ABSTRACT

Title of thesis: DYNAMIC EQUILIBRIUM BEACH PROFILES: FORCES OF OFFSHORE SEDIMENT TRANSPORT IN MARYLAND'S CHESAPEAKE BAY

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To examine the impact of shoreline erosion on the near shore environment, it is necessary to estimate the quantity and quality of yearly sediment mass that is likely to be added by erosion. Data were collected in 2008 at ten sites along the Maryland shoreline of the Chesapeake Bay and compared to both empirical and theoretical models of offshore profiles. The data collected at each site included a series of three-dimensional bathymetric profiles from offshore transects run at each site, as well as a series of sediment core data that were acquired along each transect. Relationships between grain size, beach type, sediment composition, and strength of eroding sediments were also explored. The results showed that sands dominated offshore surficial sediments at most locations, even though the source sediments were mixtures of sands and muds. The observed offshore profiles were consistent with expectation from ocean beach profile paradigms, with the exception that the steepness proportionality factor was not related to sediment grain size. An adjusted form of the classic Bruun relationship for predicting shoreline retreat was in approximate agreement with long-term observations.

DYNAMIC EQUILIBRIUM BEACH PROFILES: FORCES OF OFFSHORE SEDIMENT TRANSPORT IN MARYLAND’S CHESAPEAKE BAY

by

Lynda Bell

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland at College Park in partial fulfillment
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Dr. William Nardin, UMCES

Dedication

I dedicate this work to my father, Robert Vincent Creter, who inspired me to become a scientist from the time I was a little girl. Pop was a Maryland DNR biologist at the time when environmental science was just in its pioneering stages, from the late 1960's through the 1980's. Dad's division of the DNR piloted some of the first cleanup efforts on the Chesapeake Bay as well as some of the first protective acts for bay fisheries. The moratorium on rockfish harvesting was set during his time, helping return this native species at a commercial level today. His work, and his stories of the watermen and the Chesapeake brought me back time and again to those beloved waters. First, as a "bay kid" swimming, crabbing, and sailing in the Chesapeake. Later, as an environmental educator working at Horn Point's wonderful Environmental Ed center as a teacher helping bring students to the beautiful shores of the Choptank. And finally, today, I have the great honor of joining the MEES program as a graduate student. My time with the faculty and staff at MEES returned me to the Chesapeake in a way that allowed my curiosity and study of this fascinating place to deepen and grow. And now, it is with gratitude and honor that I present this work to the University of Maryland Graduate School in support of a degree of Master of Science.

Acknowledgements

I would like to acknowledge my advisor, Dr. Lawrence Sanford for his insight and support over the years and for the creative inspiration for this project. I would also like to acknowledge my thesis committee of Dr. Cindy Palinkas, and Dr. William Nardin for their time in helping to shape and fine tune our work. Finally, I would like to acknowledge Jeffery Halka, and Richard Ortt, of the Maryland Geological Survey for providing the field and laboratory expertise and support needed for this work.

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List of Abbreviations

1. UMCES, University of Maryland Center for Environmental Science
2. (*A*), Equilibrium Profile Parameter
3. **A-A'**, Measured Bathymetry Transect End Points
4. A, Sea Level Height used in Bruun's Rule

Chapter 1: Introduction

Sea Level Rise

Sea level is an extremely sensitive index of change and variability in the Earth's climate system. Global changes in climate can result in thermal expansion of the world's oceans, which can lead in turn to a consequent rise in global sea level. Other short-term climatological changes affecting global sea level are fluctuations in freshwater input due to rapidly melting glaciers, coupled atmosphere-ocean perturbations, and anthropogenic or climatological modification of the land hydrological cycle. Longer term changes affecting sea level include the viscoelastic response of the solid earth to isostatic rebound and tectonic activity, and changes in the mass balance of ice sheets.

While sea level has remained fairly stable since the end of the last deglaciation (Lambeck et al., 2004), more recent changes in sea level rise have been seen in the tide gauge record starting shortly after the beginning of the industrial era in the late nineteenth century (Douglas 2001, Cazenave et al, 2010). In addition to tide gauge records showing evidence of global sea level rise, mean sea level changes have been measured by high precision satellite altimeters with accurate orbits since 1992. Global mean sea level variations have been computed from 1993-2009 using TOPEX/Poseidon, Jason-1, and Jason-2 satellite altimetry, yielding rates of 3.4 +/- 0.4 mm/yr (Nerem et al, 2010, Ablain et al, 2017, Nerem et al, 2018). This rate of sea-level rise is expected to accelerate as melting of the ice sheets as well as ocean heat content increase as greenhouse gas concentrations rise.

Acceleration of sea-level rise over the 20th century has already been inferred from tide-gauge data (Church et al, 2006, Merrifield et al, 2009, Dangendorf et el, 2017), although sampling and data issues preclude a precise quantification. The satellite altimeter record of sea-level change from TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3 is now approaching 27 years in length, making it possible to begin probing the record for climate-change–driven acceleration of the rate of global mean sea level change (Chen et al, 2017).

In addition to a clear observation of global mean sea level rise from tide gauge and altimetry data, important regional variability has also been reported. In situ ocean temperature data, mountain glacier surveys, satellite measurements of the mass balance of ice sheets, and space-based gravity data from the GRACE mission have allowed quantification of the contribution of ocean warming to sea level rise (Cazenave et al, 2010, Tapley et al, 2019).

The physical impacts of sea level rise on coastal systems can include flooding in association with storm surges, wetland loss, shoreline erosion, saltwater intrusion in fresh surface water bodies and aquifers, and rising water tables. Changes in dominant wind, wave, and coastal current patterns in response to local or regional climate change and variability may also impact shoreline equilibrium. Shoreline erosion is generally believed to be accelerated due to sea level rise (Bird, 1996) with more than 70% of the world's beaches retreating because of sea level rise and anthropogenic forcing (Valiela, 1995, 2006). As sea level has risen during the 20th century, rates of beach erosion in the United States alone have averaged approximately 1 m/yr (Leatherman et al, 2000, Leatherman, 2018).

The Chesapeake Bay, the largest estuary in the United States, is a complex estuarine system surrounded by a dense network of tributaries with areas of massive marsh erosion that have been impacted by rising sea level in the last century. The Chesapeake Bay area is the third most vulnerable area of the United States to sea level rise, behind Louisiana and South Florida. For the Chesapeake Bay, global sea level rise is compounded by substantial land subsidence rates due to the combination of groundwater withdrawal and natural geologic effects associated with post glaciation adjustments (Runkle et al, 2016).

Although satellite altimetry data has been used worldwide to constrain estimates of global and regional sea level rise data to accuracies of 1-2 mm, altimetry data coverage is too broad in the area of Maryland and Virginia's Chesapeake Bay to accurately estimate sea level changes. Historic sea level rise in the Chesapeake Bay has been measured primarily with tide gauges and observations of shoreline loss. Historic eustatic sea level rise has increased from 0.5 mm per year, from 1000 to 1850AD, to more than 3.2 mm per year during the 20th century (Stevenson et al, 2002). Linear trends in relative sea level heights in the Chesapeake Bay, as measured by tide gauges from 1955-2007, ranged from 2.66 +/- 0.075 mm/yr at Baltimore, Maryland to 4.40 +/- 0.086 mm/yr at Hampton Roads, Virginia (Barbosa and Silva, 2009). Due to the gentle slope of most of the Chesapeake Bay margin, a sea level increase of this magnitude over the last 50 years poses a significant threat in terms of wetland loss and environmental impact. The decadal rate in the 1990s was also unusually high. This unprecedented rate triggered marsh losses in both the Chesapeake and Delaware bays. Historic Landsat Thematic Mapper satellite imagery suggests that more than half of the tidal marsh area of the Chesapeake Bay shows signs of degradation (Kearney et al, 2002).

The Link Between Sea Level Rise and Shoreline Erosion

One of the primary consequences of sea level rise in Maryland's Chesapeake Bay is shoreline loss, especially along marshy shorelines. Shoreline loss is an issue of concern for many coastal landowners, as well as for communities dependent on coastal habitat for recreation and commercial fishing industries. A healthy dynamic shoreline should behave in a balanced manner with episodic events of erosion and accretion, creating a dynamic equilibrium in the nearshore and offshore environment. Seasonal changes, storms, orientation of shorelines (fetch), wind, and other local factors help to shape and design a balanced, dynamic shoreline. When sea level rise increases to the level that natural dynamic processes cannot compensate for it, permanent degradation of the shoreline ensues.

Shoreline Erosion Effects on the Nearshore Coastal Environment

The effects of erosion on near shore water quality and habitat are complex, as are the effects of different types of shore protection structures. Estuaries and coastal embayments of the Mid-Atlantic region have been significantly impacted by erosion, loss of submerged aquatic vegetation (SAV), loss of marsh, increasing shoreline hardening, nutrient enrichment, declines of key species from overharvesting and disease, and hypoxia and sustained algal blooms (e.g. Hagy et al. 2004, Kemp et al. 2005, Glibert et al 2014, Griffith et al 2020). In addition, climate change and climate variability interact with these stressors to alter temperature, freshwater flow, sea level, and ultimately population dynamics of both benthic and pelagic species (Kimmel and Roman, 2004, Kimmel et al. 2006).

In general, erosion leads to increased nutrient loads, all of which degrade near shore water quality. Sediment input is greatest in near shore waters due to shore erosion in the northern (Maryland) reaches of the Chesapeake Bay. Furthermore, erosion is a source of sediment deposition into navigable channels that then require dredging (Marcus and Kearney 1991; Hobbs et al. 2002). However, natural eroding shorelines also can provide ecosystem services such as beach habitat and a source of sediment for SAV beds and marshes, which in turn improve water quality and help protect shorelines from further erosion. Thus, management of erosion is a significant challenge, particularly in estuarine systems (Koch et al, 2007).

Management and Evaluation of Shore Erosion

Several important types of information are required to evaluate and manage shore erosion appropriately. Among the most important is an understanding of historical rates of erosion and how they relate to environmental factors such as wave attack, tidal height/flooding, bank composition and height, near shore sediment composition, the near shore depth profile, and rates of sea level rise. Given a reasonable understanding of these factors, it should be possible to estimate the response of unprotected shorelines to changes in sea level and weather, due to climate change.

To examine the extent of offshore sediment transport due to shoreline erosion, a reliable estimate of the rates and composition of sediment input into near shore waters is necessary. Near shore bottom sediments may account for a third to a half of the total sediment input due to shore erosion. There are so very few detailed data sets available on near shore bathymetry and bottom sediment composition in Chesapeake Bay that recent estimates of sediment input due to shore erosion have been based on application of an assumed split between bank and near shore contributions applied uniformly to all locations (Hennessee et al. 2003; Dr. Carl Cerco, PI for USEPA Chesapeake Bay Water Quality Model development, personal communication). Analytical profile modeling is an alternative technique for modeling shoreline and profile change. By developing analytical solutions originating from mathematical models that describe the basic physics involved in shoreline change, essential features of beach response may be derived, isolated, and more readily comprehended.

Analytical Solutions to Evaluating Shoreline Change: Equilibrium Beach Profiles

An equilibrium beach profile results from steady wave forcing during the seasonal cycle. In the summer sand is deposited on to the beach creating a berm, while the winter beach is characterized by sand being eroded from the beach and deposited into the near shore and offshore profile. Beach profiles fluctuate with seasonal cycles of wave energy where beach slopes are a function of the ratio of the disturbing wave forces versus the restoring particle forces. Slopes are also related to grain size, where larger grain sizes generate steeper beaches (Benassai, 2006).

To accurately model beach profiles, closed-form mathematical solutions of the equation for shoreline and profile change have been developed (Bruun, 1968; Edelman, 1972; Dean, 1991; Kriebel and Dean, 1993). These analytical solutions serve mainly to identify characteristic trends in beach change through time and to investigate basic dependencies of the change on the incident waves and water levels as well as the initial and boundary conditions. Equilibrium beach profile models have been developed to examine various features of beach response to shoreline change.

Dean (1983) defined an equilibrium beach profile as a profile that results from steady wave forcing during the seasonal cycle with the assumption that the system is undergoing constant energy dissipation. He expressed this relationship as

$$1/h \; dF/dx = D_e \qquad (1.1)$$

where h is water depth at a distance x from the shoreline, F is the wave energy flux in shallow water, and D_e is the dissipation coefficient of energy. Using linear wave analysis and the equation for wave energy flux in shallow water, Dean was able to estimate an equilibrium parameter (A) that was related to breaking depth (d) and the distance offshore to the breaking depth (x) using the equation

$$d = Ax^{2/3} \tag{1.2}$$

Moore (1982) and Dean (1983), found that it was possible to define a relationship between the equilibrium parameter A and ranges of beach grain diameter (D) as well as to the fall velocity (w_f) of particles (Moore, 1982; Dean, 1983). For example:

$$A = (1.04 + 0.086 ln(D))^2 \quad for \quad 0.1 \times 10^{-3} m \leq D \leq 1.0 \times 10^{-3} m \tag{1.3}$$

$$A = 20 \cdot D^{0.63} \quad for \quad 0.1 \times 10^{-3} m \leq D \leq 0.2 \times 10^{-3} m \tag{1.4}$$

$$A = 0.50 \cdot w_f^{0.44} \quad where\ w_f = \text{fall velocity in } m/s \tag{1.5}$$

This allowed a beach profile model to be developed that related energy dissipation and wave energy flux in shallow water to grain size of the transported sediment. The two thirds power law relationship in equation (1.2) also estimates a particular shape of the profile. Dean’s equilibrium profile model showed that dissipation of energy due to breaking waves destabilizes sediment particles, but when destabilizing forces equal restorative forces dynamical equilibrium occurs.

