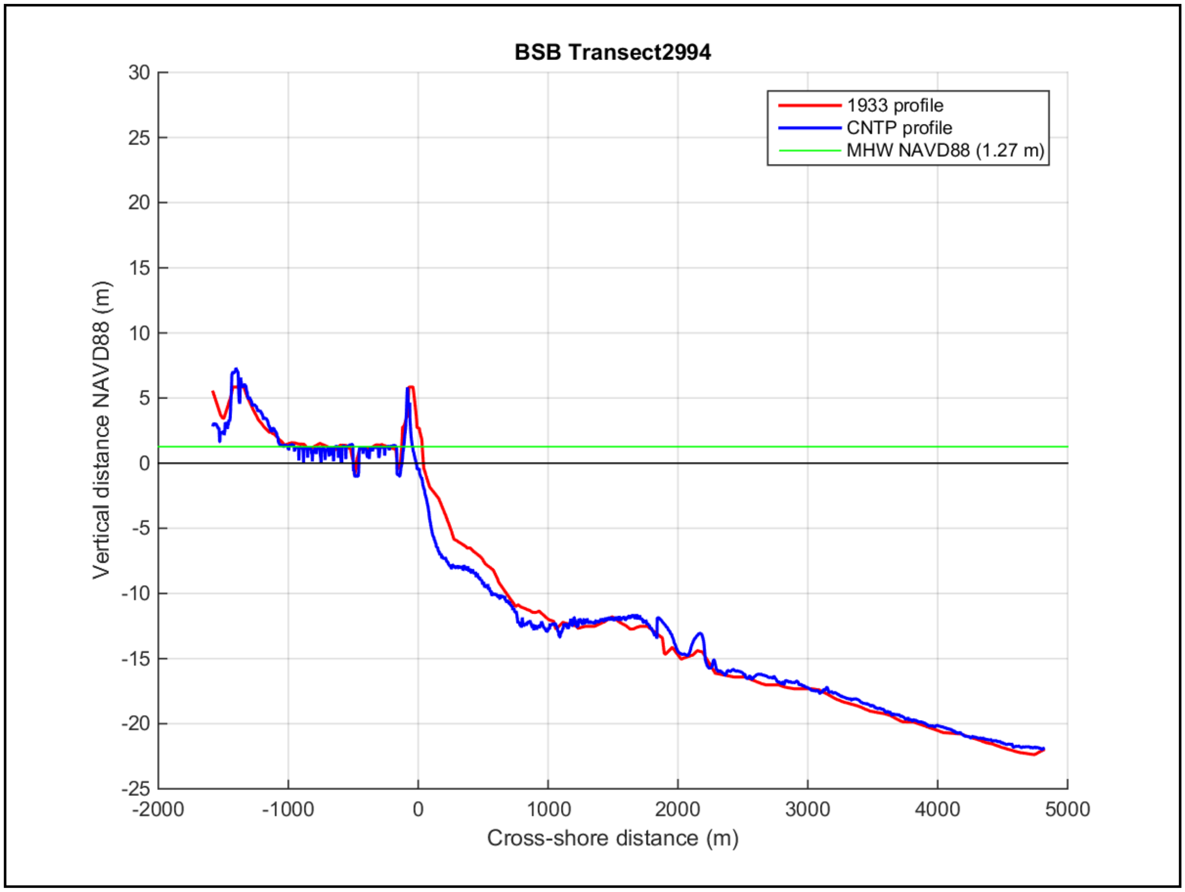

Figure 14: Profiles along transect 2994 at Town Neck in Sandwich showing erosion extending to depths of 10 m, producing a steep shore face.

CONCLUSIONS

A detailed, quantitative sediment budget was developed for the study area extending east from the Cape Cod Canal to Nobscusset Point in Dennis. Findings from this study suggest that some commonly held ideas about the processes associated with sediment transport in this portion of Cape Cod Bay may need to be re-evaluated. While the data products developed in this study can be used to guide decision-makers to better manage the dynamic nearshore coastal systems, further study is needed.

