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Assessment of the Century-Scale Sediment Budget for the Eastham and Wellfleet Coasts of Cape Cod Bay

A Report Submitted to the Towns of Eastham and Wellfleet

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EXECUTIVE SUMMARY

This project completes the sediment budget for the last section of Cape Cod Bay shoreline from the Canal to Provincetown, work which was begun by the Center for Coastal Studies scientists in 2012. Data from the 1930-40s and from 2010-2017 were used to develop historical and contemporary three-dimensional surface models. The comparison of these 2 datasets documented changes that were used to quantify the sediment budget and identify other coastal processes and geomorphic changes. Sediment budgets document the direction and volume of sediment movement as well as the sources and sinks of sediment in the nearshore zone. This then allows for the mapping of littoral cells, which when combined with an estimate of volumetric change, can be used by coastal managers to better understand coastal evolution in general and to inform decisions about the impacts associated with altering the nearshore zone with coastal engineering structures, beach replenishment projects and other related activities.

As with previous projects, the Center for Coastal Studies developed a quantitative, century-scale sediment budget for the Towns of Eastham and Wellfleet along approximately 7.6 km (4.7 miles) of shoreline from the Sunken Meadow Spit in Wellfleet south to First Encounter Spit in Eastham. A3-dimensional, quantitative spatial analysis of historical and contemporary surface models on 154 km^2 (59 mi^2) of the nearshore in Wellfleet Harbor, along the Eastham shoreline and Billingsgate Shoal was also conducted to further characterize sediment movement within the nearshore over the past 80 $\pm$ years.

Based on shore-perpendicular transects at 150-meter intervals, the sediment budget work documented the presence of a single nodal point located approximately halfway between Campground and Thumpertown Beaches in Eastham. A nodal point is a location along the shoreline where the net longshore sediment transport diverges. To the north of the nodal point the net direction of sediment transport is to the north, and south of the nodal point the net direction of sediment transport is to the south.

Based on a quantitative analysis of transects, the maximum rate of longshore sediment transport was determined to be approximately 10,000 m^3/yr both at Sunken Meadow Beach to the north and First Encounter Beach to the south. Based on records provided by the towns, the average volume of sediment introduced into the system by private shorefront property owners via annual beach replenishment since about the year 2000 is approximately 2,000 m^3 both north and south of the nodal point. This material accounts for nearly 20% of the annual north/south longshore sediment transport and this input is an important factor in mitigating the significant reduction to natural sediment sources for the longshore system as a result of the armoring of approximately 43% of the 7.6 km (4.7 miles) shoreline. Since 2015, with sand added annually by the town at four public landings, this replenishment number has increased to approximately 3,600 m^3 north of the nodal point and 2,550 m^3 south of the nodal point. This combination of public and private replenishment, while less than what would be provided in the absence of coastal engineering structures clearly lessens the impact to the nearshore environment that would otherwise occur.

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 from Chatham to Provincetown (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 the development of comprehensive sediment budgets between Long Point and Macmillan Wharf in Provincetown Harbor; between Macmillan Wharf and Jeremy Point in Wellfleet; between Nobscusset Point in Dennis and Rock Harbor on the Orleans/Eastham town line; and between the Cape Cod Canal and Barnstable Harbor. 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 a reliable estimate of century-scale sediment budgets along Cape Cod Bay's sandy shores. The results of these assessments were documented in six technical reports funded by the Island Foundation (Giese et al., 2012; Giese et al., 2013); the Massachusetts Bays Program (MBP) (Giese et al., 2014); and the Massachusetts Office of Coastal Zone Management (CZM) (Giese et al., 2015a, 2015b; Giese, et al., 2016). (see Figure 1).

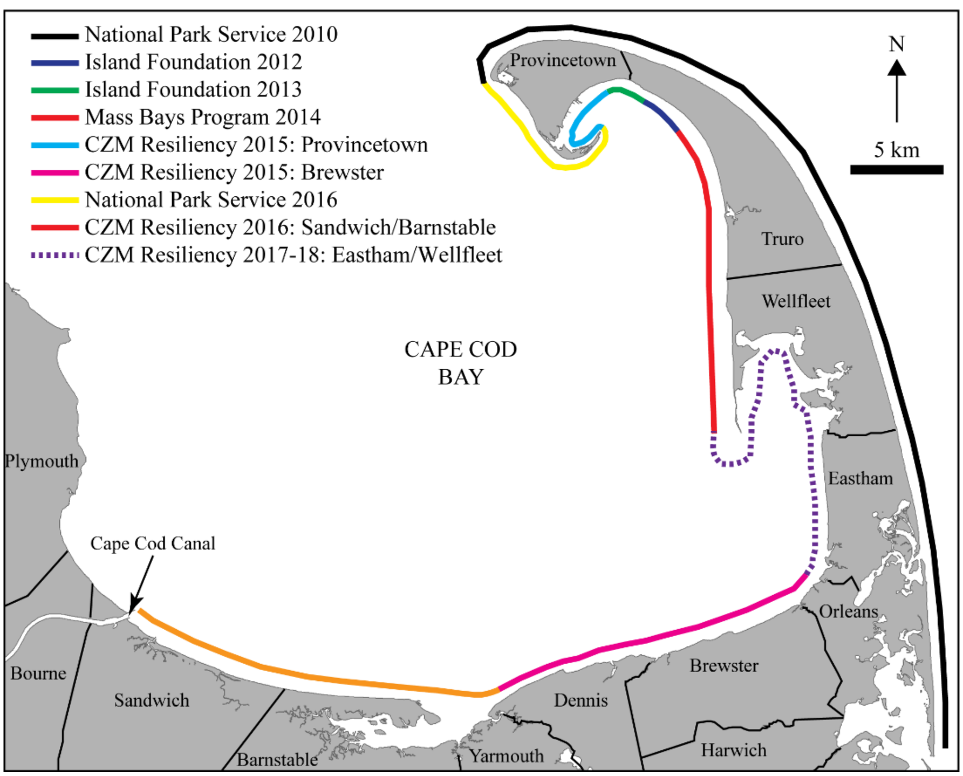


Figure 1. This project, focusing on the Eastham/Wellfleet shoreline (dashed line) completes work to quantify a comprehensive sediment budget for Cape Cod Bay, east of the Cape Cod Canal.

The present study conducted for the Towns of Eastham and Wellfleet and funded by the Coastal Resiliency Grants Program of the Massachusetts Office of Coastal Zone Management (CZM), extends south from the Duck Harbor/Jeremy Point area of Wellfleet and the southerly end of the 2014 MBP study to Rock Harbor on the Orleans/Eastham town line and the easterly edge of the 2015 Brewster work (Figure 1). This work completes sediment budget analysis for Cape Cod Bay beginning with Chatham on the backshore of the Cape north and west to the Cape Cod Canal (Giese, et al 2016).