One of the first classic beach profile models used to calculate the response of the coastline to sea water level was developed by Bruun (1968). Bruun tested his model with both lab experiments and field studies to calculate both the landward and shoreward limits of the equilibrium profile and is referred to now as *Bruun's Model* or *Bruun's Rule* (Benassai, 2006). The model looks at both the sediment volume variation on the active portion of the beach profile and the volume needed to maintain the profile in equilibrium. Bruun's Rule combines the generated sand volume variation with the required sand volume needed to maintain equilibrium. By doing this, he was able to relate shoreline retreat to the vertical extension of the equilibrium beach profile, sea level rise, and the berm height of the beach (Figure 1).

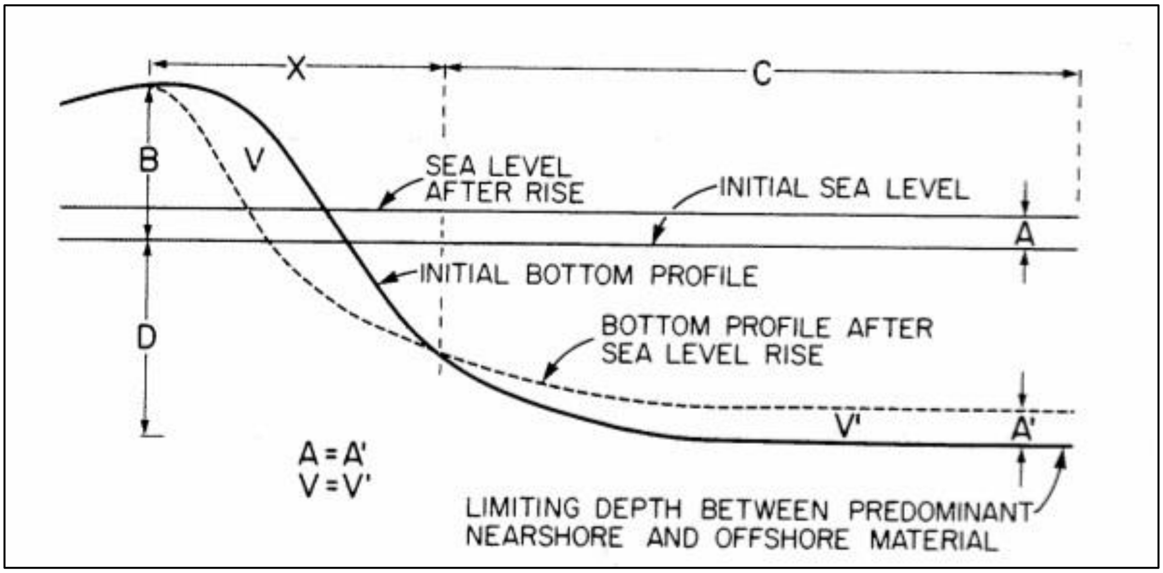


Figure 1. Bruun's equilibrium beach profile from Bruun (1968)

Bruun's Rule can be written in the form:

$$X = A \cdot C / B + D \qquad (1.6)$$

Where

X = shore retreat (regression of the coastline)

A = increase in sea level (sea level rise)

D = limiting depth between predominant near shore and offshore material

C = distance to limiting depth from the shore (amplitude of the equilibrium profile)

B = shore elevation (berm height)

Bruun's Rule is independent of profile shape where Dean's model assumes that profile shape is estimated by the $^{2/3}$ power law and is dependent on grain size. Bruun's Rule is useful for its simplicity although it often overestimates beach regression (Benassai, 2006). Dean's model incorporates the idea of grain size affecting beach slope and profile shape but may not be applicable to all types of shorelines. However, these models can be used together to estimate the amount of sands input by shoreline erosion as well as the quantity of yearly sediment mass that is likely to be added to the near shore environment.

Thesis Statement

It was proposed that the Bruun and Dean models of offshore equilibrium beach profiles could be applied to sites in the Chesapeake Bay in Maryland if consideration was made for the differences in site composition, location, and environment from the original sandy beach open ocean sites that were the basis for the Bruun and Dean models. By using bathymetry to survey and map the shape of the whole offshore physiographic profile along a transect perpendicular to the beach at each site, and choosing sediment sampling sites to obtain cores that reflected beach and transect morphology and site variability, a data set was acquired that could be used as input to several of these analytical profile models. These data were then used to attempt to answer questions on how far offshore the coarse sands get transported, whether there was a dominant amount of fine sediments being transported offshore, which types of shorelines provide the most fine sediments to the offshore sediment budget and how far offshore they are transported, and finally whether the rates calculated for shoreline erosion at each site agree or disagree with profile model predictions. By answering these important questions and comparing these measurements to models of offshore equilibrium profiles, a better estimate of the amount of shoreline retreat as well as the amount and type of sediment transported offshore during sea level rise in Maryland’s Chesapeake Bay could be made.

Chapter 2: Methods

Introduction

Site selection should be influenced by certain temporal and spatial boundaries to best survey and define a physiographic unit such as an offshore beach profile. To study short term coastal dynamics, a short time interval that allows for analysis of the daily phenomena over the observed period is a sufficient temporal scale in which to design the survey. To observe a spatial scale or shape of a physiographic unit, it is necessary to survey the entire unit, which is defined as the zone where any coastal change in plan or profile influences the adjacent coastline. Surveying the physiographic unit is important to define the limits of the area affected by coastal dynamics. Several surveys can be combined to define profile shape such as topographic transects (land survey data), bathymetric surveys, and analysis of photos and maps of historic shoreline. Sediment sampling also can provide an assessment of beach and profile morphology and variability, with sampling points located at all major changes in morphology along the cross shore transect that defines the profile. Shoreline seasonal changes and engineering structures should also be considered in selecting sampling points. This allows for samples to be spatially located and related to important changes in morphological and hydrodynamic zones. These samples can then be examined further in the sedimentological laboratory by analyzing both the physical and chemical properties of the sediment at each site. This data can then be used as input to equilibrium beach profile models and estimates of shoreline regression. The sites in this study were selected to create a survey of Maryland's Chesapeake Bay shorelines that included a variety of eroding beach types, berm heights, fetch orientations, and geographic locations (Figure

2). This diverse set of data was then used as input to test the effects of onshore and offshore sediment size and strength, physical properties of the environment, and sea level rise on the shape of the offshore profile.

The resultant profile parameters were then used in calculations of shoreline erosion rates. Sites were also selected to test whether the offshore profile shape in the Chesapeake will exhibit a degree of dependence on factors other than grain size and the associated incident wave energy. The composition and relative strength of the eroding sediments that comprise both the shore and the adjacent near shore are likely to strongly influence the resulting profile shape. Where insufficient sand sized particles are available in the eroding geologic formations to create a mobile beach and near-shore environment, it is not clear that the equilibrium profile will apply. Similarly, portions of the profile can be strongly influenced by the antecedent topography that was formed during the last glacial maximum when sea level was as much as 91 meters below its present level in the mid-Atlantic region. Where the eroding banks are sandy and relatively high, a large amount of sand sized particles are delivered into the shore zone and will influence the resultant profile shape. This survey represented a variety of beach sediment types ranging from coarse sands to fine silts as well as a variety of beach heights such as high bluffs, low sandy pocket beaches, and an eroding marsh site (Table 1, Appendix 1). These factors and their influence on the offshore profile were used to determine site selection in the 2008 Bruun Profile Survey.

The 2008 Maryland Chesapeake Bay Beach Profile Study

In 2008, data were collected at ten sites along 100 kilometers of the Maryland shoreline of the Chesapeake Bay and compared to both empirical and theoretical models of offshore profiles to better estimate a sediment budget for eroding shorelines in an estuarine environment. This effort was a multi-agency collaboration with University of Maryland Center for Environmental Science, Horn Point Labs (UMCES/HPL) and the Maryland Geological Survey (MGS), supported by NOAA Grant 14-08-1218 CZM 237. The surveyed area included bay shorelines from Kent County, north of the Chesapeake Bay Bridge (near the Estuarine Turbidity Maximum), as well as shorelines on the eastern shore (from Tilghman's Island to Hooper's Island), and the western shore of Maryland's Chesapeake Bay (St. Mary's and Calvert County). The parent project was completed in 2008, a data report was prepared and delivered to the Maryland Chesapeake and Coastal Program, and the information was added to Maryland Shorelines Online (http://shorelines.dnr.state.md.us/; now inactive). Since that time, the information from Maryland Shorelines online has been incorporated into the Maryland Coastal Atlas (https://dnr.maryland.gov/ccs/coastalatlas/Pages/default.aspx).

The data collected at each site included a series of shore normal three-dimensional bathymetric profiles of an offshore transect run at each site, differential leveling at the shoreline, and collection of sediment cores and grab samples along a surveyed offshore profile. Further analysis of these data, as well as existing historical shoreline change data, provided an assessment of whether the observed rates of shoreline retreat could be explained by simple shoreward translation of the observed Bruun profile, given the historical rate of sea level rise.

To attempt to answer the question of whether simplified closed-form mathematical solutions of offshore sediment transport can be applied to the 2008 Chesapeake Bay study, several limitations had to be examined. Dean's model for equilibrium beach profiles was based primarily on sandy beaches and the transport of a mobile sand unit into the near shore environment during shoreline recession. The beaches surveyed in the 2008 Chesapeake Bay study were not entirely composed of sand. The site compositions varied with a mixture of coarse and fine sands, as well as several of the sites being entirely composed of marsh sediments. These sites were purposefully selected to see if these profile models could be applied to sites that had a variety of sediment types. Bruun's Model may also be limited in its application to the Chesapeake Bay sites, since most of the field data used in Bruun's study was collected from open ocean sites which were dominated by ocean swells.

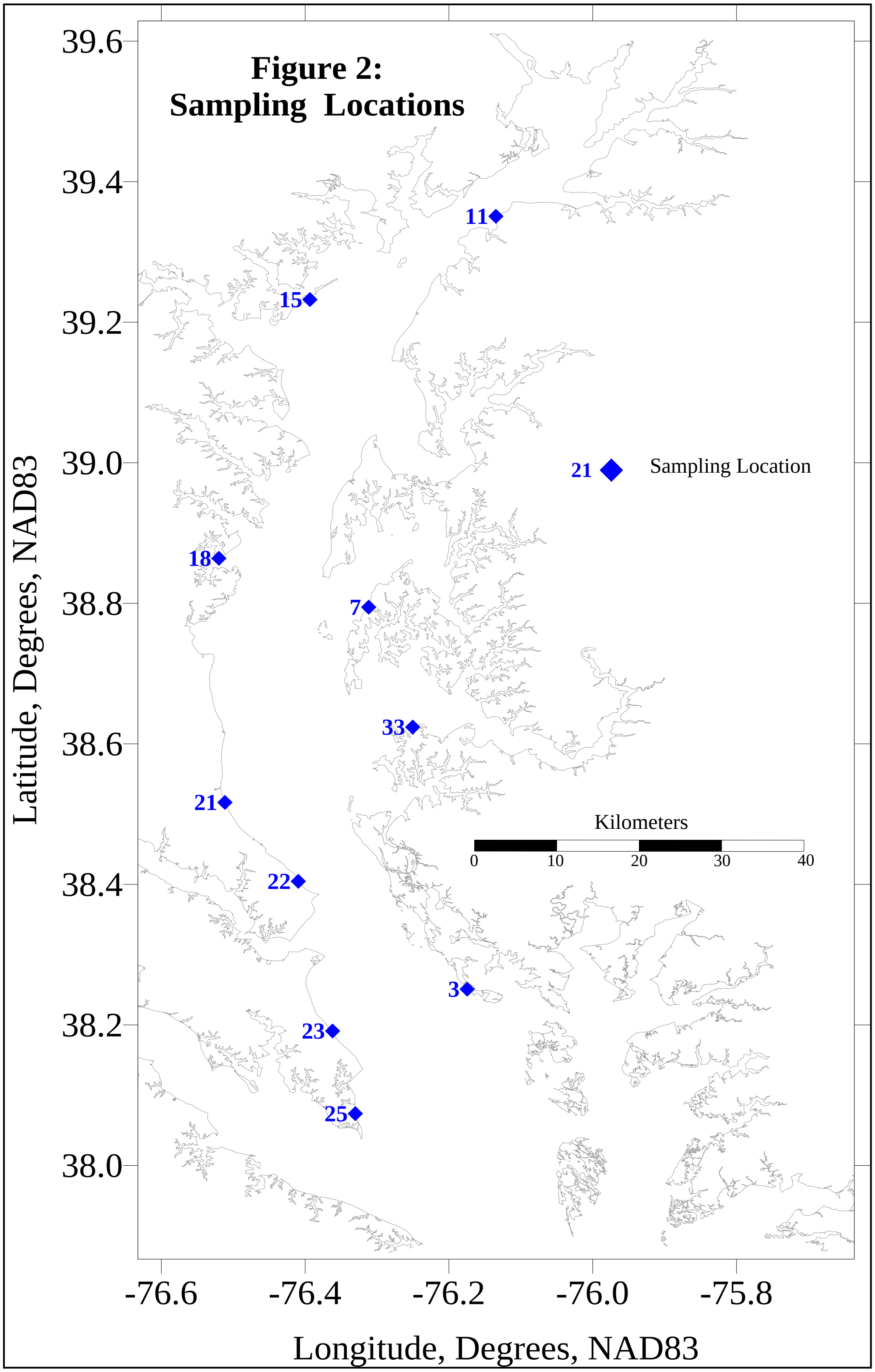


Figure 2. Sampling Locations

Site Name	Site Number	Location	GPS Position (UTC)	Shoreline Type	Bank Elev. above water	Extent Reach
Meeks Point	11	Kent County	4356452N 402345E	Eroded bluff fronted by beach	7-15m	400m
Pleasure Island	15	Baltimore County	4343481N 379605E	Graded beach	Graded shoreline	175m
Rhode River	18	Anne Arundel County	4302781N 368124E	Bluff with adjacent beach	3m	200m
Long Point	7	Dorchester County	4295313N 386287E	Eroded bluff fronted by beach	0.6-1.5m	150m
Todd’s Point	33	Dorchester County	4275778N 391156E	Low bank; pocket beach	0.9-1.2m	200m
Scientist’s Cliffs	21	Calvert County	4264203N 368244E	Bluff fronted by beach	15-18m	100m
Calvert Cliffs	22	Calvert County	4251633N 376940E	Eroding bluff	20-25m	500m
Richland Point	3	Dorchester County	4234310N 397254E	Eroding marsh	0.3m	500m
Elms Beach	23	St. Mary’s County	422791N 380739E	Bluff fronted by beach	2 m	100m
Scotland Beach	25	St. Mary’s County	4214826N 383312E	Bluff with beach	0.3-1.2m	350m