Results of this study suggest that sediment is being deposited at depths between 15-20 m in Cape Cod Bay perhaps as a result of rapid, flood tidal currents entraining sediment that has bypassed the jetty west of the Canal and subsequently transported to depths well beyond wave base. If so, this material is effectively lost to the nearshore system, representing a sink for this littoral cell. Findings of the sediment budget analysis also suggest that the net movement of material in and around Town Neck Beach is westward toward the Canal. This material would also likely be lost to the system after being entrained in the flood tidal flow of the Canal. Additional work is required to characterize the littoral cells proximate to the Canal.

ACKNOWLEDGEMENTS

The authors would like to thank Jo Anne Miller Buntich, Director, Town of Barnstable Growth Management Department and Mark Galkowski, Director of Natural Resources for the Town of Sandwich; and Steve Spear and Sharon Randall, of the Cape Cod Office of the Natural Resource Conservation Service, United States Department of Agriculture in Hyannis, MA for electronic copies of the post hurricane1938 aerial photographs.

GLOSSARY OF TERMS

Term	Symbol	Units	Description
Alongshore gradient of annual net longshore transport	d***Q***/dy	$meters^2$/year or $meters^3$/meter/year	The slope of ***Q*** when it is plotted against alongshore distance "y". It describes the gains or losses in area at a shore-perpendicular transect due to longshore sediment transport. If **q** = 0, erosion results when d***Q***/dy increases alongshore (i.e., positive d***Q***/dy); deposition results when d***Q***/dy decreases alongshore (i.e., negative d***Q***/dy).
Negative of annual rate of change in cross-shore area	***E***	$meters^2$/year, or $meters^3$/meter/year	Total loss (+) or gain (-) per year in cross-sectional area of the "active" zone (wave transport zone) of beach at any specific location along the shore. Equals d***Q***/dy + ***q.*** (+) E = erosion; (-) E = deposition or accretion.
Annual rate of change in cross-shore area along a transect	dA/dt	$meters^2$/year or $meter^3$/meter/year	Time ("t") rate of change in cross-sectional area ("A") between two cross-shore transects at a single location or the volume rate of coastal change *per unit* shoreline distance. (Note: dA/dt = - d***Q***/dy – ***q***).
Littoral cell			A coastal compartment that contains a complete cycle of sedimentation including sources, transport paths, and sinks. Cell boundaries delineate the geographical area within which the sediment budget is balanced, providing the framework for the quantitative analysis of coastal erosion and accretion. (See Berman, 2011, for full discussion)
Littoral drift or (net) longshore sediment transport	***Q***	$meters^3$/year	The annual net flow of sediment along the coast expressed as the volume rate of sediment crossing a shore-perpendicular transect that extends across the active coast from the landward limit of wave-produced sediment transport seaward to the approximate limit of sediment movement. (The result of the integration of d***Q***/dy along the shore). The model assumes that net longshore sediment transport results from waves

			striking the coast at an angle, thereby producing a flow of sediment along the shore in the direction of wave travel.
Local rate of change in net longshore transport - estimate	$\Delta \boldsymbol{Q} = \Delta V/\Delta t - \boldsymbol{q}$	meters^3/year	Where $\Delta V/\Delta t$ represents the local change in sediment volume, ΔV, between adjacent pairs of transects over the intervening time period, Δt (77 years).
Long-term sediment flow			At any particular location along the shore, the result of the composite of all waves (i.e., the actual waves) that acted on the shore over the time period of the study
Model wave			A theoretical single wave representing the composite of all "actual" waves which, acting continually on the shore over the time period of the study, would have produced the same net sediment flow as the actual waves.
Net *cross-shore* transport per unit shoreline distance	$\boldsymbol{q}$	meters^2/year or meters^3/meter/year	Gain or losses in area at a shore-perpendicular transect due to cross-shore sediment transport, *e.g.*, wind-transported sand exchange between a beach and coastal dunes, tidal inlet losses, or offshore transport of very fine sediment by storm seas.
Null point			A point along the shore that defines the updrift or downdrift boundary of a littoral cell. Where $\boldsymbol{Q} = 0$, or $d\boldsymbol{Q}/dy$ is a maximum (in the case of a source). Located where model waves approach shoreline at right angles, i.e., the angle, "θ", between wave approach and a line drawn perpendicular to the shore is zero. This point is sometimes referred to as a nodal point.
Wave angle	θ		The angle between wave approach and a line drawn perpendicular to the shore