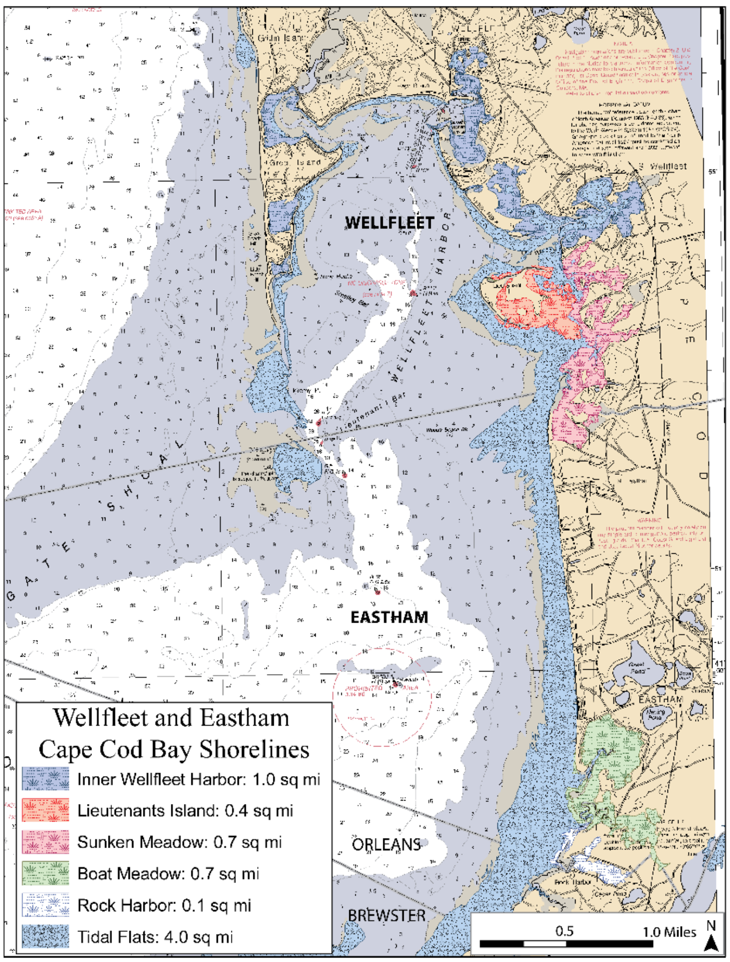


Figure 2. Study site with salt marsh locations and surficial areas

Field Setting

Cape Cod was formed as the glaciers retreated approximately 20,000 year ago. Later, as sea levels began to rise and inundate the area, the Cape began to take on its well-known configuration. Around 6,000 years ago the sea levels rose and began to erode the bluffs on the easterly or ocean side. As this occurred, the eroded material began to form what is now Provincetown Hook. The formation of the Hook further protected Bay shorelines as did Billingsgate Shoal. However, the protection afforded by the Hook reduced the amount of sediment that traveled southward along the shoreline (mostly from northwest winds and resulting waves). This reduction of sand contributed to the inundation of Billingsgate Shoal which once had a small community on the approximately 1-mile long, ½-mile wide island. The island community on Billingsgate at its height in the mid- to late1800's included a lighthouse, a prosperous fishing industry, approximately 30 homes, a schoolhouse, and a baseball team.

The shoreline that encloses much of Wellfleet Harbor (Figure 2), starting near the Truro town line, is a feature called a tomobolo. A tomobolo is an island, or series of islands, that is connected to the mainland by eroded material. Bound Brook Island, Griffin Island, Great Island

and Great Beach Hill Island make up this tomobolo. As mentioned above the formation of Provincetown Hook has reduced the volume of sediment that moves along this coast south onto Billingsgate Shoal.

With this reduction in sediment, Billingsgate Island began to erode at the turn of the 19th century and by the early 1930s had disappeared almost entirely. As relative sea level has risen, erosion along the Eastham and Wellfleet shores began to increase. As a result, shoreline armoring in both Wellfleet and Eastham began to increase significantly in the mid-1960s (Figure 3). Today approximately 43% of the bay-facing shorelines in both towns have been armored, limiting the natural supply of sediment to nearshore system.

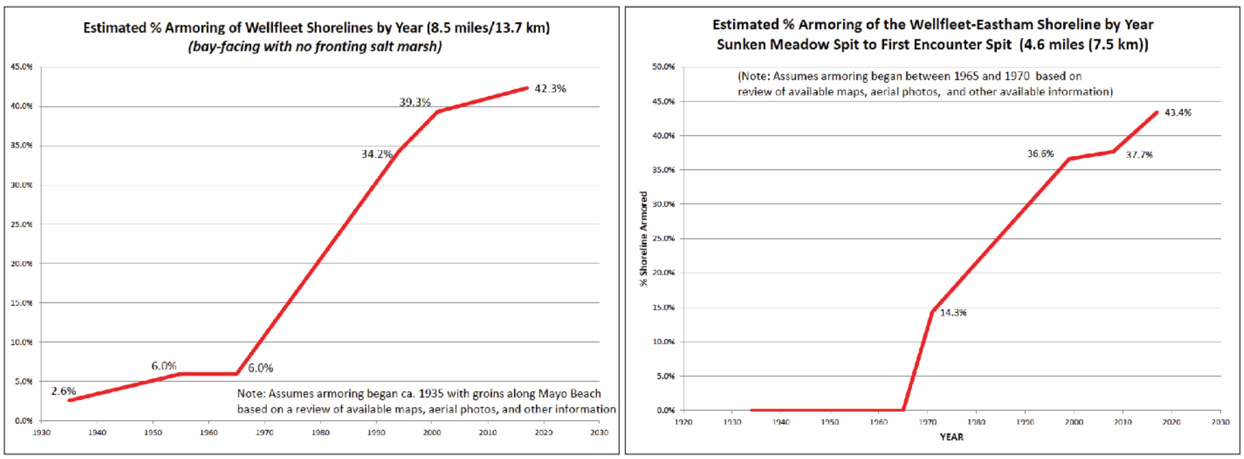


Figure 3. Armored shorelines for the study area by year for bayside shoreline only. **Left**: Wellfleet shorelines **Right:** Shorelines along Wellfleet/Eastham where the sediment budget was developed for this study.

METHODS

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 constructed at 15- meter intervals 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 $\boldsymbol{Q}$, but rather on its rate of change alongshore, d$\boldsymbol{Q}$/dy (cubic meters per meter per year), that is, the slope of $\boldsymbol{Q}$ when it is plotted against alongshore distance, "y". Erosion results when transport, $\boldsymbol{Q}$, increases alongshore (i.e., d$\boldsymbol{Q}$/dy is positive); deposition results when $\boldsymbol{Q}$ decreases alongshore (negative d$\boldsymbol{Q}$/dy). This relationship can be expressed 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. Unlike previous work along Cape Cod Bay, annual replenishment volumes along the Eastham/Wellfleet shoreline represent a significant gain for many of the transects and must be accounted for in the final calculations. These gains or losses are designated by $\boldsymbol{q}$, 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, $\boldsymbol{E}$**,** 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$\boldsymbol{Q}$/dy will yield the total values of $\boldsymbol{Q}$ at each point along the shore. At the updrift and downdrift cell boundaries are points where $\boldsymbol{Q}$ equals zero; these are termed "null points" (Dean and Dalrymple, 2002), and their location is required for a meaningful evaluation of $\boldsymbol{Q}$ 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, $\boldsymbol{Q}$, 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, "$\theta = 0$". Since the derivative of "$\sin 2\,\theta$" is proportional to "$\cos 2\,\theta$", it follows that

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

Thus $d\boldsymbol{Q}/dy$ is maximum at the null point ($\theta = 0$).

Model Adjustment

Numerical integration of $d\boldsymbol{Q}/dy$ to calculate $\boldsymbol{Q}$ is valid when transects are approximately perpendicular to the coastline and parallel to each other. For this study, $\boldsymbol{Q}$ was also calculated by summing $\Delta\boldsymbol{Q}$ values derived individually for each pair of transects. $\Delta\boldsymbol{Q}$, in turn, is the annualized change in volume between transect pairs - found from (1) the vertical change between profiles along each 1934/40 - 2010/17 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

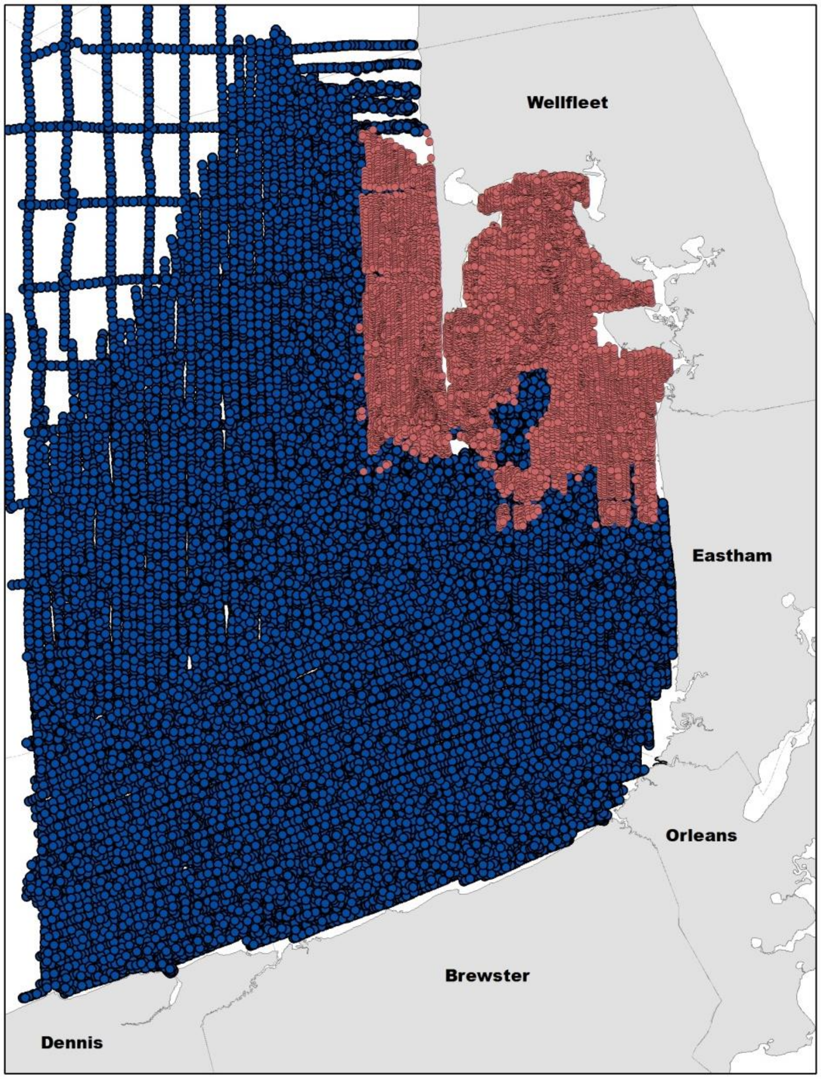


Figure 4. USC&GS Hydrographic 1933-34 Survey Point Coverage for Eastern Cape Cod Bay. Blue denotes survey H05543 data acquired May to August 1934 and red denotes survey H05401data acquired July to November 1933.