Table 1. Site Descriptions (N to S)

Materials and Procedure

To measure a long-distance offshore profile, a field definition of the profile was needed to begin the survey. For this survey, an offshore profile was defined to be a measurement profile run perpendicular to the shoreline from beach to the beginning of the main channel. Sediment cores were then collected from the beach to an offshore profile point, measured perpendicular to the shoreline for each site. Bathymetry and GPS data were collected along the profile, and grain size analysis was completed for the mobile sand layers of the beach and near-shore sediments in order to examine the relationship between sediment size and the equilibrium profile parameter for Chesapeake Bay shorelines (Figure 3, Appendix 2, Appendix 3).

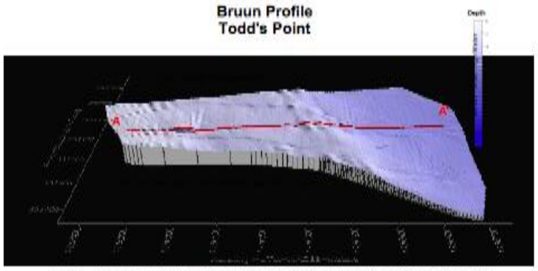


Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.

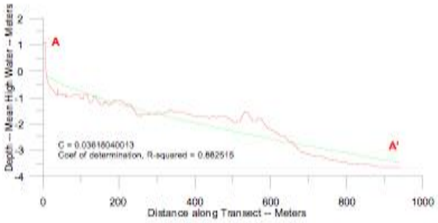


Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

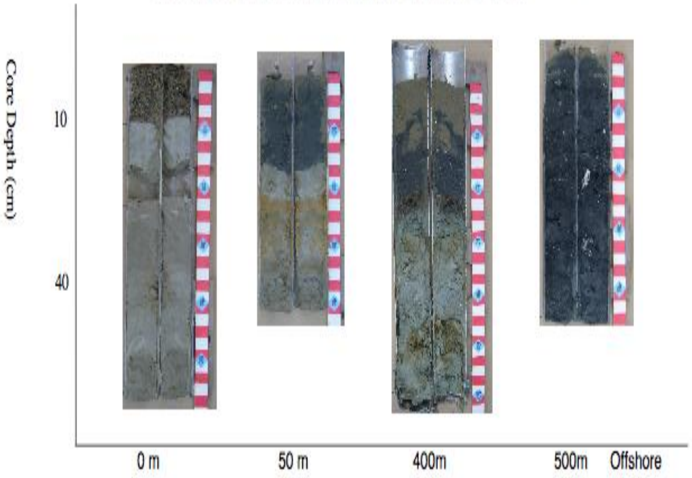


Figure 3. Bathymetric profile with core locations for Todd's Point

Field Procedures

Bathymetry data were taken with an echo sounder collocated with an onboard, boat mounted Trimble GPS receiver across a grid covering the offshore profile both along reach and perpendicular to the shore. This allowed for a sampling interval large enough to create a three-dimensional offshore profile of the bottom along the profile (Figure 4). To tie the beginning of the onboard bathymetry profile with the beach site, local land survey ties were needed. Leveling lines were run from the beach site into the water to the beginning of the onboard bathymetry profile site using leveling equipment and handheld Trimble GPS receivers (Figure 5). These surveys were correlated with historic ties in the study area where previous site sediment studies were conducted by the Maryland Geological Survey.

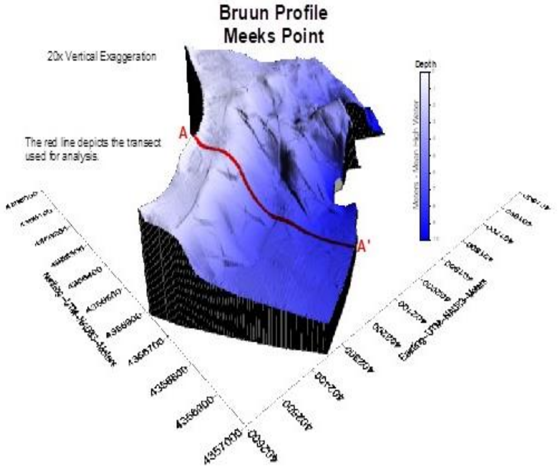


Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.

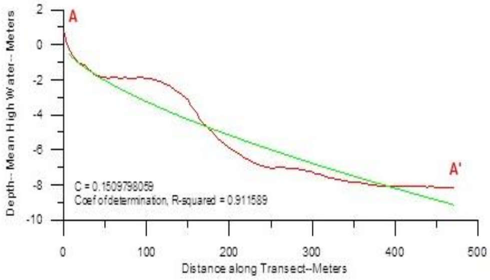


Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

Figure 4. Three-dimensional image of the local bathymetry collected at the Meeks Point sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as **A** and the most offshore point labelled as **A'**. The bathymetry has been oriented for the best view of the transect. Secondary plot represents the bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

Figure 5. Survey ties using leveling lines and handheld GPS at Meeks Point

Sediment core data were then simultaneously taken from the shore along the profile, out to approximately 9 meters depth at the edge of the main channel, with an average sampling interval of four cores per site (Figure 6). Core locations were also marked with a Trimble handheld GPS receiver. Core selection criterion were based on representation of geomorphological changes along the profile observed while on site, either at the beach or through bottom profiling on the survey boat. A beach core was taken at each site. The near-shore profile was sampled at the mean tide line and several meters offshore at 1m water depth. The remaining offshore profile was sampled based on bottom structure viewed through the depth finder, such as sand waves, and finally out to the profile end point at approximately 9 meters depth. Instructions were developed in the field to accurately describe the process of profile measurement and coring (Figure 7).

Figure 6. All cores collected along the Rhodes River transect (bank toe, surf zone, plateau, and slope). Each core collected is split, labeled, and photographed.

Field Measurement Instructions

Task 1: Identify site
Purpose: Understand current conditions and fetch which influences erosion.

Step 1. Go to coordinates on site page. Verify site has not been armored or changed to prevent erosion. If site has been armored, see if there is an acceptable site in the near vicinity that appears to be the same structure (bank height, soil type, etc.). Record a short description of site, take some pictures, and describe fetch and shoreline.

Task 2: Conduct a bathymetric survey of site
Purpose: To develop a profile from the shore to the offshore. The lines surrounding the main profile are used to verify there are no anomalies in the profile. Execute using Knudsen Echo control software and load config file: D:\bruun\bruunconfig.cfg. Verify GPS coordinates are being read. Record both binary and ascii file with everything selected for the ascii file (this is default and should not need to be changed)

Step 1. Run a line (in either direction) perpendicular to the shoreline using the site coordinates (generally) as one end. The line should run far enough out that you see the depth drop off significantly to a plateau. The goal is to run the line long enough to where the sediment is being lost in the sink rather than active mobility. At Pt. Lookout that looks to be around 14-foot depth, and at Scotland beach that looks to be around 21-foot depth. It was found best to watch Ozi to run this line straight and perpendicular to the beach. Record the ending point of this line as the transect end point on the datasheet. For documentation purposes, try to run this at the same speed and fairly straight.

Step 2. After this profile (in a new file), run two lines to the north of your profile line and two lines to the south of your profile line (all perpendicular to shoreline). This is just to demonstrate that there are no major variations in the profile. If necessary, you can pick one of those lines as your main profile line if there is something in the way or anomalous in the first one. If you move the main profile line to one of these other ones, change the transect end points on the datasheet to match the one you pick.

Step 3. Finally, do two or three cross tracks (new file) just to have some tie-ins for the survey. Try to make one of these as close to shore as possible to help with the bathymetry creation.

Task 3: Differential Leveling at shoreline
Purpose: Tie-in upland topography with bathymetric profile.

Step 1. Setup the tripod and level at high spot (typically on bank). If the bank is unmanageably high (i.e. > 15 feet or so), then just setup at base and provide an estimate of bank height. Record GPS (white Magellan) of tripod and height of instrument (stadia rod measurement from ground to the center of the level objective). Annotate on datasheet.

Step 2. Record several points to generally describe upland topography to near shore bathymetry. Typically, complete a top of bank reading, toe of bank reading, high water mark (rack line), tide level mark (current water level), and two or three readings of the near shore. Each site is different. If there is a bluff with a straight drop to the water, it will not be necessary to survey as many points. At each location record GPS, and level readings (middle most important, top, and bottom readings for distance). Annotate on data sheet. Also annotate the time (UTC from the white GPS) for the tide level mark so it is possible to go back and retrieve tide information to tie both the upland and the bathymetry surveys together. For points collected in the near shore, record estimated depths also.

Task 4: Collect cores and grab samples along profile line
Purpose: Collect and describe the active mobile sediment layer along the profile. Secondary purpose is to attempt to describe the thickness of this layer.

Step 1. Collect a core sample and grab sample at a location near the tide line, but in the water. Typically, this is in water depths of less than a foot. Annotate GPS, depth, and any other data on datasheet. Label core and grab bag with site name, date, and core #. Cores will generally be between 6” and 2 feet in length depending upon substrate.

Step 2. Collect 3-4 more cores and grab samples along the surveyed profile. At each site record depth, GPS location, and obtain a grab sample and core. In general, attempt to core along significant structural changes and before the profile rolls off to depth. This has been more complicated to determine in the field and generally turns into collecting a core at 1 meter of depth along the profile, two meters of depth along the profile, and three meters of depth along the profile. If there are sand waves in the profile attempt to collect a core at a peak and trough of the waves, and then one more before the profile rolls off to depth. With anything deeper than 2.5 meters or so, it is necessary to use the aluminum liners. It was found that simply driving the CABs to refusal and pulling them out with the plumber’s test bob is the best method for obtaining the cores. Twisting the cores rather than just purely pulling them out also seems to help in retrieval.

Figure 7. Field Measurement Instructions, R. Ortt, Maryland Geological Survey

Laboratory Procedures for the 2008 Bruun Survey

The definition of sediment morphology and texture gives some indications of their origin and evolution; the analysis of petrography is useful to define the origin of sediment matrix. Grain size can be defined by direct measurement of particle diameters or, indirectly, by determination of their ‘hydraulic equivalents’ based on settling velocities of quartz spheres. The most important sediment characteristic is the particle grain size (the measure of grain dimensions and their statistical distribution). Other interesting parameters are color, texture, surface morphology (aspect and structure), shape and degree of rounding.

One technique of grain size determination uses a set of nested sieves with different mesh sizes. An amount of sediments passes through a set of nested sieves in which the size is gradually smaller down the stack. Grains are trapped on a sieve if their size is smaller than mesh openings. The sieves are agitated by hand or mechanically to make the selection more efficient (without forcing the grains through the mesh). The weight of each size class is expressed as a percent of the total sample weight.

Analysis of muddy sediments is commonly carried out by pipette analysis. The sample of sediments is put in a one-liter graduated cylinder containing distilled water. An amount of dispersing agent is added to avoid particle flocculation. After agitation, 20 ml aliquots of mixture are taken using a pipette, at specific intervals, assuming Stoke's settling. The water in each aliquot is evaporated and the sediment amount is determined measuring weights of containers with and without sediments. In some cases, the presence of contaminants can have a significant influence on the accuracy of measurements.

Sediment size classification is usually performed with the assumption that particles are roughly circular, and the grain size can be expressed as a projected cross section. Most common classifications are based on Wentworth scale and Krumbein scale. Statistical analysis of sediments demonstrates that size distribution of particles has a logarithmic distribution called a 'phi scale' (the diameter of a particle D (mm) = $2^{-\varphi}$). Sedimentological analyses and interpretations clearly depend on the quality of data; quality data can be best achieved through standardized sample preparation and analytical procedures." Maryland Geological Society's Coastal and Estuarine Program's Sedimentology Lab has carefully developed procedures for grain analysis. These procedures are detailed in their laboratory procedures manual and were followed in the processing of the 2008 Bruun Survey samples.