REFERENCES

Adams, K.T., 1942. *Hydrographic Manual*. U.S. Department of Commerce, Coast and Geodetic Survey, Special Publication 143, 940 p.

Anders, F.J. and Byrnes, M.R., 1991. *Accuracy of shoreline change rates as determined from maps and aerial photographs*. Shore and Beach. 59(1):17-26.

Ayers, John C., 1959, *The Hydrography of Barnstable Harbor, Massachusetts*. Limnology and Oceanography: 448-462

Berman, G.A., 2011, *Longshore Sediment Transport, Cape Cod, Massachusetts*. Marine Extension Bulletin, Woods Hole Sea Grant & Cape Cod Cooperative Extension. 48 p.

Boston Survey Consultants, Inc. (BSC), 2007. *Massachusetts Chapter 91 Mapping Project*. Final report prepared for the Massachusetts Office of Coastal Zone Management, Executive Office of Environmental Affairs, Commonwealth of Massachusetts. February 23, 2007.

Byrnes, M.R. et al., 2002, *Quantifying Potential Measurement Errors and Uncertainties Associated with Bathymetric Change Analysis.* ERDC/CHL CHETN-IV-50. Coastal and Hydraulics Engineering Technical Note (CHETN). U.S. Army Corps of Engineers. September 2002.

Byrnes, M.R. and F. Li, 1999. *Regional Analysis of Sediment Transport and Dredged Material Disposal Patterns, Columbia River Mouth, Washington/Oregon, and Adjacent Shores.* Final Report to USAE Waterways Experiment Station, Coastal and Hydraulics Laboratory, Vicksburg, MS, 45 p.

Byrnes, M.R. and M.W. Hiland, 1994a. *Shoreline position and nearshore bathymetric change.* (Chapter 3). In: N.C. Kraus, L.T. Gorman, and J. Pope (editors), Kings Bay Coastal and Estuarine Monitoring and Evaluation Program: Coastal Studies. Technical Report CERC-94-09, Coastal Engineering Research Center, Vicksburg, MS, p. 61-143.

Byrnes, M.R. and M.W. Hiland, (1994b). *Compilation and analysis of shoreline and bathymetry data (Appendix B),* N.C. Kraus, L.T. Gorman, and J. Pope, ed., "Kings Bay Coastal and Estuarine Monitoring and Evaluation Program: Coastal Studies," Technical Report CERC-94-09, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Calder, B., 2006. *On the Uncertainty of Archive Hydrographic Datasets.* IEEE Journal of Oceanic Engineering, Vol. 31, No. 2, April 2006.

Cole, L.A. 1929. *Tidal Bench Marks, State of Massachusetts, Special Publication No. 155.* Department of Commerce, U.S. Coast & Geodetic Survey. Washington. U.S. Government Printing Office, Washington.

Crowell, M. et al., 1991. *Historical Shoreline Change: Error Analysis and Mapping Accuracy.* Journal of Coastal Research, 7(3), p. 839-852.

Daniels, R.C. and R.H. Huxford, 2001. *An error assessment of vector data derived from scanned National Ocean Service topographic sheets.* Journal of Coastal Research, 17(3), p. 611-619.

Dean, R.G., and Dalrymple, 2002, *Coastal Processes with Engineering Applications.* Cambridge University Press, Cambridge, UK, 475 p.