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. Two hydrographic surveys were conducted in eastern Cape Cod Bay by the USC&GS (predecessor to NOAA's Coast Survey) during 1933-34 (Figure 4). For the current work, these surveys were combined with adjacent terrestrial information provided on USC&GS topographic surveys (T-sheets), U.S. Geological Survey (USGS) Quadrangles, and U.S. Department of Agriculture, Natural Resource Conservation Service (USDA-NRCS) 1938 aerial photographs to provide a relatively seamless, synoptic coverage of the entire Cape Cod Bay study area

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 1:20,000 and related horizontally to 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 spatially 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 1933-34 and 1938 - 43 T-sheets, U.S. Geological Survey (USGS) quadrangles surveyed between 1940-1941, 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 mapped in 1933 prior to the 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, referenced vertically to local mean sea level and horizontally to NAD27, 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 depicted on the 1930s/40s Coast Survey T- and H-sheets.
3. 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. (see e.g., 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. For this study, all contemporary and historical 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)).

Data Compilation
The original horizontal reference system for the two USC&GS hydrographic data sets (H5543, and H5401) used to create the historical base map was the North American Datum (NAD). The horizontal conversion from NAD to NAD83 utilized the original survey control points established by USC&GS and its predecessor the U.S. Coast Survey to develop the mathematical relationship between NAD and NAD83 for the Cape Cod region and convert the hydrographic surveys to the project's horizontal datum (BSC, 2007).

To minimize vertical uncertainty, historical datasets were converted vertically to NAVD88 from the local 1933 MLW tidal datum used in the hydrographic surveys by reoccupying reference stations or benchmarks established 80 years ago to memorialize this 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. Field recovery and reoccupation of these benchmarks minimizes or eliminates much of the associated with the soundings.

The present study incorporates field work conducted in Provincetown to recover Tidal Benchmark 6 set by the United States Coast & Geodetic Survey in 1933 (TBM 6 of 1933). The Descriptive Reports for the H05401 and H05543 survey work memorialized the plane of reference for both surveys as "mean low water, reading 4.0 ft. on [a] tide staff at Provincetown, 15.8 ft. below B.M. 6". Based on archived information, the location of this tidal benchmark (TBM) was described as located in the top of a granite retaining wall on the east side of today's Macmillan Wharf. Using recovery methods developed for earlier CCS projects (Mague, 2012), this tidal benchmark was found under a soft drink machine located adjacent to the *Surf's Up* restaurant. Occupied with the Center's Real-Time Kinematic (RTK) GPS equipment, the survey results were used to relate the soundings of surveys H05401 and H05543 to NAVD88. The elevation of TBM #6 was compared with 1933 benchmarks recovered in the top step of the Post Office (TBM #8 of 1933), the easterly end of the "Bas Relief" on Bradford Street (TBM #7 of 1933) and the NE corner of the lowest step of the World War I monument in the eastern corner of the town hall lawn. These elevations agreed within 0.03 feet (~ 1cm). Based on this work, the relationship between the local mean low water used as the plane of reference for the 1933/34 surveys and contemporary MLW is shown in Figure 5.

Over 36,000 soundings from the two 1930s 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 a rigorous 84-year dataset (1933-2017) that covers an area of Cape Cod Bay in excess of 310 km^2 (120 mi^2). Approximately, half (48%) of these soundings (17,660) were located in the 96 km^2 (37 mi^2) nearshore area of this study, providing a valuable and reliable record upon which to apply the sediment budget-based geomorphic model approach of this study.

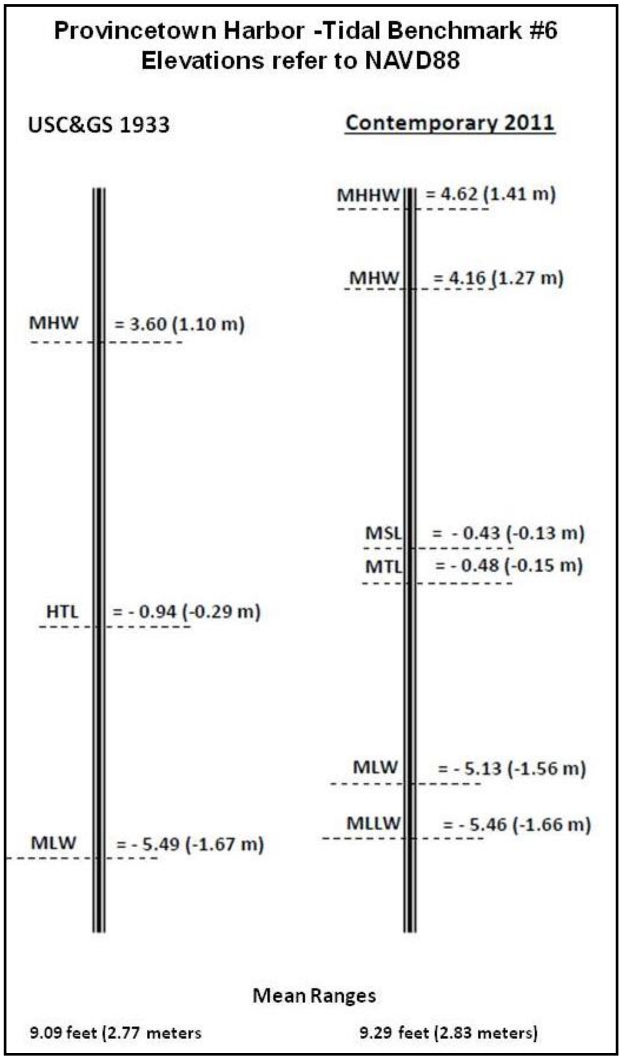


Figure 5. The Relationship between Contemporary and Historical Vertical Datums for the study area. Units: Feet (meters)

With the 1930s/40s vertical datum relationships established, 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 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

After converting historical data to the project datums, a 3-dimensional model of the surface was developed from the 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 spline method was chosen as the best interpolation method for this study as it holds the actual values of the survey data and interpolates in a manner that mimics 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 supplemented with vessel-based acoustic data collected by the Center for Coastal Studies in 2012 (Borrelli, et al., 2016), 2016 (Borrelli, et al., 2018) and 2017 (this study). 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.

Accounting for Uncertainty

To effectively use historical geospatial data, such as those central to the methodology discussed above, 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 both contemporary and historical hydrographic surveys, the accuracy of the final data product is related directly to the error associated with obtaining measurements.

As described in previous reports (see e.g., Giese, et al. 2016), where historical benchmarks can be reoccupied to eliminate uncertainty related to the plane of reference, the uncertainty associated with mid-1930s surveys conducted with lead lines close to shore, in shallow water (< 20 m), along regular seafloors such as the study area is estimated to be between 0.8 (0.25 ± m) -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). 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 21.5 km shoreline of the study area. These transects were combined with transects of previous studies, as shown in Figure 6. One hundred and forty-three (143) transects, were spaced at 150-meter intervals and extend initially out to a minimum depth of 10 meters.