Sediment sampling

Subaqueous sediment samples were collected for analysis using specialized equipment. Grab samples and cores were collected at each site. Cored sediments were collected in either cellulose acetate butyrate (CAB) or aluminum core liners.

Recovered cores were trimmed at the sediment-water interface, capped, and returned to the lab for analysis (Figure 8).

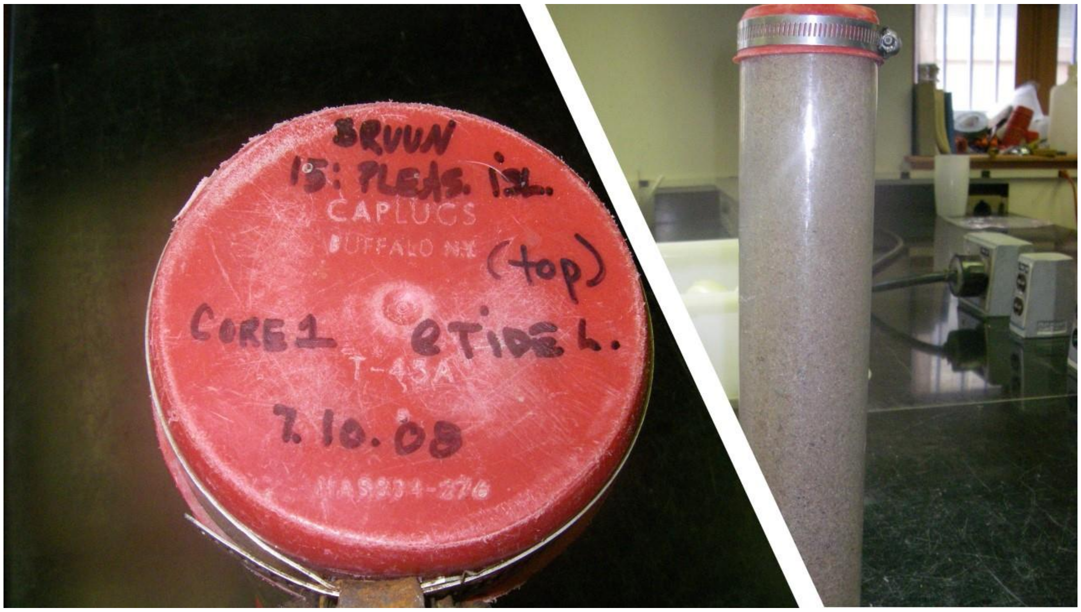


Figure 8. Cored Sediment in Cellulose Acetate Butyrate (CAB) tube capped and labeled, Pleasure Island site. Pictured in the Maryland Geological Survey Sed Lab, Baltimore, Maryland.

Core processing

In the lab, sediment cores were split, photographed, and described. Each core was carefully examined to identify sedimentary units and classified using the Munsell system of sediment classification. Sediments were then subsequently sub-sampled and readied for analyses (Figure 9).

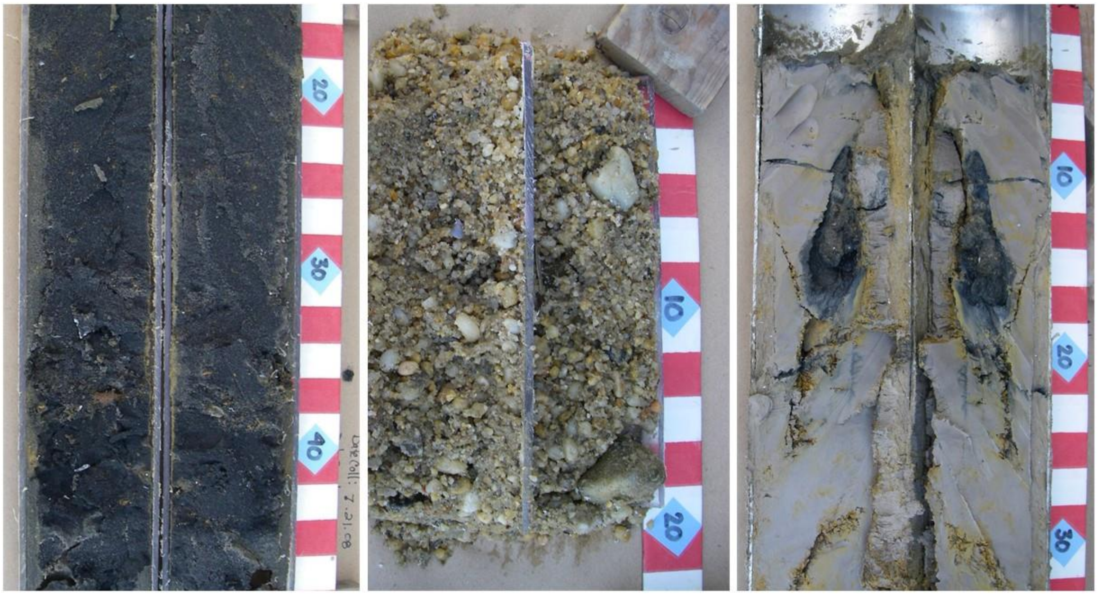


Figure 9. Split, Photographed Cores from Scotland Beach site from tide line, beach, and channel

Preparing the sample

Sediment samples were analyzed for water content, bulk density, and grain size. Two homogenous splits of each sample were processed, one for bulk property analyses and the other for grain size characterization. Samples used for water content analysis were divided into 15-20 g portions, dried at 65ºC, and then reweighed. Water content was calculated as the percentage of water weight to the total weight of wet sediment. Samples used for grain size analyses were divided into 35-40 g portions and immediately introduced into a multi-step cleaning process to remove salts, carbonates, and organic matter that could interfere with analysis (Maryland Geological Survey Sed Lab Procedure, personal communication, J. Halka).

Sieving the sample

The separation of sand and silt-clay portions of the sample was accomplished by wet sieving through a 4-phi mesh sieve. The sand fraction was dried and weighed. The finer silt and clay sized particles were suspended in 1000mL of dispersant solution and readied to pipette.

Pipetting

In a 1000 mL graduated cylinder, the sediment was agitated and suspended. At specified times thereafter, 20mL aliquots were pipetted (Carver 1971, Folk, 1974): these sub-samples were assumed to represent the fine-grained sediment present in the sample. The pipette method employs Stokes' Law (1851) to calculate the distribution of fine particles in the sample. Based on the theory that the larger particles will fall at a faster rate, and velocity is proportional to the square of the diameter, the size distribution was determined by recording the change in the sample weight as a function of time.

Drying sand, silt, and clay fractions

The sieved sand fraction and pipetted silt and clay aliquots were dried at 65ºC and weighed. The percentages of dry weight of sand, silt, and clay were calculated for each sample. Sand fractions were then further analyzed using a rapid sediment analyzer (RSA). All fraction percentages were calculated based on the dry weight of sand, silt, or clay relative to the dry weight of the entire dewatered sediment sample.

Sediment classification

Given the proportions of sand, silt, and clay size particles, sediments were classified according to Shepard's and Pejrup's systems of classification. The procedure was completed by calculating the necessary parameters needed to determine water content and grain size distribution.

RSA analysis

The sand only portions of each sample were further analyzed using the rapid sediment analyzer in the Sedimentology Laboratory at the Maryland Geological Survey. The rapid sediment analyzer developed by the Maryland Geological Survey is based on a microbalance system designed by Gibbs (1974), and modified by the Coastal Engineering Research Center of the Army Corps of Engineers (*The Design and Calibration of a Rapid Sediment Analyzer and Techniques for Interfacing to a Dedicated Computer System*, Halka et al, 1980). The basic system consists of three elements: a plexiglass tube filled with degassed water, a sample introduction, or injector assembly; and a digital electrobalance (Cahn model DTL 7500-10) resting on an adjustable XY table. The electrobalance and injector are interfaced with a Hewlett Packard 9821A programmable calculator. The Rapid Sediment Analyzer (RSA) is basically a long cylinder containing distilled water, where an amount of sediment is introduced and allowed to settle. Particles are collected on a pan connected with a balance recording sediments weight. The RSA has a computerized system to record weight data over time. The method is based on the principle that the falling velocity of grains in water varies with the diameter, shape, and specific weight of particles. The system measures indirectly the grain size, on the basis of settling and hydraulic behavior of particles. Measured velocities are compared with known settling rates and the distribution of particles is expressed as "equivalent diameters".

Calculations and Calibrations

Bathymetric Data Processing

This study required the processing of several uniquely different data sets. For analysis of offshore transects, and bottom slope features, bathymetry data was taken with an echo sounder collocated with an onboard, boat mounted Trimble GPS receiver across a grid covering the offshore profile both along reach and perpendicular to the shore (Figure 10).

Figure 10. Research Vessel 2008 Bruun Profile Survey with an onboard perspective of transect distance from shore

This allowed for a sampling interval large enough to create a three-dimensional offshore profile of the bottom along the profile. To tie the beginning of the onboard bathymetry profile with the beach site, local land survey ties were needed. Leveling lines were run from the beach site into the water to the beginning of the onboard bathymetry profile site using leveling equipment and handheld Trimble GPS receivers (Figure 11).

Figure 11. Leveling lines run from beach to beginning of measured offshore 2008 bathymetric profile at Calvert Cliffs

These surveys were correlated with historic ties in the study area, where previous site sediment studies were conducted by the Maryland Geological Survey. Analysis of the bathymetry data, and all the ties to the land surveys, as well as the GPS weigh points that were collected, was completed using Golden Software's *Grapher*^{TM}, a 2-D and 3-D graphing, plotting, and analysis software package. This program was used to fit the measured transect data to Dean's Rule, written as the equation

$$d=Ax^{2/3}$$

where the y axis is the depth, and the x axis is the measured transect. This allows (d) to be calculated from points along the transect as they are fit to the equation. (*A*) is then a fit-derived constant, as opposed to being calculated from grain size. This was the first approach to calculating (*A)*, using the bathymetric transect data only, and no core or grain size data along the offshore profile.

RSA Analysis

Improved accuracy of dry weight estimates for the sand fraction of the sample was completed using the Rapid Sediment Analyzer described above in [Methods, Laboratory Procedures]. Sediment classification was then completed by calculating the necessary parameters needed to determine both water content and grain size distribution (Appendix 4).

Estimates of the Equilibrium Parameter (*A)*

Using linear wave analysis and the equation for wave energy flux in shallow water, Dean was able to estimate an equilibrium parameter (*A*) that was related to breaking depth (d) and the distance offshore to the breaking depth (x) using the equation

$$d = Ax^{2/3} \qquad (1.2).$$

Additionally, Moore (1982) and Dean (1983), found that it was possible to define a relationship between the equilibrium parameter (*A)* and ranges of beach grain diameter (D) as well as to the fall velocity (w_f) of particles (Moore, 1982; Dean, 1983). For example:

$$A = (1.04 + 0.086\,ln(\mathrm{D}))^2 \qquad for \quad 0.1 \times 10^{-3}m \leq \mathrm{D} \leq 1.0 \times 10^{-3}m \qquad (1.3)$$

$$A = 20 \cdot \mathrm{D}^{\,0.63} \qquad for \quad 0.1 \times 10^{-3}m \leq \mathrm{D} \leq 0.2 \times 10^{-3}m \qquad (1.4)$$

$$A = 0.50 \cdot w_f^{\,0.44} \qquad where\ w_f = \text{fall velocity in } m/s \qquad (1.5)$$

In the 2008 Chesapeake Bay Bruun Profile Study, estimates of grain size in the sand portion of the core top samples were then used to define the beach grain diameter, D. Additionally, the fall velocity w_f was measured for each sand aliquot tested in the Rapid Sediment Analyzer (RSA). These measurements of D and w_f were then used to calculate the equilibrium parameter (*A*) as dependent on grain size for comparison of estimates of (*A)* as defined in the bathymetry analysis, which was dependent on profile shape.

Estimates of Shoreline Retreat, X

Bruun's Rule combines the generated sand volume variation with the required sand volume needed to maintain equilibrium. By doing this, he was able to relate shoreline retreat to the vertical extension of the equilibrium beach profile, sea level rise, and the berm height of the beach. Using input variables of profile length (C) and depth (D) at the end of transect from the 2008 Bruun Profile Survey, as well as local sea level rise from tide gauge data at each site (A), and historic shoreline berm height (B), Bruun's Rule, written in the form:

$$X = A \cdot C / B + D \qquad (1.6)$$

was used to estimate shoreline retreat (X) from the 2008 survey data.

Analytical Methods

Overview

Various models have been proposed to explain the shape of a shore perpendicular profile across a beach and the associated nearshore environment. The profile at any location is presumed to represent a dynamic equilibrium in which the forces that tend to erode the shore and move sediment offshore are in relative balance with the forces that tend to move sediment onshore, resulting in an equilibrium profile. This equilibrium represents a balance between the destructive and constructive forces of beach development over a long period of time, which, on sandy shores results in a profile shape that is almost invariably concave upward. [R. Ortt, personal communication].