Gibbs, A.E. and G. Gelfenbaum, 1999. *Bathymetric Change off The Washington-Oregon Coast.* Coastal Sediments '99. Proceedings of the 4th International Conference on Coastal Engineering and Coastal Sediment Processes. American Society of Civil Engineers. June 20-24 1999, Long Island, NY. 17 pps.

Giese, G.S., M. Borrelli, M., S.T. Mague, T. L. Smith, and P. Barger. 2015. *Assessment of the Century Scale Sediment Budget of the Brewster Coast.* Marine Geology Report No.15-X, Center for Coastal Studies, Provincetown, MA. Prepared for the Town of Brewster, MA

Giese, G. S., Borrelli, M., Mague, S.T., Smith, T., Barger, P., Adams, M.B., and Hughes, P. 2014a. *Century -Scale Longshore Sediment Transport Rates Calculated From Reconstructed Historical Coastal Surfaces.* Coastal Sediments. 2015. San Diego, CA.

Giese, G. S., Borrelli, M., Mague, S. T., Adams, M. B., & Smith, T. L. 2014b. *Application of a Simple Geomorphic Model to Cape Cod Coastal Change.* Presented at the Ocean Sciences Meeting, Honolulu, Hawaii. 23-28 Feb 2014.

Giese, G.S., M. Borrelli, S.T. Mague, T. Smith and P. Barger, 2014c, *Assessment of Multi-Decadal Coastal Change: Provincetown Harbor to Jeremy Point, Wellfleet.* A Report Submitted to the Massachusetts Bays Program. January 2014. 23 p.

Giese, G.S., M. Borrelli, S.T. Mague, and P. Hughes, 2013, *Evaluating century-scale coastal change: Provincetown/Truro line to Provincetown Harbor*. Marine Geology Report No.13-1, Center for Coastal Studies, Provincetown, MA, 11 p.

Giese, G.S., M. Borrelli, S.T. Mague, and P. Hughes, 2012, *Evaluating century-scale coastal change: a pilot project for the Beach Point area in Truro and Provincetown, Massachusetts*. Marine Geology Report No.12-2, Center for Coastal Studies, Provincetown, MA, 18 p.

Giese, G.S., M.B. Adams, S.S. Rogers, S.L. Dingman, M.Borrelli and T.L. Smith. 2011, *Coastal sediment transport on outer Cape Cod, Massachusetts.* In P. Wang, J.D. Rosati and T. M. Roberts (eds.) Coastal Sediments '11, American Society of Civil Engineers, v. 3, p. 2353-2356.

Giese, G.S. and M.B. Adams. 2007, *Changing orientation of ocean-facing bluffs on a transgressive coast, Cape Cod, Massachusetts*. In: Kraus, N.C., and J.D. Rosati (eds.), Coastal Sediments '07, American Society of Civil Engineers, v. 2, p. 1142-1152.

Gorman, L., et al., 1998. *Monitoring the Coastal Environment; Part IV: Mapping, Shoreline Changes, and Bathymetric Analysis.* Journal of Coastal Research, V. 14, No. 1, pp. 61-92.

Hare, R., et al., 2011. *Modeling bathymetric uncertainty.* U.S. HYDRO 2011. Tampa, FL. 14 pp.

Hawley, J.H., 1931. *Hydrographic manual* (Edition 1). Special Publication No. 143. U.S. Department of Commerce, U.S. Coast and Geodetic Survey, U.S. Government Printing Office, Washington, DC, 191 pp.

Higgins, S.A., B.E. Jaffe and C.C. Fuller, 2007. *Reconstructing sediment age profiles from historical bathymetry changes in San Pablo Bay*. California. Estuarine, Coastal, and Shelf Science, 73 (2007): 165-174. 2007.

International Hydrographic Organization (IHO), 2008. *Standards for Hydrographic Surveys*: 5th Edition, Special Publication No. 44. 27 pp.