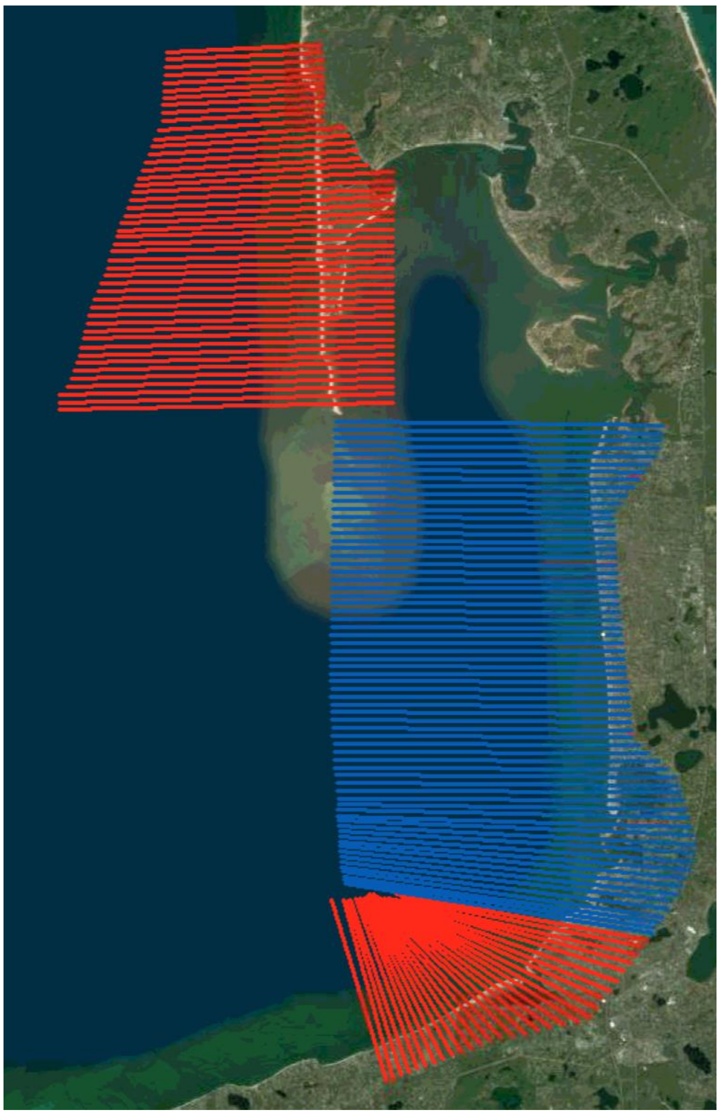


Figure 6. Study area with Historical surface with 143 transects overlain. The blue transects were those used to develop the quantitative sediment budget from Sunken Meadow Spit in Wellfleet to the First Encounter Spit in Eastham.

Using the historical and contemporary surface models, 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 ΔV/Δt 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, ***q***, for each segment. The local rate of change in net longshore transport, Δ***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 north and south of the null point".

RESULTS

This study created two digital elevation models extending across the land-sea interface, historical (ca. 1933) and contemporary (ca. 2017), from which profiles were extracted to develop a sediment budget and to complete a surface difference analysis. The latter is a quantitative, 3-dimensional comparison between the historical and contemporary surfaces that identifies nearshore areas of erosion and deposition over the previous ~84 years to understand the coastal processes at work in this continuously evolving area of Cape Cod Bay.

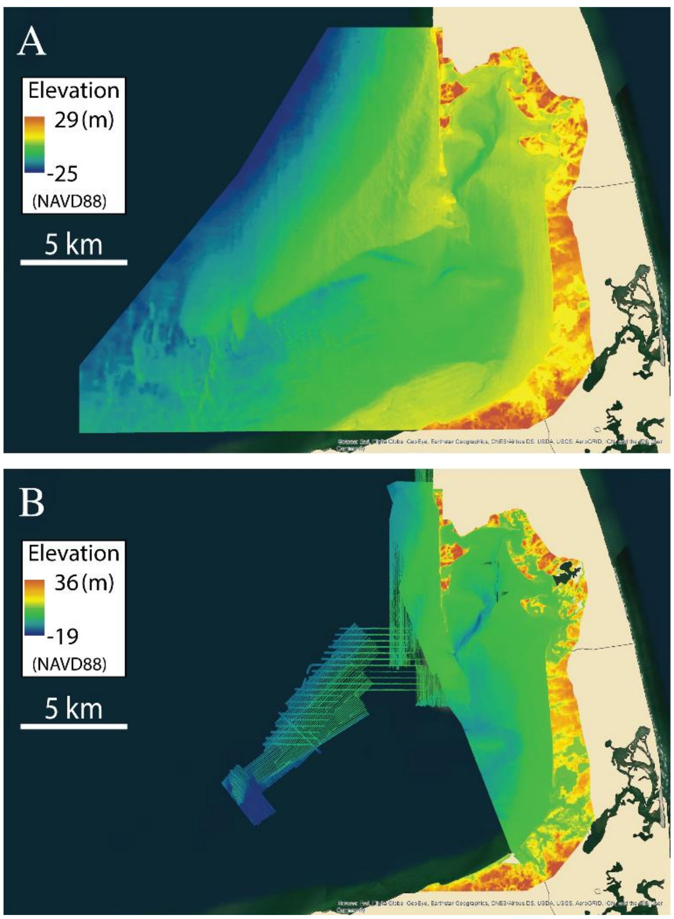


Figure 7. **A)** Study Area with historical surface (1930-40). **B)** Study area with contemporary surface (2010-17).

The historical surface is a seamless onshore/offshore map using both hydrographic and topographic survey data (Figure 7A). The contemporary surface is also a seamless onshore/offshore map created from multiple bathymetric and topographic Lidar data sets supplemented with vessel-based surveys filling in gaps and focusing on the areas of interest, including the shoreline along the 143 transects, Wellfleet Harbor, and Billingsgate Shoal (Figure 7B).

The sediment budget work is based upon the mathematical analysis of 2-dimensional shore perpendicular profiles. Although all 143 transects were analyzed, the focus of the sediment budget work was a subset of those transects from the Sunken Meadow Spit in Wellfleet south to the First Encounter Spit in Eastham. Figure 6 shows all transects considered in the analysis and the subset of 51 transects constructed along the 4.7 mile, north-south oriented westerly facing shoreline extending from Sunken Meadow in Wellfleet south to First Encounter Eastham.

Several factors influence the sediment budget development. First, transects north from Jeremy's Point to Provincetown and south and east to Brewster were largely analyzed during previous sediment budget work (Giese, et al., 2014c, Giese, et al., 2015), Second, similar to Barnstable Harbor in previous studies (Borrelli, et al., 2016b), Wellfleet Harbor is known to be fundamentally an area of uni-directional sediment movement fringed with extensive areas of salt marsh. For this reason, the alongshore bi-directional model of sediment transport was not applied to Wellfleet Harbor, which is treated similar to Barnstable Harbor in the 2016 analysis of the Sandwich/Barnstable shoreline, as a net sediment sink where transect analysis reveals little additional information.

Sediment Budget

The annualized volumetric sediment loss rates ("E" values) over the study period, 1933 to 2017, as determined for each cross-shore transect between Sunken Meadow Spit to the north and First Encounter Spit to the south are presented in Figure 8. As indicated in previous studies, positive "E" values denote erosion while negative "E" values denote accretion. As shown on Figure 8, over the 80+ year period, all but the extreme northern tip of Sunken Meadow Spit eroded at an average rate of 2.6 m^3/m/year (as indicated by the longer horizontal dotted blue line from transect 1978 to 2118), while the northern-most sector accreted at a rate of 3.2 m^3/m/year (short dotted blue line from transect 1968 to transect 1978). It is important to note that the E values are developed from the "active coastal zone", therefore, erosion or accretion along a stretch of beach may not be reflected in the 'E' values for a profile. In fact, in the northern part of the study area where the E values are denoting accretion, the shoreline change rates are among the highest for the entire study area.

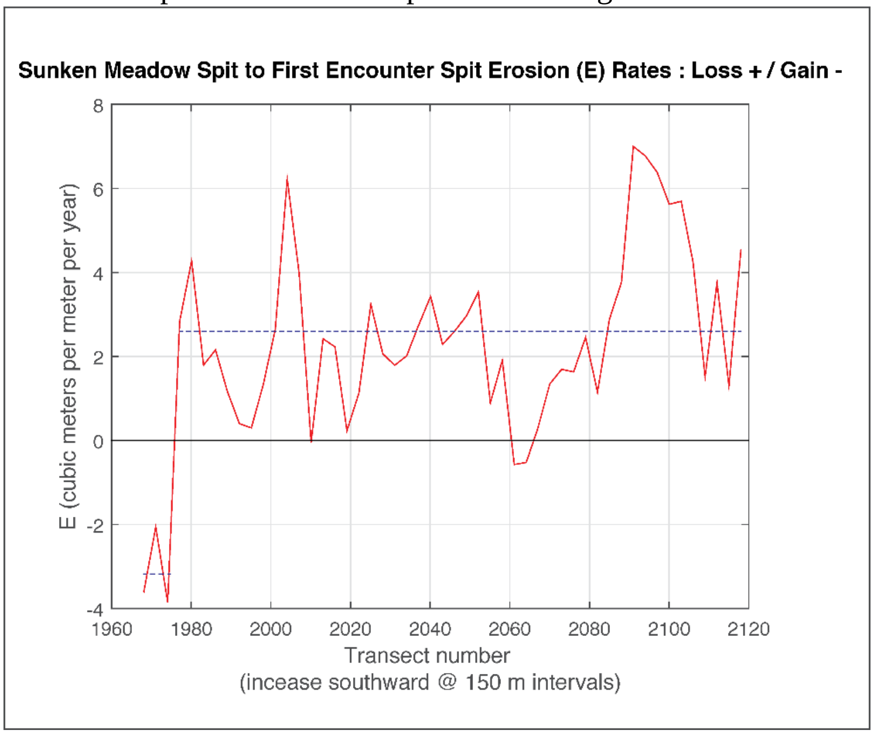


Figure 8. Distribution of E for all transects (net cross-sectional erosion/accretion rate) within the study area. Negative E values indicate accretion, positive values indicate erosion.