In the 2008 survey, analyses of the bathymetry data and how it relates to equilibrium profiles was based on the relatively simple mathematical form of

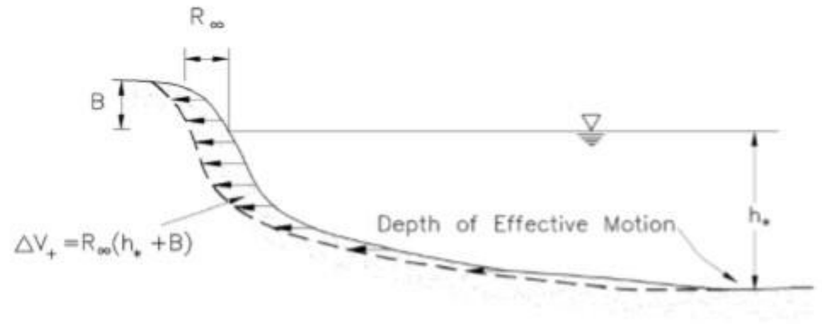
$d = Ax^{2/3}$ based on Dean's 2/3 law stated in Equation (1.2).

Here, d was understood to be the equilibrium depth (d) as a function of the distance offshore (x). The equilibrium profile constant (A) was then empirically calculated for each 2008 profile location for the best fit to the data.

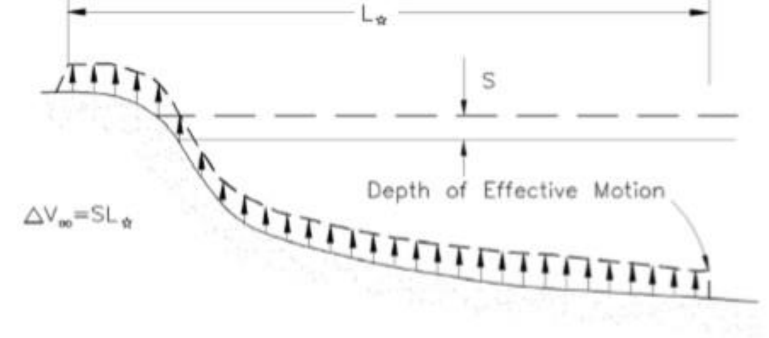
The appropriateness of this equation for open ocean sandy coasts was documented in a study of 500 profiles from the East and Gulf coasts of the United States (Dean 1977). Justification of the use of the 2/3 power function in the 2008 analysis was that it provided a reasonable fit to the data set, and has been recommended for use in describing equilibrium beach profiles in the U.S. Army Corps of Engineers, Coastal Engineering Manual (Dean et al., 2006).

Objections to the use of this equation have been related to the fact that it is a two dimensional representation of a three dimensional environment and does not account for longshore transport of eroded sand, nor does it account for interruptions to that longshore movement by coastal inlets or other features. The equation is also monotonic in form and cannot adequately represent offshore bars that often occur in the Chesapeake Bay. In addition, the equation assumes that the profile is closed at both the landward and seaward sides. Thus, no sediment moves landward of the dune line or berm and none leaves seaward of a "closure depth". Many barrier beaches which have been utilized for verification of this equilibrium equation migrate landward in response to rising sea-level via over wash and thus violate the assumption that movement of sediment is only between the beach and the nearshore environment. However, the general verification in the work of Dean (Dean, 1977), and the recommendation of its use by the Amy Corps (Dean et al., 2006) argues in favor of its use in describing the characteristics of the beach and associated nearshore environment in the Chesapeake Bay (Maryland Geological Survey, R. Ortt, 2008).

The profile shape described by Equation (1.2) has been utilized to estimate the landward translation of the shore (i.e. shore erosion) in response to sea level rise that is necessary to maintain the equilibrium profile. This relationship can be illustrated schematically as a shoreline regression profile (Figure 12).



a) Volume of Sand "Generated" by Horizontal Retreat, R_∞, of Equilibrium Profile Over Vertical Distance $(h_* + B)$



b) Volume of Sand Required to Maintain an Equilibrium Profile of Active Width, L_*, Due to a Rise, S, in Mean Water Level

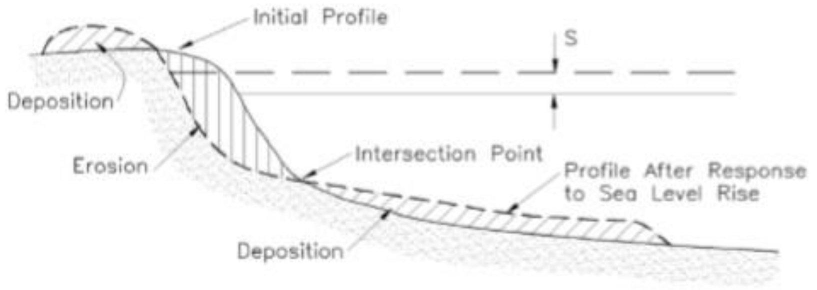


Figure III-3-32. Components of sand volume balance due to sea level rise and associated profile retreat according to the Bruun Rule

12. Equilibrium profile showing the relation between areas of deposition and erosion in response to a given sea level rise. From U.S. Army Corps of Engineers Coastal Engineering Manual, 2008, Figure III-3-32

In response to a given rise in sea level, sediment is deposited on the bottom seaward of the 'intersection point.' In the absence of significant longshore transport into or away from the profile location, the shore will erode to provide a volume of sand roughly equivalent to that deposited in the adjacent nearshore zone. The profile shape immediately adjacent to the shoreline will determine the amount of erosion that takes place. Thus, with knowledge of the equilibrium profile shape and the constant (*A*) in Equation (1.2), the potential shore erosion for a given sea-level rise can be estimated from the Bruun equation. Despite the simplifications inherent in this equation as noted above, an analysis of nearly 300 profile locations along the mid-Atlantic coast that were not influenced by inlets or coastal engineering projects found a high correlation between sea level rise and shore erosion as predicted by the Bruun rule (Leatherman et al, 2000).

Statistics

The shape of the equilibrium profile, and thus the parameter (*A*) in equation (1.2), has been shown to be related to the sediment grain size or fall velocity as a consequence of the ability of the incoming wave energy to erode and move particles of different sizes (Dean, 1991: Hanson and Kraus, 1989). For fine sands, the value of (*A*) has been estimated to range from approximately 0.063 to 0.15 (Dean et al, 2006), and for sediments finer than sands, (*A)* values are less than 0.05.

To examine influence on the estimates of (*A)* further, correlation between empirical estimates of the equilibrium parameter (*A)* using bathymetry data, and calculated estimates of the equilibrium parameter (*A)* using grain size data was completed using a regression analysis. The correlation between these two estimates of (*A)* was completed using MS Excel's CORREL function and solving for the coefficient of determination (R, R^2, adjusted R^2), and standard error. An ANOVA regression was also completed (Appendix 4).

In addition to examining the bathymetric and grain size data to look at the relationship between sediment size and the equilibrium profile parameter, the shape of the profile itself was plotted using the bathymetric data. The bathymetric cross sections shown in Figure 13 are three dimensional images of the local bathymetry collected at a sample site. The analyzed transect is highlighted in red with the most shoreward point labelled **A** and the most offshore point labelled as **A'**. The bathymetry has been oriented for the best view of the transect. Located below the three-dimensional image of the bathymetric profile are bathymetric cross-sections showing collected bathymetry in red and the fitted equilibrium profile curve in green. The calculated equilibrium coefficient (*A*) (labeled here as C), and the coefficient of determination R^2 are both presented in the cross-sectional plot for the fitted line.

Bruun Profile
Scotland Beach

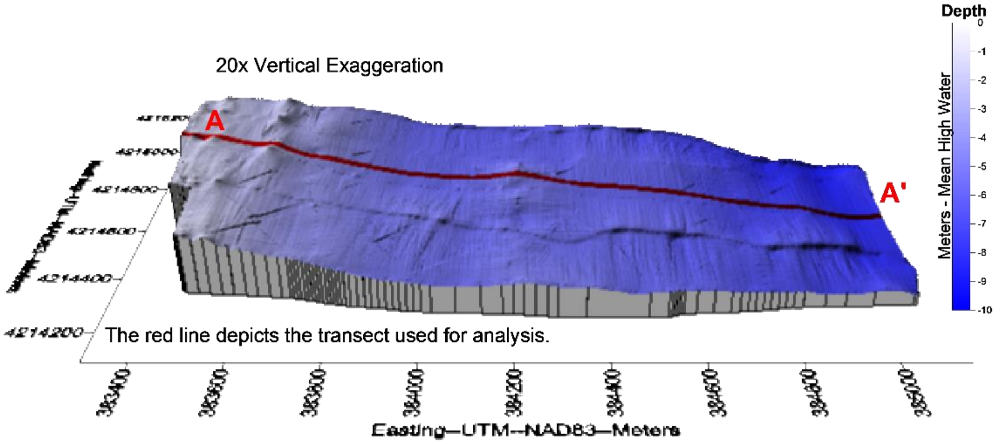


Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.

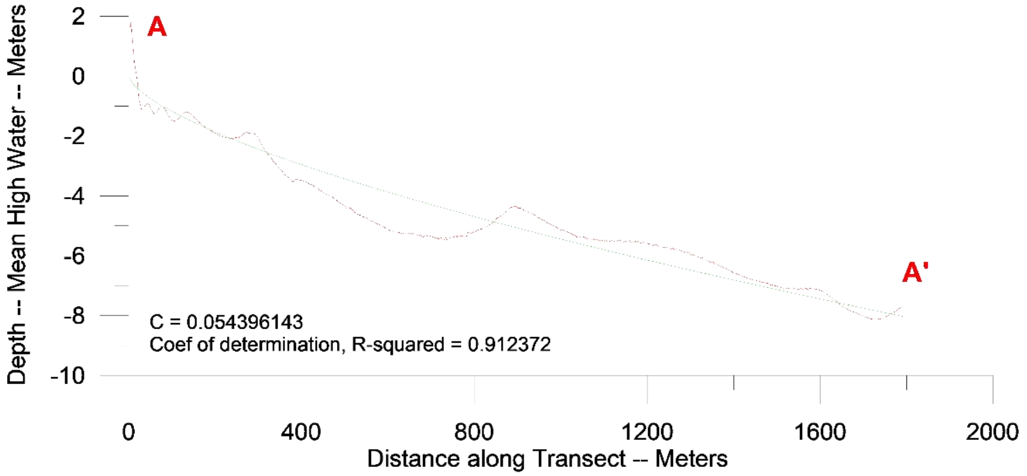


Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

Figure 13: Bathymetric Profile Example, Scotland Beach Site

Potential Sources of Error

Survey geometry in the 2008 Bruun Profile Survey was designed to best estimate the equilibrium beach profile at each site. However, these assumptions in geometry may have contributed to potential sources of error in the equilibrium profile models tested in this study. The first assumption made in the field was the definition of the transect length to be measured during the bathymetry surveys. The transect length was defined as a line with a starting point on the shoreline (point **A**, figure 13) and an end point at the location in the Chesapeake Bay channel where the bay bottom flattened out, or when the water depth plunged when watching the bottom through sonar on the boat (point **A'**, figure 13). The plotted transect profiles shown in Figure 13 then represent the entire measured beach profile, with the upland survey data incorporated in the profile. Using Dean's equation of $d = Ax^{2/3}$ (1.2), d was then assumed to be the total profile height, and x assumed to be total profile length. When solving empirically for the equilibrium parameter, A and using Dean's Rule of $d= Ax^{2/3}$, variable definitions were set from the bathymetry data to be defined as follows: x = length of **A-A'** or transect length; d = difference in measured profile height from point **A to A'**.

Finally, when choosing input data to solve for shoreline erosion, using Bruun's Law, X = AC/B+D, the equation variables were defined to be X = historic rate of shoreline change; A = sea level rise from closest tide gauge; B = measured berm height from MGS's SEDNUTS Survey; C = distance to limiting depth (measured length of the profile) and D = limiting depth (measured height of the profile). A regression analysis was then run on this calculation of shoreline change at each site to define closeness of fit (Appendix 5).

Methods Conclusion

In the 2008 survey, it was also anticipated that the profile shape in the Chesapeake would exhibit a degree of dependence on factors other than grain size and associated incident wave energy. The composition and relative strength of the eroding sediments that comprise both the shore and the adjacent nearshore are likely to strongly influence the resulting profile shape. Where insufficient sand sized particles are available in the eroding geologic formations to create a mobile beach and nearshore environment, it is not clear that the equilibrium profile will apply. Similarly, portions of the profile can be strongly influenced by the antecedent topography that was formed during the last glacial maximum when sea level was as much as 91 m below its present level in the mid-Atlantic region. Where the eroding banks are sandy and relatively high a large amount of sand sized particles are delivered into the shore zone and will influence the resultant profile shape. These factors and their influence on the profile were an important consideration when analyzing the data set in more detail.

Chapter 3: Results and Discussion

Introduction

Analysis of the data gathered in the 2008 Bruun Profile study provided an assessment of whether observed rates of shoreline retreat can be explained by simple shoreward translation of the observed offshore profile, given the historical rate of sea level rise. By using a bathymetry survey to map the shape of the whole offshore physiographic profile along a transect perpendicular to the beach at each site, and choosing sediment sampling sites to obtain cores that reflected beach and transect morphology and site variability, a data set was acquired that could be used as input to several analytical profile models. Several data sets from the 2008 Bruun Profile Survey were then used to test the relationship between grain size versus profile shape and the equilibrium parameter (A).