Jakobsson, M., A. Armstrong, B. Calder, L. Huff, L. Mayer, and L. Ward, 2005, *On the Use of Historical Bathymetric Data to Determine Changes in Bathymetry: An Analysis of Errors and Application to Great Bay Estuary, NH.* International Hydrographic Review, Vol. 6, No. 3, pps. 25-41. November 2005.

Johnston, S., 2003. *Uncertainty in Bathymetric Surveys*. ERDC/CHL CHETN-IV-59. Coastal and Hydraulics Engineering Technical Note (CHETN). U.S. Army Corps of Engineers. March 2003.

Komar, P.D., 1998, *Beach Processes and Sedimentation, Second Edition.* Prentice Hall, New Jersey. 544 p.

Mague, S.T. (2012) *Retracing the Past: Recovering 19th Century Benchmarks to Measure Shoreline Change Along the Outer Shore of Cape Cod, Massachusetts.* Cartography and Geographic Information Science, Vol. 39, No. 1, pp. 30-47.

NOAA Coastal Services Center, 2007. *Topographic and Bathymetric Data Considerations: Datums, Datum Conversion Techniques, and Data Integration (Data Considerations)*. National Oceanic and Atmospheric Administration (NOAA)Technical Report NOAA/CSC/20718-PUB.

Redfield, A.C. 1972. *Development of a New England Salt Marsh.* Ecological Monographs, v.42, p.201-237.

Redfield, A.C. and M. Rubin. 1962. *The Age of Salt Marsh Peat and Its Relation to Recent Changes in Sea Level at Barnstable, Massachusetts*. Proceedings of the National Academy of Sciences of the United States of America. Vol. 48, No. 10. October 15, 1962. Pp. 1728-1735.

Ruggerio, P., et al., 2003. *Linking Proxy-Based and Datum-Based Shorelines an a High Energy Coastline: Implications for Shoreline Change Analysis.* Journal of Coastal Research. SI 38, 57-82. Fall 2003.

Sallenger, A.H., et al., 1975. *Bathymetric Comparisons: A Manual of Methodology, Error Criteria, and Techniques*. Special Report No. 66. in Applied Marine Science and Ocean Engineering. Virginia Institute of Marine Science, Gloucester Point, Virginia. July 1975. 80 pages.

Shalowitz, A.L., 1964. *Shore and Sea Boundaries: Interpretation and Use of Coast and Geodetic Survey Data*, Volume Two, Pub. 10-1, U.S. Dept. of Commerce, Coast and Geodetic Survey, U.S. Government Printing Office, Washington, DC.

Uchupi, E., G.S. Giese, D.G. Aubrey and D.J. Kim, 1996, *The Late Quaternary Construction of Cape Cod, Massachusetts: A Reconsideration of the W.M. Davis Model*. Geological Society of America Special Paper, 309, 69 pp.

U.S. Coast & Geodetic Survey. 1938. *Tidal Bench Marks, State of Massachusetts*, Department of Commerce, Washington, D.C. Re-issued by: Mass. Geodetic Survey, 100 Nashua St., Boston. 1938.

Van der Wal, D. and K. Pye. (2003). *The use of historical bathymetric charts in a GIS to assess morphological change in estuaries.* The Geographic Journal, Vol. 169, No. 1, pps. 21-31. March 2003.

Van Heteren, S. and O. Van de Plassche. 1997. *Influence of Relative Sea-Level Change and Tidal Inlet Development on Barrier-Spit Stratigraphy, Sandy Neck Massachusetts.* Journal of Sedimentary Research, Vol. 67, No. 2, March, 1997, pps. 350-363.

Wong, A. M., J. G. Campagnoli and M. A. Cole, 2007. *Assessing 155 Years of Hydrographic Survey Data for High Resolution Bathymetry Grids, OCEANS 2007*, Vancouver, BC, 2007, pp. 1-8.

Wood, J.D., J.S. Ramsey, and S.W. Kelley. 1999. *Two-Dimensional Hydrodynamic Modeling of Barnstable Harbor and Great Marsh, Barnstable MA.* Prepared for: The Town of Barnstable, MA. Final Report – December 1999. Applied Coastal Research and Engineering, Inc, 766 Falmouth Road, Building A-Unit 1C, Mashpee, MA 02649. 33 pps.