The calculated net alongshore sediment transport (“Q”) values – the quantity of principle concern for this segment of the study are plotted in Figure 9. The mid-point indicating no net transport, or “null point”, is found to be in the mid-section of the study area between Campground Beach and Thumpertown Beach. South of the null-point, southward transport rates increase to a maximum and level off at a rate of approximately 10,000 m^3/year in the vicinity of the base of First Encounter Spit. A similar pattern is found north of the null-point where northward transport increases to a maximum of 10,000 m^3/year and levels off at Sunken Meadow Spit.

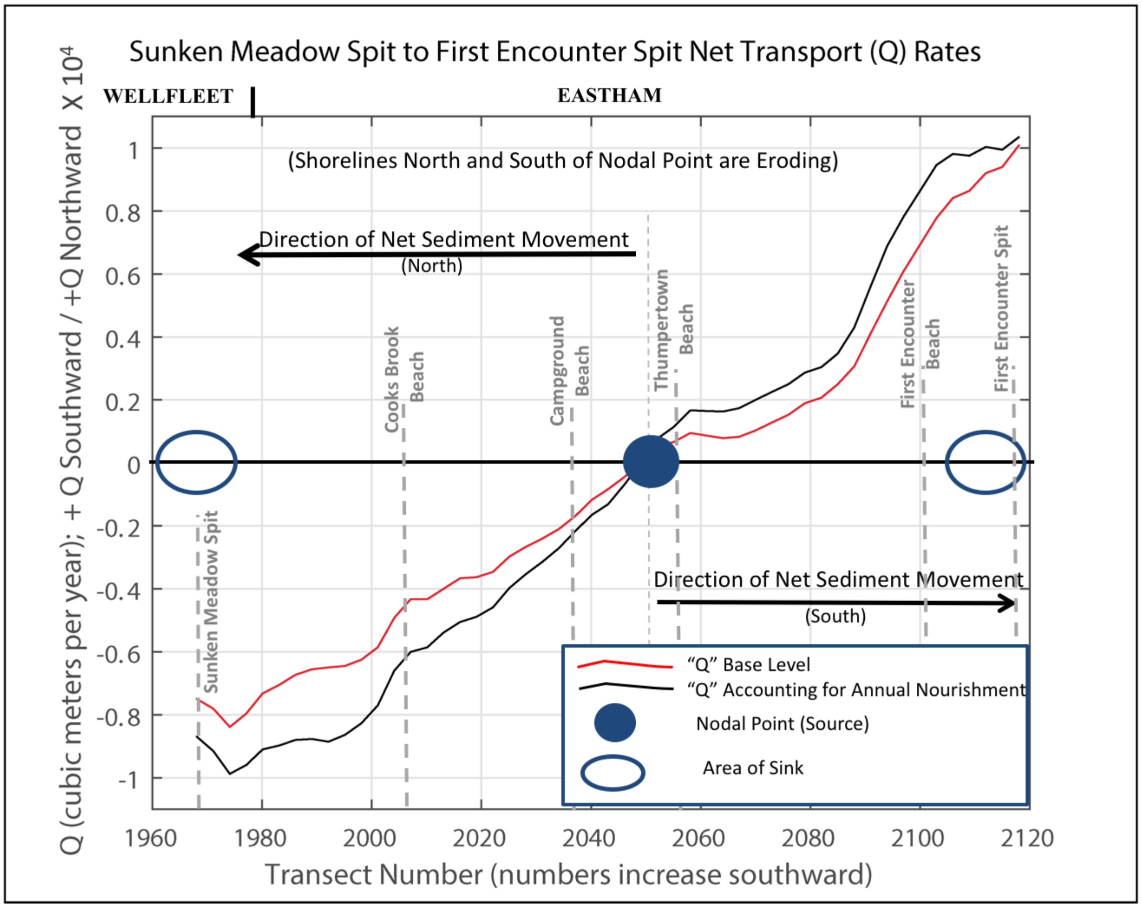


Figure 9. The Q-plot with beach locations, directions of net sediment transport, sinks and sources and nodal point. The red line is the ‘preliminary Q-plot’, the black line is the ‘actual Q-Plot’ that accounts for sediment input via required beach replenishment by shorefront properties protected by coastal engineering structures. These volumes were supplied by the Town of Eastham.

Beach Replenishment

Based on records provided by the Town of Eastham approximately 2,000 m^3 of sediment is added both north and south of the nodal point to the nearshore system annually. Figure 10 provides a general depiction of the current distribution of replenishment amounts along the shore. Since 2015 material has also been added to the system at four town landings, however, due to the short time frame these volumes are not reflected in the plots of “Q” shown in Figure 9.

These volumes represent cumulative annual replenishment provided by shorefront landowners as a condition of approval for the construction of coastal engineering structures. Replenishment volumes to be provided by individual parcel owners are calculated by multiplying the long-term shoreline retreat rate available through the CZM Shoreline Change Project, the average height of the adjacent coastal bluff to be armored, and the shoreline parcel length. Generally, replenishment activities take place in early spring of each year with all work completed by the middle of April. Significant replenishment has been ongoing since approximately 1999 when this requirement was added as a condition of approval by the Conservation Commission to Orders of Conditions allowing coastal bluff armoring in accordance with the Wetlands Protection Act.

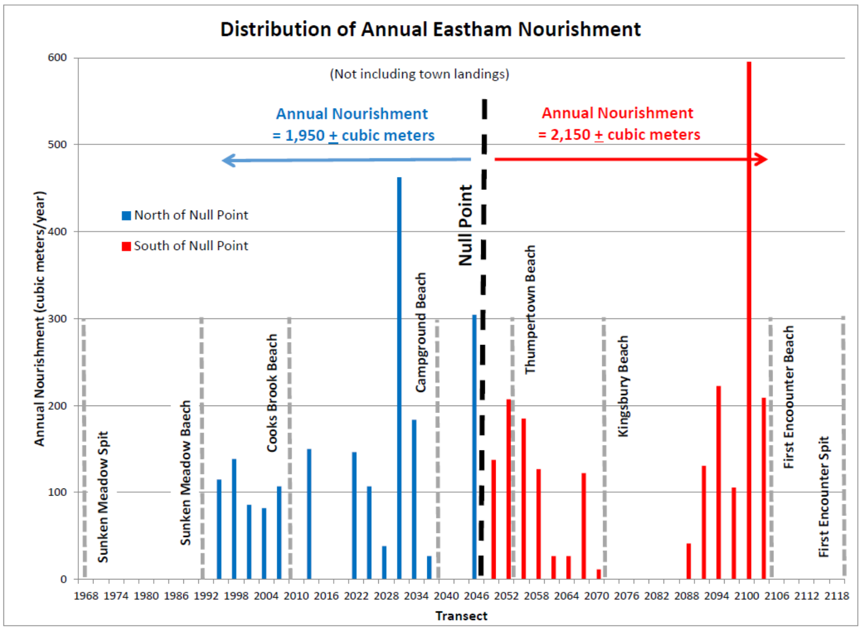


Figure 10. Annual replenishment throughout the area where the sediment budget was developed.

To better understand the effect of annual beach replenishment efforts in the study area we developed a “Preliminary Q” (or “pre-Q”) diagram – a line providing an estimate of what the Q plot would have looked like if all such “cross-shore” losses or gains from or to the active zone were neglected. Such a “pre-Q plot” for the study area is represented by the red line in Figure 9 together with the “actual Q plot” (black line). Remembering that the actual transport rates, estimated by the “actual Q plot”, are the product of the physical environmental processes acting on the coast and is altered by cross-shore losses or gains, the differences between the lines provides an estimate of the contribution of those cross-shore losses and gains to the actual transport rates. Estimates made from Figure 9 suggest that total wave and tide induced erosion of the active zone in the study area is reduced by approximately 20% as the result of the town-mandated beach replenishment.

The sediment budget, as seen in Figure 9, shows no net longshore sediment transport at the nodal point along the entire active zone. Although this seems counterintuitive, two points should be noted. First, the ‘E’ values in Figure 8 reflect the ongoing erosion along most of this nearshore zone and second, ‘E’ values (Erosion) and subsequent ‘Q’ (Sediment Budget) values are measuring change along the entire active coastal zone, not just the beach. The net sediment increases as it moves away from the nodal point. This increase is seen in either direction, both north and south and with similar values. This occurs because of the cumulative nature of net sediment transport calculations.