First, the equilibrium parameter A was calculated using 2008 Bruun Profile Bathymetry Survey transect heights and lengths (Table 2). Table 2 summarizes the (A) value calculated from the bathymetry data for each of the sites examined in this study, and most fall within the reported ranges of 0.063-0.15 for fine sands, and less than 0.05 for sediments finer than sands, with high degrees of confidence as expressed by the coefficient of determination, (R^2) values.

These estimates were then correlated with estimates of the equilibrium parameter A calculated from rapid sediment analyzer core top grain size data using equation (1.4) with D defined as mean grain size diameter (Table 3, Figure 14 a, b).

$$A = 20 \cdot D^{0.63} \qquad \textit{for} \quad 0.1 \times 10^{-3} m \le D \le 0.2 \times 10^{-3} m \qquad (1.4)$$

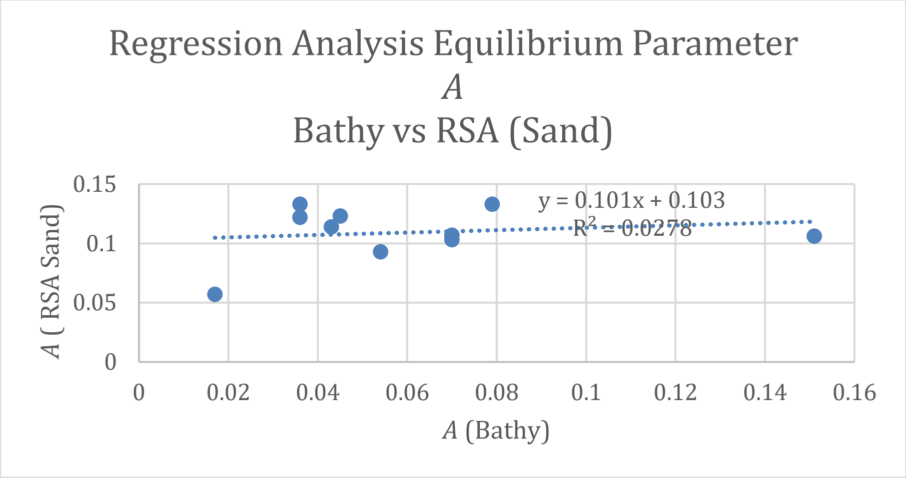
Additionally, by looking at the variation in beach types and heights, as well as the amount of sand versus fine sediment at each site, characteristics of the mobile sand unit and variations in the profile were able to be examined (Table 4, Figure 15).

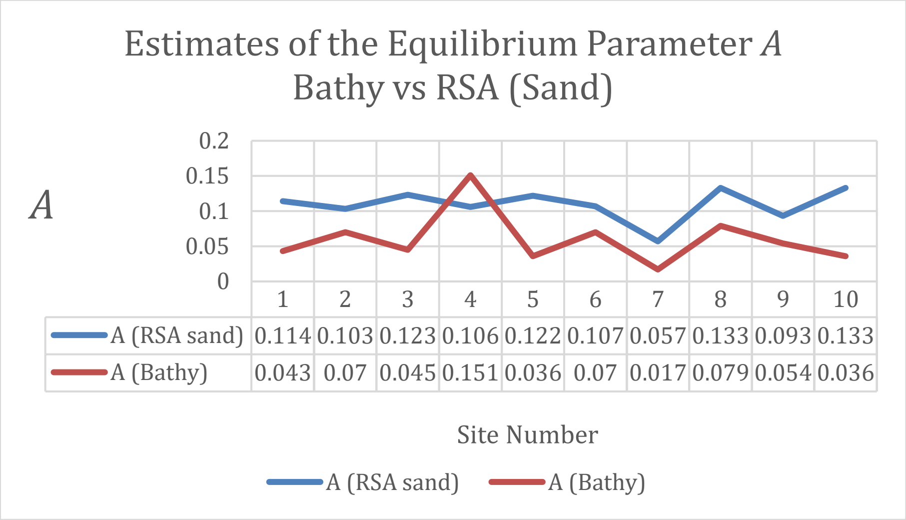
Site Name	Calculated Constant (*A*)	R^2
Todd's Point	0.036	0.882
Calvert Cliffs	0.043	0.814
Long Point	0.045	0.836
Richland Point	0.017	0.678
Elms	0.069	0.910
Scotland Beach	0.054	0.912
Scientist's Cliffs	0.079	0.932
Rhodes River	0.069	0.932
Pleasure Island	0.036	0.866
Meeks Point	0.150	0.912

Table 2. Calculated Equilibrium Profile Constant (*A*) values from best fits to the Dean equation for the 2008 Bruun Profile Survey, with R^2

Site	*Profile Par. A (RSA)*	
	Sand Only	*Total Sample*
Calvert	0.114	0.217
Elms	0.103	0.442
Long	0.123	0.314
Meeks	0.106	0.766
Pl. Isl.	0.122	0.225
Rhode R.	0.107	0.148
Richland	0.057	0.038
S. Cliffs	0.133	0.552
Scotland	0.093	1.467
Todd's Point	0.133	0.956

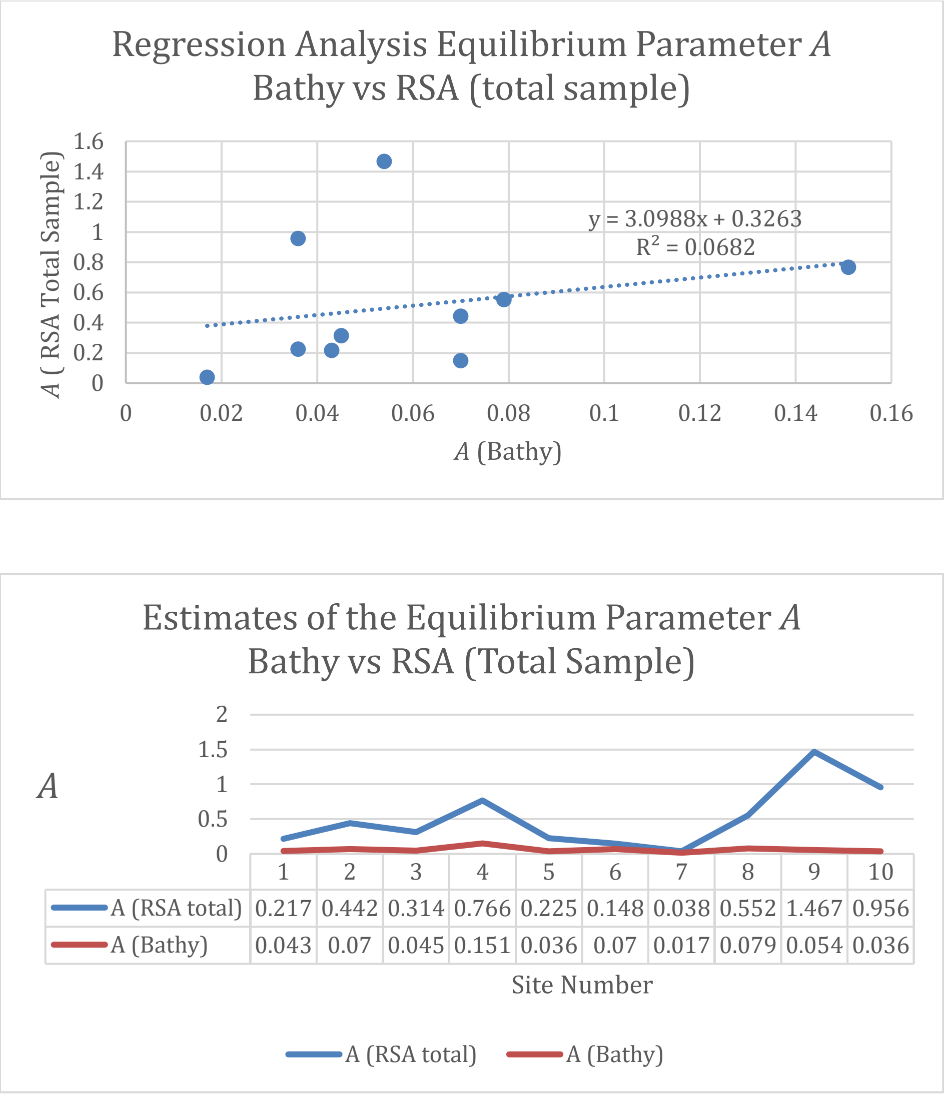
Table 3. Core top grain size analysis results from the Rapid Sediment Analyzer (estimates of mean grain diameter D(mm) – sand portion only as well as the total sample) used to calculate the Equilibrium Profile Constant (A) using Equation (1.4) $A = 20 \cdot D^{0.63}$ for $0.1 \times 10^{-3}\text{m} \leq D \leq 0.2 \times 10^{-3}\text{m}$ [Maryland Geological Survey, 2008 Bruun Profile Survey]





	1	2	3	4	5	6	7	8	9	10
A (RSA sand)	0.114	0.103	0.123	0.106	0.122	0.107	0.057	0.133	0.093	0.133
A (Bathy)	0.043	0.07	0.045	0.151	0.036	0.07	0.017	0.079	0.054	0.036

Figure 14a. Equilibrium Parameter *A* calculated using 2008 Bathymetry transect height and length; correlated with Equilibrium Parameter *A* calculated from Rapid Sediment Analyzer core top data, sand only.

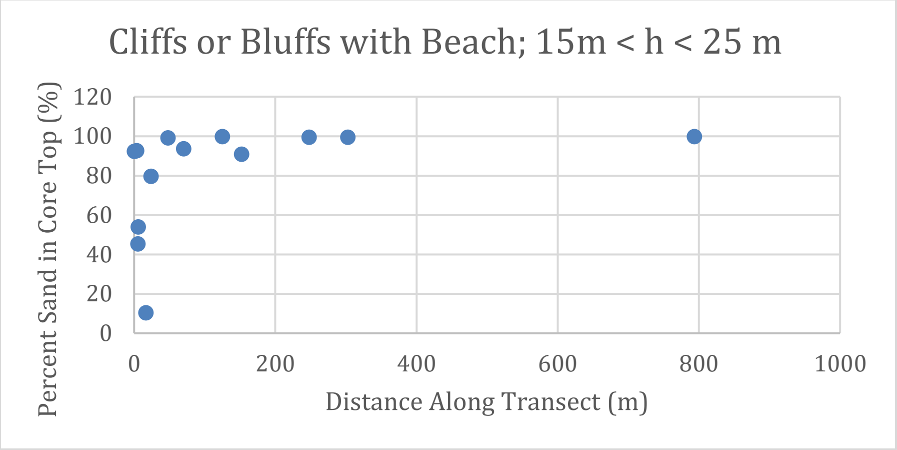


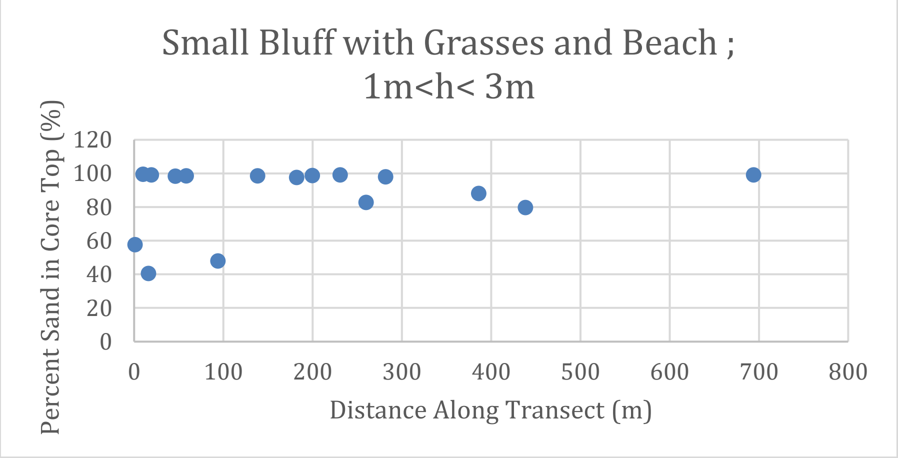
	1	2	3	4	5	6	7	8	9	10
A (RSA total)	0.217	0.442	0.314	0.766	0.225	0.148	0.038	0.552	1.467	0.956
A (Bathy)	0.043	0.07	0.045	0.151	0.036	0.07	0.017	0.079	0.054	0.036

Figure 14b. Equilibrium Parameter *A* calculated using 2008 Bathymetry transect height and length; correlated with Equilibrium Parameter A calculated from Rapid Sediment Analyzer core top data, total sample

Site	*Core #*	*Distance(m)*	*%Sand*
Pleasure Island	Beach	12.40	99.36
	Core1	19.38	76.17
	Core2	58.39	93.73
	Core3	230.83	97.64
	Core4	693.96	98.01
Richland Point	Core1	6.89	13.91
	Core2	119.31	98.47
	Core3	1071.92	96.47
Todd's Point	Core 1	14.80	96.32
	Core 2	78.02	97.86
	Core 3	544.12	90.72
	Core 4	762.52	97.80
Meeks Point	Core 1	0.17	92.23
	Core 2	5.32	45.34
	Core 3	16.80	10.34
	Core 4	125.22	99.74
	Core 5	152.33	90.82
Scientist Cliffs	Core1	5.74	53.86
	Core 2	48.15	99.08
	Core 3	70.04	93.54
	Core4	302.71	99.39
Calvert Cliffs	Core1	3.60	92.68
	Core 2	23.99	79.57
	Core 3	247.66	99.41
	Core 4	793.80	99.76
Scotland Beach	Core1	93.73	47.95
	Core 2	259.93	82.79
	Core 3	281.60	98.14
	Core 4	386.07	88.12
Rhode River	Core 1	1.08	57.80
	Core 2	10.09	99.57
	Core 3	46.05	98.49
	Core 4	181.95	97.64
Long Point	Core 1	19.37	99.30
	Core 2	58.39	98.60
	Core 3	230.83	99.19
	Core 4	693.96	99.19
Elms Beach	Core 1	15.92	40.65
	Core 2	138.18	98.71
	Core 3	199.63	98.92
	Core 4	438.22	79.78