T and H-sheet Descriptive Reports

U.S. Coast and Geodetic Survey. 1909. *Descriptive Report, Topographic Sheets [revisions to] 1062a, 901a & b, 795, 1088a & b, 1078a, 1077a & b, 1704, 368, 579, 259a & b, 260a & b, 616 a & b, and 1982. Massachusetts, Cape Cod Bay. 11 pages.*

U.S. Coast and Geodetic Survey. 1934. *Descriptive Report, Hydrographic Sheet 5588. Cape Cod, Vicinity of Barnstable Harbor. 18 pages.*

U.S. Coast and Geodetic Survey. 1934. *Descriptive Report, Hydrographic Sheet 5589. Cape Cod, Barnstable Harbor. 25 pages.*

U.S. Coast and Geodetic Survey. 1934. *Descriptive Report, Hydrographic Sheet No. 5543. Cape Cod, Billingsgate Shoal. 22 pages.*

U.S. Coast and Geodetic Survey. 1934. *Descriptive Report, Topographic Sheet 6113. Massachusetts, Cape Cod, East Dennis to Brewster. 11 pages.*

U.S. Coast and Geodetic Survey. 1934. *Descriptive Report, Topographic Sheet 6114. Massachusetts, Cape Cod, Yarmouthport to Nobscusset Pt. 10 pages.*

U.S. Coast and Geodetic Survey. 1934. *Descriptive Report, Topographic Sheet 6122 & 6123. Massachusetts, Cape Cod, Barnstable Harbor & Scorton Neck. 16 pages.*

U.S. Coast and Geodetic Survey. 1940. *Descriptive Report, Topographic Sheet T-6740. Massachusetts, Cape Cod, Springhill Beach to & Scorton Neck. 10 pages.*

U.S. Coast and Geodetic Survey. 1940. *Descriptive Report, Topographic Sheet T-6741. Massachusetts, Cape Cod, Sagamore Beach to Springhill Beach. 10 pages.*

U.S. Coast and Geodetic Survey. 1940. *Descriptive Report, Topographic Sheet T-6742. Massachusetts, Cape Cod, Indian Hill to Sagamore Beach. 10 pages.*

U.S. Coast and Geodetic Survey. 1940. *Descriptive Report, Hydrographic Sheet No. 6561. Massachusetts, Cape Cod Bay, Sagamore Beach to Scorton Neck. 22 pages.*

U.S. Coast and Geodetic Survey. 1940. *Descriptive Report, Hydrographic Sheet No. 6562. Massachusetts, Cape Cod Bay, Indian Hill to Sagamore Beach. 25 pages.*

U.S. Coast and Geodetic Survey. 1940. *Descriptive Report, Hydrographic Sheet No. 6563. Massachusetts, Cape Cod Bay. 25 pages.*

U.S. Coast and Geodetic Survey. 1952-58. *Descriptive Report, Topographic Sheet T-11193, 11193a, & 11194. Cape Cod, Barnstable Harbor. 42 pages.*

U.S. Coast and Geodetic Survey. 1951-54. *Descriptive Report, Topographic Sheet T-11185.Massachusetts, Cape Cod Bay, Sagamore. 24 pages.*

U.S. Coast and Geodetic Survey. 1951-54. *Descriptive Report, Topographic Sheet T-11186.Massachusetts, Cape Cod Bay, Springhill Beach to Cape Cod Canal Entrance. 22 pages.*

U.S. Coast and Geodetic Survey. 1952-55. *Descriptive Report, Topographic Sheet T-11187 & 11188. Cape Cod Bay, Nobscusset Point to Boatmeadow River. 26 pages.*

U.S. Coast and Geodetic Survey. 1951-55. *Descriptive Report, Topographic Sheet T-11192. Cape Cod Bay, Scorton Harbor. 20 pages.*

Cartographic and Bathymetric Data Used in this Project

1825 – *Survey of a Valley and Ponds Auxiliary to a Contemplated Canal between Buzzards & Barnstable Bays.* State of Massachusetts and Town of Sandwich. 1825.