DISCUSSION

A central objective of this study’s sediment budget analysis is to estimate the century-scale volume rate of net sediment transport, “Q”, along the “active zone” of the area from Sunken Meadow Spit to First Encounter Spit and to identify the source and sink areas of the transported sediment. We have estimated that approximately 20,000 m^3 of sediment are exported from the study area each year, about half of that leaving to the south and about half to the north. Thus, practically the entire area serves as a source of sediment for the greater Wellfleet-Eastham-Orleans coast of Cape Cod Bay. Only the area near the northern tip of Sunken Meadow Spit has accreted (Figure 8).

Figure 9, a plot of Q showing the annualized rate of sediment transport along the Eastham-Wellfleet shoreline represents a summary of the sediment budget work completed for the study area. Negative “***Q***” values indicate northward transport; positive values, southward transport. As shown on the figure, the volume of sediment transport increases as you move away from the nodal point, shown as the blue dot. As explained in the Methods section above; net transport rates range from zero at this location to a maximum of almost 10,000 cubic meters per year, which includes replenishment estimates as discussed below, at the northerly and southerly ends of the system.

As shown on Figure 9, the positive slope associated with the plot of the Q values indicates that almost the entire shoreline is an area of erosion, functioning historically as a source area for the northerly and southerly littoral drift in the region. An area of accretion begins at the northerly end of the study where the slope of the Q-plot becomes negative, leading into the net sink area of Wellfleet Harbor. As discussed above, the degree to which the shoreline has been armored has limited the amount of sediment available to the system in recent years. Although material is added annually along the shoreline both north and south of the nodal point as shown in Figure 10, a more effective placement of material may be possible when viewed in the context of the Q-plot.

As mentioned above, it is helpful in reviewing the results to recall that this analysis is based on two distinct data sets. The first of these is the set of "E" values, the annualized sediment loss (or gain) measured at each of the 51 cross-shore transects within the "active zone" of the study area; the second is the set "q" values, the annualized sediment addition to, or removal from, the active zone of each transect - that is to say, sediment additions that did not originate in that zone, or sediment losses from it.

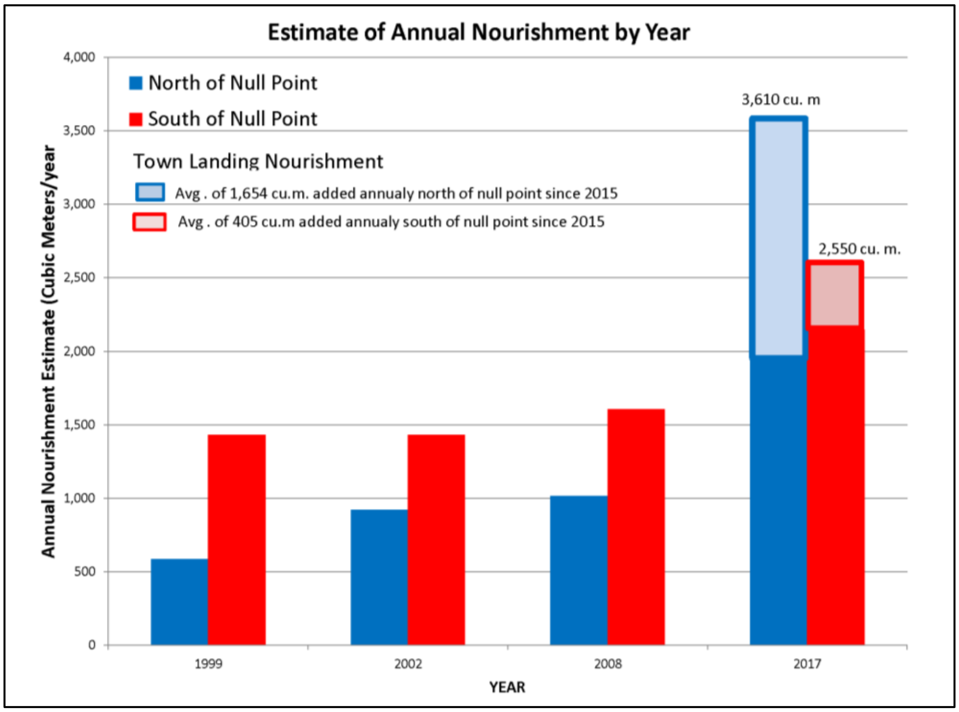


Figure 11. Estimates of annual beach replenishment within the Town of Eastham.

Figure 11 shows the annual replenishment by the town at four town beaches (Sunken Meadow, Cook's Brook, Campground, and Thumpertown Beaches). Since records extend back only to 2015, these replenishment activities were not incorporated into budget calculations, however, if continued they will add on average 1,650 cu. m^3 of sediment north of nodal point and 400 cu. m^3 south of the nodal point. Combined with the replenishment requirements for individual landowners, approximately 3,600 cu. m^3 of sediment is being introduced north of the nodal point while 2,550 cu. m^3 south of the nodal point. Representing, in excess of, 20% of the maximum rates of longshore sediment transport at the northerly and southerly ends of this shoreline, this annual replenishment clearly has helped to mitigate the potential sediment depletion effects of armoring approximately 43% of this shoreline (Figure 12).

As a net sink similar (but significantly smaller than) Wellfleet and Barnstable Harbors, Rock Harbor, the small embayment between the Towns of Eastham and Orleans, is episodically dredged to maintain navigable waters. The Harbor has been dredged three times since the mid-1970s. In 1977 approximately 23,000 m^3 were dredged, in 2004 more than 15,250 m^3 was removed from the harbor and most recently in 2014, more than 16,000 m^3. From 1977 to 2014 54,250 m^3 of sediment was removed from Rock Harbor. From 1997 to 2004 more than 15,250 m^3 were removed which is a rate of ~565 m^3/yr. From 2004 to 2014 16,000 m^3 were removed which is a rate of more than ~1600 m^3 /yr. Given the volumes and directions of sediment transport determined by the sediment budget the material deposited into this sink could serve as a beneficial source of sediment with which to supplement the town's annual replenishment program.

Sediment Budgets and Coastal Management

Quantitative sediment budget information depicting base level volumetric transport rates, directions of net sediment transport, littoral cell definition, and the locations of sediment sources, sinks, and nodal points provides coastal mangers with science-based data upon which to base decisions related to optimizing sediment placement and amounts, the identification of potential sources of nearshore replenishment material, and conversely the identification areas where replenishment material should not be placed.

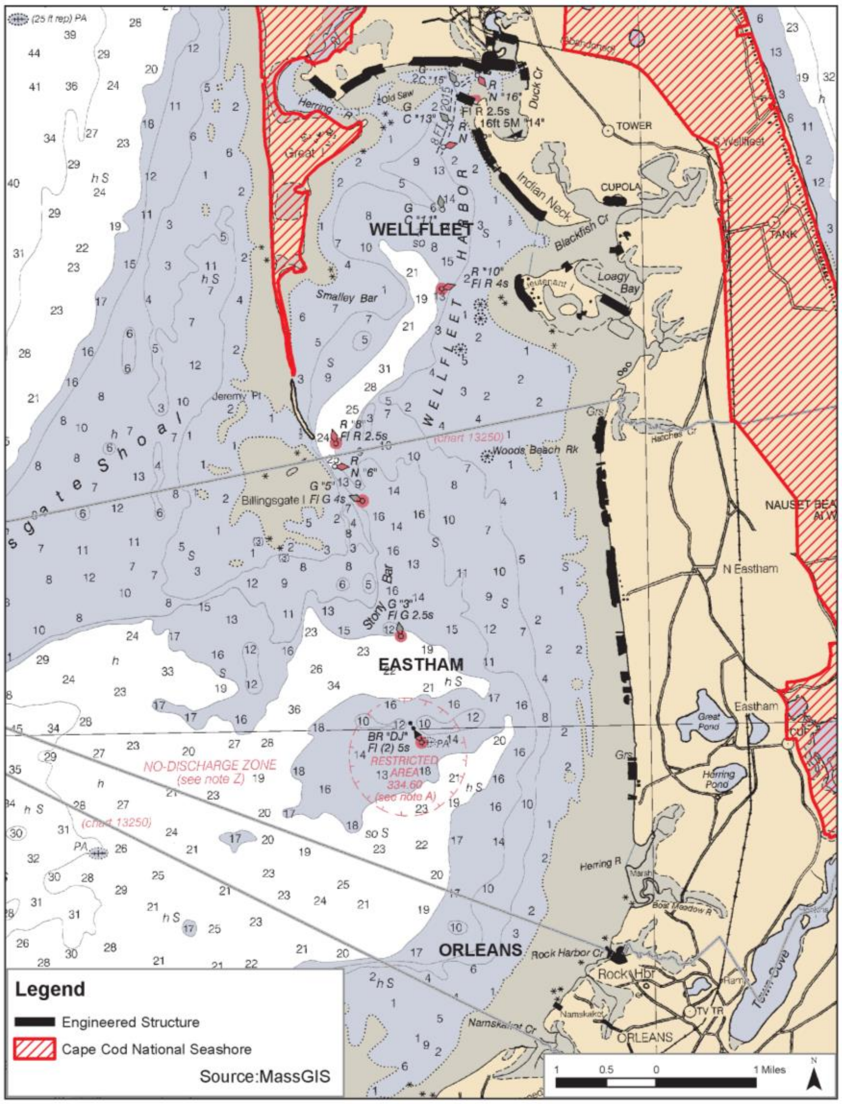


Figure 12. Location of Public and private engineering structures in Eastham and Wellfleet. Note: as shown in Figure 2 approximately 43% of the bay-facing Wellfleet shores and the westerly facing Eastham/Wellfleet shorelines are armored. Armoring is prohibited along the shores of the Cape Cod National Seashore