Table 4. Mobile Sand Unit Characteristics. Percent Sand (%Sand) calculated from grain size analysis of core samples from the 2008 survey.
Distance = distance along transect in meters from beginning of 2008 bathymetry transect for each sampled core position





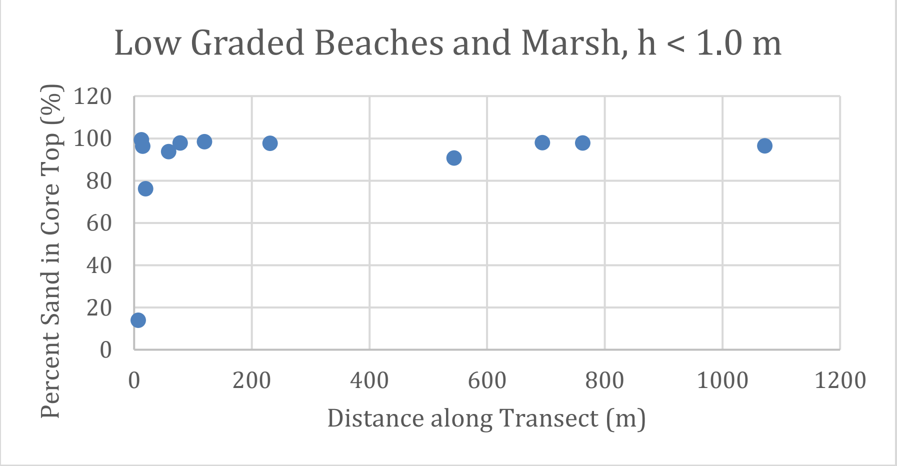


Figure 15. Mobile Sand Unit Characteristics. Percent sand in core top at each core location along the 2008 Bruun Profile Study transect, illustrating mobile sand distribution from beach to end of transect.

Finally, shoreline retreat estimates were made at each site using historic measurements of regional sea level and berm height, and the 2008 Bruun Survey measurements of offshore transect length and depth as input to the equation for equilibrium profiles stated by Bruun's Law ($X = A{\cdot}C/B+D$) (Table 5, Figures 16 a, b).

Site	A *(m/yr)* *	B* *(m)*	C* *(m)*	D* *(m)*	X_{calc} *(m/yr)*	X_{hist} *(m/yr)*
Calvert	0.0034 S	22.86	1351.67	6.53	0.16	1.28
Rhode	0.0034 A	2.74	468.09	3.77	0.24	0.58
Elms	0.0034 S	2.13	1046.52	6.92	0.39	0.56
Long Pt	0.0035 C	1.52	1411.16	6.3	0.63	0.74
Meeks	0.0031 B	15.24	471.38	8.15	0.06	0.69
Pl Island	0.0031 B	0.15	1374.78	4.38	0.94	2.63
Richland	0.0035 C	0.31	2334.94	5.19	1.49	3.23
Sc Cliffs	0.0034 S	18.29	1082.62	7.61	0.14	0.54
Scotland	0.0034 S	1.22	1802.83	20.18	0.29	1.23
Todd's Pt	0.0035 C	0.90	939.33	3.66	0.72	2.78

Table 5. Bruun Model Analysis, Input Data

**Sources:*
A = *NOAA Tides and Currents, Sea Level Rise in the Chesapeake Bay, MD.*
Tide Gauges: S: Solomon's Island 1937-2006
A: Annapolis 1928-2006
B: Baltimore 1902-2006
C: Cambridge 1943-2006
B = *Berm Height from MGS SEDNUTS Survey*
C = *Transect Length from 2008 Bruun Survey Bathymetry Data where transect length = GPS Position* A_{NE} *– GPS Position* A'_{NE}. *Assumption that C, as defined in the Bruun model to be the distance offshore to the limiting depth or the end of the mobile sand unit is the same as the measured transect length. Bathymetry collected along a transect assumed to end near the end of the mobile sand unit based on sonar, bottom shape, and grain size analysis of cores collected along the transect.*
D = *Depth at Location C (assumed to at be the end of the transect, point* A'_{NE}*) measured with Bathymetry and Sonar*
$X_{calc} = A \cdot C / B+D$ = *Shoreline Change*
X_{hist}= *Maryland Geological Survey's MD Coastal Atlas data for historic shoreline change, L. Hennesy, MGS*

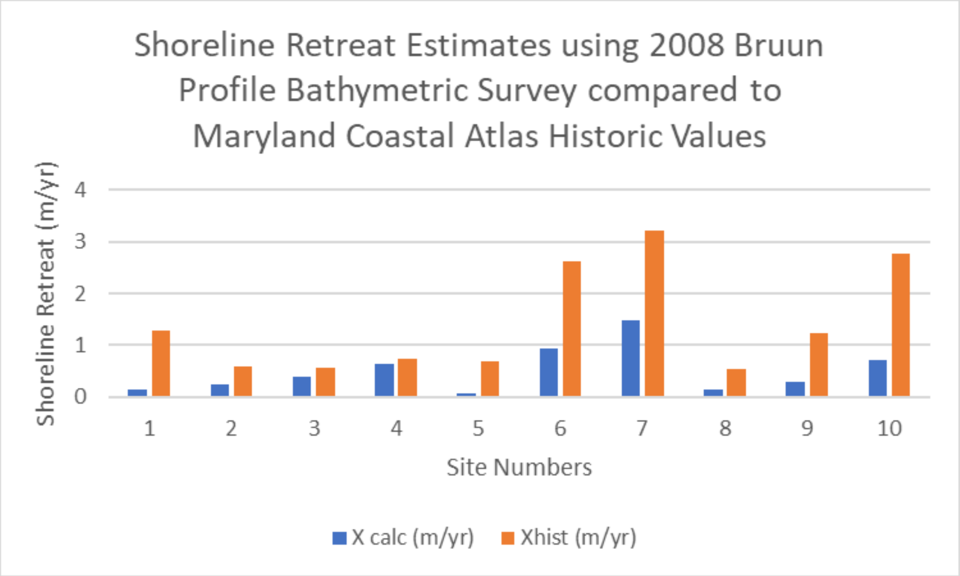


Figure 16 (a) Shoreline retreat estimates using 2008 Bruun Profile Bathymetric Survey compared to Maryland Coastal Atlas historic values dnr.maryland.gov/ccs/coastalatlas

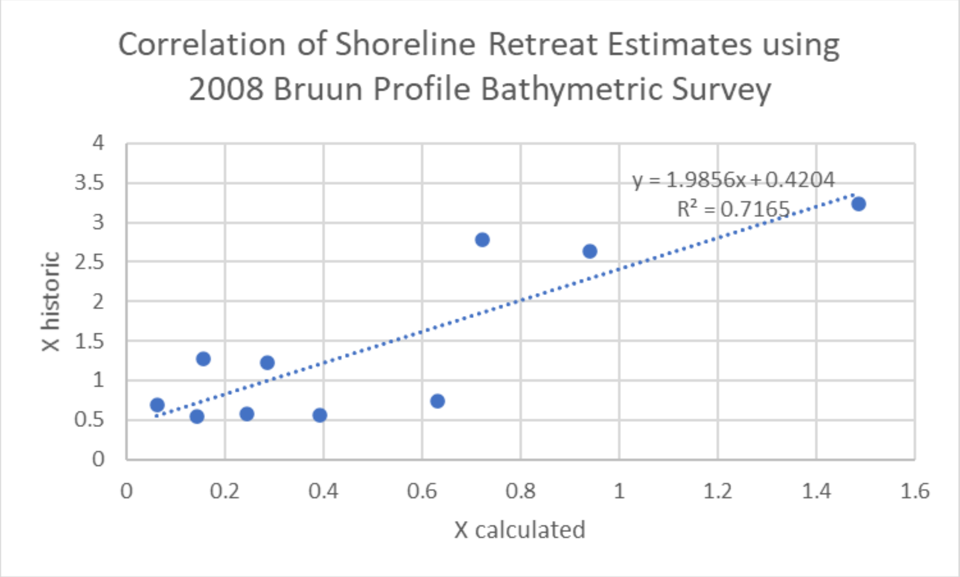


Figure 16 (b) Correlation of historic shoreline retreat with estimates using the 2008 Bruun Profile Bathymetric Survey.

Analytical Results

Estimates of the Equilibrium Parameter (*A)**

Initial calculations of the equilibrium parameter were made using Dean's equation d= (*A*)$x^{2/3}$ where (*A*) is the equilibrium parameter, d is the equilibrium depth and x is the distance offshore. The values for equilibrium depth (d) and the distance offshore (x) were calculated by differencing the three dimensional latitudinal and longitudinal GPS coordinates of the end points of the bathymetry transects (**A-A'**) (Figure 13). In 2008, when this survey was completed, The Geodetic Positioning System (GPS) used the World Geodetic System (WGS 84) as its reference coordinate system which is comprised of a reference ellipsoid, a standard coordinate system, altitude data, and a geoid, using the Earth's center mass as the coordinate origin (similar to the North American Datum of 1983 (NAD83)). The equilibrium parameter (A)was then empirically solved for based on the measured transect shape only, with R^2 best fit estimates computed (Table 2).

For comparison, calculations were made of the equilibrium parameter (A) calculated from rapid sediment analyzer core top grain size data. This allowed for calculations of the Profile Parameter (*A*) based on the equations relating A to the diameter of the sand grains (D mean) in each core top sample (Equation 1.4, Table 3).

*note: The Equilibrium Parameter is noted as (*A*) whereas the end points of the bathymetric transect are noted as **A-A'**.

Comparison of (*A*): Grain size dependency vs. shape dependency

To compare estimates of the equilibrium parameter (*A*) using the analytical methods described above; a regression analysis was completed using estimates of (*A*) determined from the 2008 bathymetry survey transect height and length (Table 2) and compared to estimates of (*A*) using core top grain size analysis (Table 3). The results of this regression analysis shows a poor correlation between the estimates of (*A*) using bathymetry data vs estimates of (*A*) using core top grain size data, sand only (Appendix 4). By plotting *A* (RSA Sand) vs. *A* (Bathy) and running a regression analysis, an R^2 of 0.0278 was found, showing very little to no correlation between the two estimates of (*A*) (Figure 14a). To examine this possibility further, estimates of *A* from site to site were tabulated and plotted with *A* (RSA Sand) as series 1 and *A* (Bathy) as series 2, plotted as the dependent variable (y axis) versus site number (x axis) (Figure 14a). A stronger agreement between estimates of (*A*) did seem to appear between sites with more similar beach composition, particularly the marsh sites. However, in general, (*A*) estimated with shape only data (bathymetry) appears to trend significantly lower than (*A*) estimated with grain size and has an overall average R^2 of 0.867 within the data set.

To examine the influence of grain size on estimates of (*A*) further, calculations of *A* using the *total* core top sample were made to see if the sand only portion of the sample yielded a different estimate of (*A*) than the total sample (Appendix 4, Table 3). When performing a regression analysis of estimates of (*A*) calculated from the total core top sample versus the sand only portion of the sample and correlating with estimates of (A) using the bathymetry data, a marginally higher but still insignificant correlation was seen for the total sample with an R^2 of 0.0682 (Figure 14b).

However, estimates of (*A*) using the 2008 bathymetry data still appear much more consistent within the datasets than those estimated with grain size data. This may be an indication, that at sites with a wide range of beach sediment types and berm heights, such as those surveyed in the 2008 Bruun Profile survey, it is more likely that antecedent geology and the resistance to erosion of the underlying clays limit the depth of erosion, keeping most of the observed beaches shallower than grain size alone would predict.

Mobile Sand Unit Analysis

By looking at the variation in beach types and heights, as well as the amount of sand vs fines at each site, we were able to examine variations in the profile, particularly in the mobile sand unit. To illustrate the mobile sand distribution from beach to end of transect at each site, the percent sand in each core top at each sample location along the 2008 Profile Study transect was calculated from laboratory grain size analysis [Methods]. To illustrate the mobile sand distribution, percent sand from each core top was calculated from grain size analysis of core samples at each sample location along site transects. Using bathymetry and GPS transect positions taken at each core sample site, a distance along transect to each core was calculated (Table 4). Comparing the distribution of sand from each core top along the transect at sites with similar berm heights, a profile of mobile sand distribution was plotted. The general trend of the mobile sand unit was to continue to near end of transect at most sites (Figure 15).