1825 – *Survey across the Isthmus Cape Cod State of Massachusetts and Town of Sandwich, of a proposed Canal between Buzzard's and Barnstable Bays. 1825.* Surveyed under the Direction of Maj. Perault, U.S.T.E.

1856 – U.S. Coast Survey Hydrographic Survey, H-578. *Cape Cod Bay with Provincetown Harbor. By the Hydrographic Party under the Command of Comder, H.S. Stellwagen, U.S.N. Asst C.S. Scale 1/40,000 1856.*

1860 – U.S. Coast Survey Hydrographic Survey, H-772, A.D. Bache Supt. *A part of Barnstable Bay off Scusset Beach) Massachusetts.* Hydrography Surveyed by the Party under command of Lieut. Jno. Wilkinson, U.S. Navy. Prepared by request of the Advising Council of the Committee of Legislature of the State of Massachusetts on the Canal between Barnstable and Buzzards Bays. Scale 1:10,000. 1860.

1860 – U.S. Coast Survey Topographic Survey, T-1530. *Map of the Route of the proposed Cape Cod Canal Ship Canal.* A.D. Bache, Supdt. Prepared by request of the Advising Council of the Committee of Legislature of [the] State of Massachusetts on the Canal between Barnstable and Buzzards Bays. Scale: 1/10,000. Surveyed by W.H. Dennis. 1860

1861 – U.S. Survey, A.D. Bache, Superintendent. *Barnstable Harbor, Massachusetts.* Hydrography by the party under the command of Henry Mitchell, Asst., U.S.C.S. Scale: 1/10,000. 1861

1862 – *Map of the Route of the of a Proposed Ship Channel across Cape Cod from Buzzards Bay to Barnstable Bay with a Profile of the Located links and Designs for Locks, Feeding-Sluice, Breakwaters, &c.* Prepared for the Committees of the Mass. Legislature in Conformity to acts passed 1860 and march 1861 under the superintendence of Geo. R. Baldwin C.E. by J.C. Chase, Engineer & Surveyor. Cambridgeport. 1862.

1909 - U.S. Coast & Geodetic Survey Topographic Survey, T-901a. *Tracing showing topographic changes on original sheet No. 901, west end, by O.B. French, Assistant,1909.*

1909 - U.S. Coast & Geodetic Survey Topographic Survey, T-1062a. *Tracing showing topographic changes on original sheet No. 1062, by O.B. French, Assistant,1909.*

1909 - U.S. Coast & Geodetic Survey Topographic Survey, T-1063a. *O.H. Tittmann, Superintendent. Tracing showing topographic changes on original sheet No. 1063, Collected and plotted by O.B. French, Assistant,1909. Scale: 1/10,000.*

1934 - U.S. Coast & Geodetic Survey Topographic Survey No. 6114, *Yarmouthport to Nobscusset Pt.,* Cape Cod, Massachusetts. Scale 1:10,000.

1934 - U.S. Coast & Geodetic Survey Topographic Survey No. 6122, *Barnstable Harbor,* Cape Cod, Massachusetts. Scale 1:10,000.

1934 - U.S. Coast & Geodetic Survey Topographic Survey No. 6123, *Scorton Neck*, Cape Cod, Massachusetts. Scale 1:10,000.

1934 - U.S. Coast & Geodetic Survey Hydrographic Survey No. 5543, *Billingsgate Shoal,* Cape Cod, Massachusetts. Scale 1:20,000. (*x,y,z* soundings point data available for download at http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html).

1934 - U.S. Coast & Geodetic Survey Hydrographic Survey No. 5588, *Vicinity of Barnstable Harbor,* Cape Cod, Massachusetts. Scale 1:20,000. (*x,y,z* soundings point data available for download at http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html).