Depositional and Erosional Trends in the Nearshore

Comparisons of historical and contemporary surfaces, or surface differences, can depict overall trends in deposition or erosion throughout nearshore areas (Figure 13). Figure 14 shows profiles comparing elevations from each surface along two transects from the study area. The main navigation channel in the southern part of Wellfleet

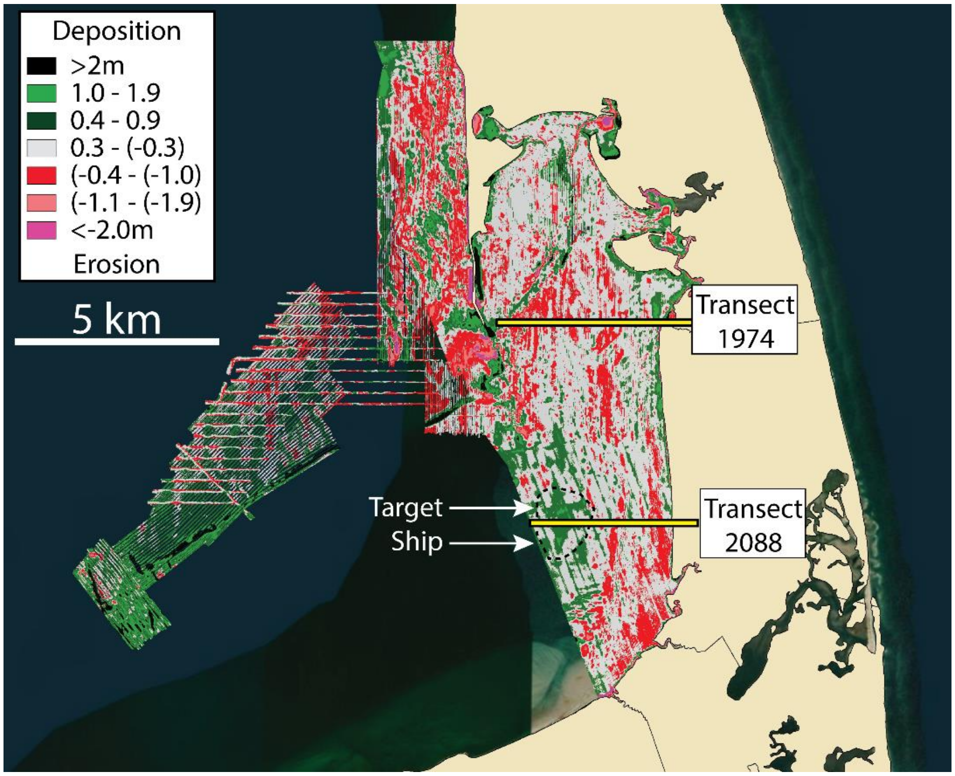
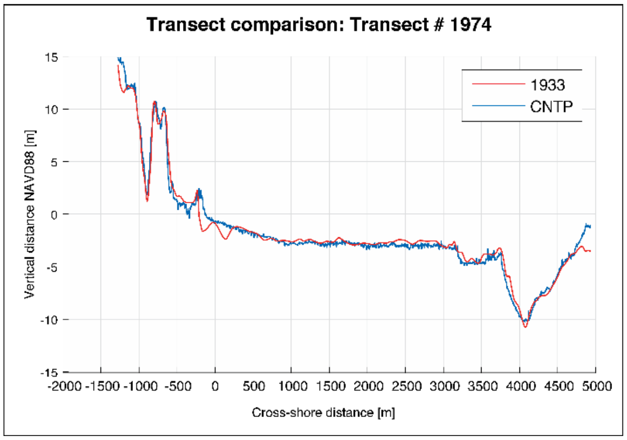


Figure 13. The surface difference between the historical and contemporary surfaces. The light gray areas are within the range of uncertainty (±0.30 m). The 2 yellow lines indicate the approximate location of the two transects in Figure 13.

Harbor as seen in Figure 14 (profile 1974), shows a channel that is slightly widening. The eastside of the channel has migrated eastward. This long-term change provides insights into channel evolution and migration and could have implications for future dredging projects. The surface difference shows similar changes in several places along the main harbor channel (Figure 13). Similarly, both the surface difference and the profiles document the changing morphology of the area in proximity to the former US Navy target ship, the SS James Longstreet. Sediment has been depositing in the lee (eastward) of the Longstreet between 1933 and the present. This can be seen in the surface difference (Figure 12) as a large area of deposition as well as in the profile nearest the area (Figure 14). It is likely th2t the antecedent, or pre-existing, topography on which the ship was sunk served to reduce the wave energy that reaches the shoreline in this area prior to the intentional grounding of the ship. Subsequently, more deposition has occurred in the lee of the ship, similar to what one would expect landward an offshore breakwater. Other areas along this shoreline have likely experienced decreased wave energy in the ‘wave shadow’ of the former target ship, an effect that will be most prominent for west and northwest winds.

Regional Implications for Coastal Processes and Management

The sediment budget quantified for the west-facing Wellfleet/Eastham shoreline uses historical and contemporary data to measure volumetric change in the active coastal zone for the 84-year period from 1933 to 2017. These areas have many erosion control structures that limit sediment input from eroding coastal bluffs. A better understanding of the impacts of these structures is needed to optimize future management decisions. Although clearly having a positive effect, continued use of the long-term shoreline erosion rate and the height of the coastal bluff may be inadequate to determine the amount of sediment required to sustain the system. In addition to the visually prominent landward migration of the high water line, the entire active sediment transport zone continues to evolve and must be considered as part of comprehensive sediment management decisions.



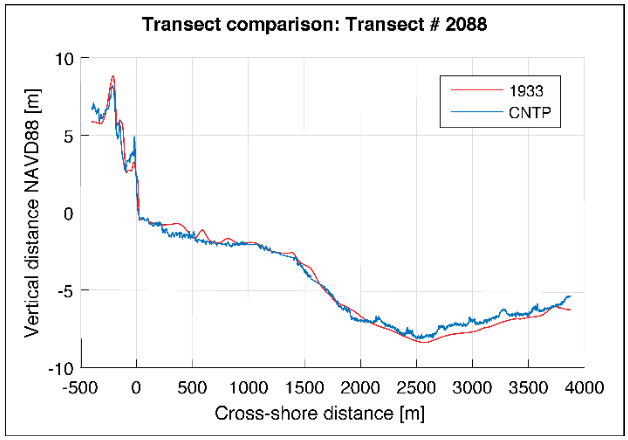


Figure 14. Example of profiles from study area. **Left:** Transect exhibits both erosion and deposition. Note the contemporary (CNTP) profile has more data associated with it and therefore more detail is seen. **Right:** Profiles along transect 2888 that pass near the *Target Ship*. Note that from ~2500 m to ~3500 m there is substantial deposition, >1 m in the proximity to the *Target Ship*. The location of the two transects is shown in Figure 12.

Billingsgate Shoal provides some protection for these shorelines. A closer examination of the evolution of this feature is necessary, however, to provide more insight into the historical evolution of the area as well as a better understanding of future shoreline and sediment budget responses to sea level rise and increased storm tides. How will Billingsgate Shoal be affected by sea level rise? Is there an elevation or rate of sea level rise that will reflect a point at which steps must be taken along this shoreline? What are those steps? The area in and around the target ship could also be studied in a similar way and although it is a much smaller feature, its proximity to the shoreline could make it equally important to an understanding of the evolution of both the Wellfleet and Eastham shorelines.

CONCLUSIONS

A quantitative sediment budget was developed for the Wellfleet/Eastham shore of Cape Cod Bay combining previous work performed for the Massachusetts Bay Program 2014 ending at Jeremy's Point in Wellfleet with similar work performed as part of a CZM Resiliency Grant ending west of Rock Harbor along the Brewster shore completed in 2015. The present study represents completion of work by CCS to develop a century-scale sediment budget and to map littoral cells for Cape Cod Bay from the Cape Cod Canal to Provincetown.

For this study data from the 1930s and recent data from 2010-2017 were used to develop historical and contemporary three-dimensional surface models, respectively. These data were then used to quantify the sediment budget and document volumetric changes for this 84± year time period. Sediment budgets document the direction and volume of sediment movement as well as the sources and sinks of sediment in the nearshore zone.

A quantitative, century-scale sediment budget for the Towns of Eastham and Wellfleet along approximately 7.6 km (4.7 miles) of shoreline from the Sunken Meadow Spit in Wellfleet to First Encounter Spit in Eastham was developed. Based on shore-perpendicular transects constructed at 150-meter intervals, single nodal point was estimated to occur being approximately halfway between Campground and Thumpertown Beaches in Eastham. A nodal point is a location along the shoreline where the net longshore sediment transport diverges.

Based on a quantitative analysis of transects, the maximum rate of longshore sediment transport was determined to approach 10,000 m^3/yr both at Sunken Meadow Beach to the north and First Encounter Beach to the south for a total of 20,000 m^3 exported from the area annually. The average volume of sediment introduced into the system by private shorefront property owners since approximately the year 2000 via annual beach replenishment is approximately 2,000 m^3 both north and south of the nodal point. This introduced material accounts for nearly 20% of the annual north/south longshore sediment transport and is an important factor in mitigating the reduction in sediment provided to the longshore system associated with the armoring of approximately 43% of the 7.6 km (4.7 miles) shoreline. Since 2015, with sand added annually by the town at four public landings, this replenishment number has increased to approximately 3,600 m^3 north of the nodal and 2,550 m^3 south of the nodal point.

The surface difference analysis shows relatively little sediment erosion or deposition in the nearshore system, which along with the relatively low rates of longshore sediment transport discussed above is indicative of a low energy shoreline. Notwithstanding this observation, however, in addition to annual replenishment activities, the sediment dredged from Rock Harbor, if compatible and placed at effective locations, would benefit efforts to manage the ongoing erosion problem seen along this shoreline. If this option is pursued the results of this work and in particular the sediment budget should be used when placing the sediment from Rock Harbor along the beach. In particular, the location of the replenishment material, the nodal point and the desired beaches to be replenished should be considered in tandem.

Toward that end, towns may want to consider a regional approach to sediment management, that promotes proactive planning for the annual placement of replenishment material and the periodic placement of Rock Harbor dredged material at the most effective locations along the shoreline. These and other issues, such as administration and management of this type of approach could be overseen by a shoreline management commission with representatives from both Wellfleet and Eastham to ensure effective and efficient management of natural resources.

ACKNOWLEDGEMENTS

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GLOSSARY OF TERMS

Term	Symbo l	Units	Description
Alongshore gradient of annual net longshore transport	d***Q***/dy	meters^2/year or meters^3/meter/y ear	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/y ear	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/y ear	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/y ear	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.

Borrelli, M., Giese, G.S., Mague, S.T., Smith, T.L., Legare, B. and Barger, P., 2016a. Assessment of the Century Scale Sediment Budget for the Sandwich and Barnstable Coasts of Cape Cod Bay: Cape Cod Canal to Barnstable Harbor, Center for Coastal Studies.

Borrelli, M., Smith, T.L., Legare, B., Shumchenia, E.J., Norton, A.R. and Brown, T.L.B., 2016b. Nearshore Seafloor Mapping in Cape Cod Bay, Massachusetts: Technology, Methods and Lessons Learned. A Report Submitted to the Massachusetts Office of Coastal Zone Management.

Borrelli, M., Fox, S.E., Shumchenia, E.J., Kennedy, C.G., Oakley, B.A., Hubeny, J.B., Love, H., Smith, T.L., Legare, B., Mittermayr, A., McFarland, S.J. and Giese, G.S., 2018. Submerged Marine Habitat Mapping, Cape Cod National Seashore: A Post-Hurricane Sandy Study, National Park Service, Fort Collins, CO.

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.

Massachusetts Department of Conservation and Recreation, Office of Waterways. 2009. *Massachusetts Coastal Infrastructure Inventory and Assessment Project: Inventory of Publicly Owned Coastal Structures***.** *Outer Cape Cod North – Provincetwon, Truro, Wellfleet, Eastham.* July 6, 2009. https://www.mass.gov/service-details/inventories-of-seawalls-and-other-coastal-structures, accessed: June 6, 2018.

Massachusetts Office of Coastal Zone Management, 2013. *Mapping and Analysis of Privately Owned Coastal Structures along the Massachusetts Shoreline*. Applied Science Associates, Inc., (dba RPS ASA). March 31, 2013. https://www.mass.gov/files/documents/2016/08/nk/private-coastal-structures-2013.pdf, accessed June 6, 2018.

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.

T and H-Sheet Descriptive Reports

1933 - U.S. Coast and Geodetic Survey. *Descriptive Report, Hydrographic Sheet No. 1, 5400. Cape Cod, Provincetown Harbor and Vicinity. 15 pages.*

1933 - U.S. Coast and Geodetic Survey. *Descriptive Report, Hydrographic Sheet No. 2, 5401. Cape Cod, Wellfleet Harbor. 38 pages.*

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

Cartographic and Bathymetric Data Used in this Project

1848 - U.S. Coast Survey. T-259. *Map of Cape Cod from Billingsgate to Pamet River,* A.D. Bache, Supt., Topographical Survey made during part of July and August. 1848. Scale 1/10,000.

1851 - U.S. Coast Survey. T-368. A.D. Bache, Superintendent, *Wellfleet Harbor, Cape Cod, Massachusetts*. Surveyed by J.B. Gluck. Scale 1/10,000.

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.*

1933 - U.S. Coast & Geodetic Survey, R.S. Patton, Director, Topographic Survey No. 6034. *Wellfleet and Vicinity, Cape Cod, Mass.* Date of Survey: June 1 to Nov. 1, 1933. Scale: 1:20,000. Chief of Party: K.T. Adams. Surveyed By: R.K. Lynt, C.N. Strong.

1933 - U.S. Coast & Geodetic Survey Hydrographic Survey No. 5401, *Wellfleet Harbor,* Cape Cod, Massachusetts. July 1 – Nov. 8, 1933. 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, R.S. Patton, Director, Topographic Survey No. 6112. *Brewster to Wellfleet Harbor, Cape Cod, Massachusetts.* Date of Survey: May, June 1934. Scale: 1:20,000. Chief of Party: E.A. Daily. Surveyed By: E.A. Fowler.

1934 - U.S. Coast & Geodetic Survey Hydrographic Survey No. 5543, *Billingsgate Shoal,* Cape Cod, Massachusetts. May to Aug, 1934. Scale 1:20,000. (*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, & 1943 - U.S. Coast & Geodetic Survey Topographic Map No. T-5733, Massachusetts, Cape Cod, *Wellfleet-Truro and Vicinity*. Scale 1:10,000.

1938, 1941, & 1943 - U.S. Coast & Geodetic Survey Topographic Map No. T-5734, Massachusetts, Cape Cod, *Wellfleet Harbor and Vicinity*. Scale 1:10,000.

1938, 1941, & 1943 - U.S. Coast & Geodetic Survey Topographic Map No. T-5735, Massachusetts, Cape Cod, *Orleans and Vicinity*. Scale 1:10,000.

1952, & '53 – U.S. Coast & Geodetic Shoreline Manuscript, T-11181, Massachusetts, Cape Cod Bay, *Wellfleet Harbor*. Scale – 1:10,000.

1952, '53, & '55 – U.S. Coast & Geodetic Shoreline Manuscript, T-11183, Massachusetts, Cape Cod Bay, *Eastham*. Scale – 1:10,000.

1952 & '55 – U.S. Coast & Geodetic Shoreline Manuscript, T-11188, Massachusetts, Cape Cod Bay, *Quivett Creek to Boatmeadow River*. Scale – 1:10,000.

1941 - U.S. Geological Survey, Wellfleet Quadrangle. Based on Survey performed in 1941. Scale: 1:31,680.

1942 - U.S. Geological Survey, Orleans Quadrangle. Based on Survey performed in 1940, 1941. Scale: 1:31,680.

1943 - U.S. Geological Survey, Dennis Quadrangle. Based on Survey performed in 1940. Scale: 1:31,6