1934 - U.S. Coast & Geodetic Survey Hydrographic Survey No. 5589, *Barnstable Harbor,* Cape Cod, Massachusetts. Scale 1:10,000. (*x,y,z* soundings point data available for download at http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html).

1938 – United States Department of Agriculture, Natural Resource Conservation Service, Aerial Photographs. Date of Photographs: November 21, 1938. Ground Scale 1:24,000. Time of photos: ~ 1000 HRS. Time of High Water: ~ 1000 HRS. Weather: Clear, west winds 10-15 mph.

1938 & 1941 - U.S. Coast & Geodetic Survey Topographic Map No. T-5611, Massachusetts, Cape Cod Bay, *Cape Cod Canal; Northeast Entrance*. Scale 1:10,000.

1940 - U.S. Coast & Geodetic Survey Hydrographic Survey No. 6561, Massachusetts, Cape Cod Bay, *Sagamore Beach to Scorton Neck*. Scale 1:10,000. (*x,y,z* soundings point data available for download at http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html).

1940 - U.S. Coast & Geodetic Survey Hydrographic Survey No. 6562, Massachusetts, Cape Cod Bay, *Indian Hill to Sagamore Beach*. Scale 1:10,000. (*x,y,z* soundings point data available for download at http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html).

1940 - U.S. Coast & Geodetic Survey Hydrographic Survey No. 6563, Massachusetts, Cape Cod Bay. Scale 1:40,000. (*x,y,z* soundings point data available for download at http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html).

1940 - U.S. Coast & Geodetic Survey Topographic Survey No. 6742, Massachusetts, Cape Cod Bay, *Indian Hill to Sagamore Beach*. Scale 1:10,000.

1940 - U.S. Coast & Geodetic Survey Topographic Survey No. 6741, Massachusetts, Cape Cod Bay, *Sagamore Beach to Spring Hill Beach*. Scale 1:10,000.

1940 - U.S. Coast & Geodetic Survey Topographic Survey No. 6740, Massachusetts, Cape Cod Bay, *Spring Hill Beach to Scorton Neck*. Scale 1:10,000.

1940 - U.S. Geological Survey, Sagamore Quadrangle. Based on Surveys performed in 1932, ’33, & ’37. Scale: 1:31,680.

1942 - U.S. Geological Survey, Hyannis Quadrangle. Based on Survey performed in 1939. Scale: 1:31,680.

1943 - U.S. Geological Survey, Dennis Quadrangle. Based on Survey performed in 1940. Scale: 1:31,680.

1943 - U.S. Geological Survey, Sandwich Quadrangle. Based on Surveys performed in 1932, ’33, & ’37. Scale: 1:31,680.

1951 - U.S. Coast & Geodetic Shoreline Manuscript, T-11185, Massachusetts, Cape Cod Bay, *Cape Cod Canal and Vicinity*. Scale – 1:10,000.

1951, ’54, & ’55 - U.S. Coast & Geodetic Shoreline Manuscript, T-11186, Cape Cod Bay, *Springhill Beach to Cape Cod Canal Entrance*. Scale – 1:10,000.

1952, ‘53, & ‘55 – U.S. Coast & Geodetic Shoreline Manuscript, T-11187, Massachusetts, Cape Cod Bay, *Nobscusset Point to Quivett Creek*. Scale – 1:10,000.

1951, ’54, & ’55 - U.S. Coast & Geodetic Shoreline Manuscript, T-11192, Massachusetts Cape Cod Bay, *Scorton Harbor*. Scale – 1:10,000.

1952, ’53, & ‘55 – U.S. Coast & Geodetic Shoreline Manuscript, T-11193, Massachusetts, Cape Cod Bay, *Barnstable Harbor*. Scale – 1:10,000.

1952, ’53, & ‘55 – U.S. Coast & Geodetic Shoreline Manuscript, T-11194, Massachusetts, Cape Cod Bay, *Dennis*. Scale – 1:10,000.