Sites such as Meeks Point, Scientist Cliffs, and Calvert Cliffs with bluffs or berm heights between 15-25 m maintained a 90-99% core top sand content to the end of their measured offshore transect (which range from 152-793 meters offshore). Sites such as Scotland Beach, Rhode River, Long Point, and Elms Beach with shorelines described as small bluffs with grasses and beach (1-3 m berm heights) show a slight pinching out of the mobile sand unit. These sites maintain a 79.78 - 99.19% core top sand unit across offshore transects ranging from 182-694 meters offshore. Finally, sites with low graded beaches and marsh shorelines (berm heights < 1 meter) showed a core top mobile sand unit continuing along most of the offshore transect, maintaining a 96.5 – 98.1 % core top sand content along profiles ranging from 694 – 1071 meters offshore (Figure 15).

Transect lengths were chosen during the survey to represent the location where the bottom suddenly dropped off, which created a variety of transect lengths, depending on the shape of the offshore profile and the distance the offshore remained shallow as the bay channel was approached. It appears as if this was a good estimate of the possible end of the mobile sand unit, with high percentages of core top sands remaining to end of transect (Table 4). It was this reasoning that led to the assumption that the input to the Bruun model for shoreline regression for the 2008 Bruun Profile Survey could be a series of variables that define the shape of the offshore profile, independent of grain size.

Bruun Model Analysis

Bruun's Rule combines the generated sand volume variation with the required sand volume needed to maintain equilibrium, relating shoreline retreat to the vertical extension of the equilibrium beach profile, sea level rise, and the berm height of the beach using the equation

$$X = A \cdot C / B+D \tag{1.6}$$

Where

X = shore retreat (regression of the coastline)

A = increase of sea level wave setup (sea level rise)

D = limiting depth between predominant near shore and offshore material

C = distance to limiting depth from the shore (amplitude of the equilibrium profile)

B = shore elevation (berm height)

To calculate rates of shoreline retreat at each site in the 2008 Bruun Profile Survey, several assumptions were made about the measured profile shape as defined in the classic Bruun profile. The limiting depth between predominant near shore and offshore material (D), and the distance to the limiting depth from the shore (C) were derived from the transect length and the depth at the end of the transect. Specifically, C was defined as transect length derived from the horizontal position (NE) at one end of the transect minus the NE position at the other end of the transect. The assumption was made that C, as defined in the Bruun model to be the distance offshore to the limiting depth (or the end of the mobile sand unit) is the same as the measured transect length. Bathymetric data collected along the transect was taken until the assumed end of the mobile sand unit based on sonar, bottom shape, and grain size analysis of cores collected along the transect. The limiting depth (D) between predominant near shore and offshore material was defined as the depth of the profile at the end of the transect, and was measured with bathymetry and sonar and positioned with GPS. Finally, the berm height of the shoreline (B) was defined as the berm height at each site as measured in the Maryland Geological Survey's SEDNUTS land survey.

The increase in sea level (A) was assumed to be the measured regional sea level rise at the closest local tide gauge at each site. Tide gauge data was taken from NOAA Tides and Currents, Sea Level Rise in the Chesapeake Bay, MD (https://tidesandcurrents.noaa.gov). Tide gauge data used in this study was taken from the Solomon's Island gauge (1937 – 2006) for Calvert Cliffs, Elms Beach, Scientist Cliffs, and Scotland Beach; the Annapolis gauge (1928-2006) for Rhode River; the Baltimore gauge (1902-2006) for Meeks Point and Pleasure Island; and the Cambridge gauge (1943-2006) for Long Point, and Richland Point.

Using each of these data sets as input variables to the Bruun model ($X = A \cdot C/B+D$), shoreline change was calculated for each site (X_{calc}) and compared to Maryland Geological Survey's MD Coastal Atlas data for historic shoreline change (L. Hennessey, MGS) (Table 5, Figure 16a). A regression analysis was then run correlating historic shoreline retreat with calculated estimates of shoreline retreat using the 2008 Bruun Profile Bathymetric Survey data for values of C and D (Appendix 5). Plotting the historic estimates for shoreline retreat against the calculated estimates of shoreline retreat at each site using the 2008 Bruun Profile Survey data, the coefficient of determination (R^2) was estimated at 0.7165 (Figure 16b), illustrating a reasonable correlation between 2008 estimates of shoreline erosion and historic estimates of shoreline erosion at each site. The estimation of D and C (the limiting depth, and the distance to the limiting depth) as defined from the 2008 measured transect shape appear to yield a strongly correlated estimate of shoreline retreat when compared to historic values at each site. Although this correlation may indicate that the 2008 bathymetric measurements of D and C will yield accurate estimates of shoreline retreat at these sites, a systematic bias between the historic and 2008 shoreline retreat estimates may be present due to differences in the temporal scale of each data set.

Chapter 4: Conclusions and Future Applications

This project was designed to investigate the assumption that an inwardly translating, constant geometry depth offshore profile forms accompanying shore erosion. The technique developed in the 2008 Bruun Profile survey was developed to provide improved techniques for extrapolating shore erosion rates into the future and estimating the amounts and impacts of associated sediment inputs. At a minimum, the project allowed a more detailed understanding and estimation of sediment inputs at the ten sites that were investigated in the survey.

The sites in this survey were purposely chosen to be as free of the influence of shoreline protection measures as possible in the modern Bay, and to avoid convergences or divergences in longshore littoral transport that might invalidate the essentially 2-D approach used. Longshore transport only affects on-offshore transport of sediment if there are longshore convergences or divergences. If the longshore transport has no gradients in the longshore direction, then on-offshore transport is governed mostly by on-offshore forcing (Dean, 1977). Longshore transport dominates along ocean shorelines, but on-offshore processes on long straight beaches with uniform incoming wave energy are well described by the Dean equation.

The first objective of the project was to combine shore erosion rate estimates, bank height and composition data, bottom sediment composition data, and depth profile information to obtain better estimates of the inputs of fine and coarse sediments that accompany shore erosion at each of the sites. The second objective was to determine how well the offshore depth profiles fit the classic Bruun equilibrium profile by exploring potential patterns in the Bruun profile fits, and the deviations in that fit that help explain the data. Additionally, an objective was set to further explore how well Bruun's law for the shoreline retreat accompanying a given sea level rise or a modified version of it, fits the historical data at each of these sites. The third objective of the project was to determine the feasibility of using these techniques for estimating future estimates of sediment inputs from shoreline erosion and to see if these results can increase the predictive capabilities at other sites around Chesapeake Bay.

These data were then used to attempt to answer questions on how far offshore the coarse sands get transported, whether there was a dominant amount of fine sediments being transported offshore, which types of shorelines provide the most fine sediments to the offshore sediment budget and how far offshore they are transported, and finally whether the rates calculated for shoreline erosion at each site agree or disagree with profile model predictions. By answering these important questions and comparing these measurements to models of offshore equilibrium profiles, a better estimate of the amount of shoreline retreat as well as the amount and type of sediment transported offshore during sea level rise in Maryland's Chesapeake Bay could be made.

The results of the 2008 Bruun profile study showed that sands dominated offshore surficial sediments at most locations, even though the source sediments were mixtures of sands and muds. These results allowed us to estimate sediment input to the near shore environment as well as the landward translation of the shore (shore erosion) in response to sea level rise. (2010 Spring Meeting of the Atlantic Estuarine Research Society

(AERS), L. Bell).

The observed offshore profiles were consistent with expectation from ocean beach profile paradigms, with the exception that the steepness proportionality factor (the equilibrium profile *A*) was not related to sediment grain size. An adjusted form of the classic Bruun relationship for predicting shoreline retreat was in approximate agreement with long-term observations. The Bruun rule is best described as the response of an equilibrium profile to slowly increasing sea level. The Bruun Rule has been found to apply in a regionally averaged sense in the southern Bay, at Virginia's Chesapeake Bay, as well (Rosen, 1978). Whether actual rates of erosion keep up with translation of an equilibrium profile will likely depend on shoreline protection measures that act to dissipate wave energy (oyster reefs, breakwaters, SAV beds) or decrease shoreline erodibility (riprap, consolidated clay deposits).

Future applications

Future applications of this work could be to attempt to use the Bruun profile model as a baseline in analyzing offshore profiles in the Chesapeake. The technique developed in the 2008 Bruun Profile study could then be used as a process to examine offshore geology (depositional history) and translation of sediments from beach to beginning of channel (estimates of the mobile sand unit). This can allow for further exploration of relationships between grain size, beach types, and composition. Estimates of sediment input due to shore erosion, and how these might be derived from a shoreward translating equilibrium profile can be further calculated to improve this method of estimating shore erosion during sea level rise.

Additionally, this technique could allow modeling of the effects on the profile of longshore drift as well as effects of engineered coastlines. These estimates of sediment input to the nearshore environment due to sea level rise and shoreline erosion will help to assess sources of turbidity more accurately in the water column and the amount of sand provided to SAV beds during these events. This could then lead to improvement in understanding sources that lead to changes in water quality and nearshore habitat quality in Chesapeake Bay shorelines in the future.

APPENDICES

Appendix 1. Site Descriptions
Appendix 2. Bathymetric Profiles
Appendix 3. Core Descriptions and Photos
Appendix 4. Regression Analysis: Estimates of Equilibrium Parameter *A* (Bathymetry vs RSA Sand)
Appendix 5. Regression Analysis: Bruun Model Estimates for X

Appendix 1. Site Descriptions generated from 2008 Site Survey Sheets, L.Bell

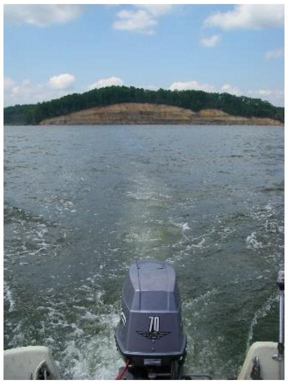
Bruun Profile Study 2008 Site Description

Site Name: Calvert Cliffs
Site Position: 4251633N 376940E
Location: Calvert Cliffs State Park, Calvert County
Date Collected: 7.1.08
Shoreline Type: Eroding bluff
Extent of Reach: ~500 Meters
Bank Elevation above water (ft.): ~20-25 meters (75 feet)
Land use/cover along reach: Cliffs/Deciduous Forest

Site and Reach Description: The site is located at Calvert Cliffs State Park at an eroding bluff of approximately 20 to 25 meters high. This bluff consists of Miocene age sediments occurring in sub-horizontal layers of unconsolidated to relatively compacted sediments. There are major slumps along the reach; however, they are rather sparse with a frequency of one per 100 meters. The beach is approximately 3 meters in width and is composed of medium sand with plentiful shells along the tideline. These cliffs dominate the shoreline for thirty miles in Calvert County. This particular reach continues to the north for at least 450 meters. 100 meters to the south, the bluff decreases in elevation and the beach becomes approximately 50 meters wide.

Site Photos:

Shoreline



Reach

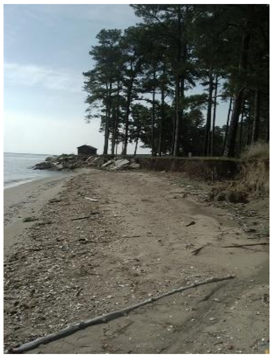
Bruun Profile Study 2008 Site Description

Site Name: Elms Beach South
Site Position: 4227917N 380739E
Location: Elms Beach, St. Mary’s County
Date Collected: 7.24.08
Shoreline Type: Bluff fronted by beach
Extent of Reach: 100 Meters
Bank Elevation above water (ft.): ~2 meters (6-7 feet)
Land use/cover along reach: Light residential to evergreen forest

Site and Reach Description: Shoreline is a 2 meter high eroding bluff containing exposed horizons composed of muddy sand and laminated sand. The beach is composed of poorly sorted fine sand to cobbles with some shell fragments. The width of the beach is approximately 8 meters. The bay bottom becomes rocky offshore at depths greater than 3m. There is a riprap section of shoreline 20 meters to the south of the site. An eroding section of shoreline owned by the Navy is approximately 75 meters to the north with the land cover changing to an evergreen forest. Approximately 400 meters further to the north there is a park with offshore protection.

Site Photos:

Shoreline



Reach to the South

Reach to the North

Bruun Profile Study 2008 Site Description

Site Name:	Long Point N
Site Position:	4295313.5N 386286.8E
Location:	North of Long Point, Dorchester County
Date Collected:	7.15.08
Shoreline Type:	Eroded bluff fronted by beach
Extent of Reach:	150 Meters
Bank Elevation above water (ft.):	2-5 feet
Land use/cover along reach:	Residential

Site and Reach Description: The site is a weathered and eroded bluff fronted by a small beach of approximately 7 meters in width. The bluff is partially covered in deciduous vegetation and grasses. The reach has a small riprap section to the north and a marsh to the south with a single family home and vegetated property adjacent to the beach. The landowner commented that his beach has been accreting for the last decade while all of his neighbors face shoreline erosion.

Site Photos:

Shoreline

Reach

Bruun Profile Study 2008 Site Description

Site Name:	Meeks Point
Site Position:	4356452N 402345E
Location:	Meeks Point, Kent County
Date Collected:	7.14.08
Shoreline Type:	Eroded bluff fronted by beach
Extent of Reach:	400 Meters
Bank Elevation above water (ft.):	25-50 ft
Land use/cover along reach:	Deciduous and evergreen forest above bluff

Site and Reach Description: The site is an eroding bluff consisting of both compacted and unconsolidated layers of gravel, sand, and sandy clay. The upper portion of the bluff is vegetated and variable in elevation. The bluff is characterized with numerous rills and it displays significant slumping along the reach. A beach is present in front of the bluff and it is approximately 4 meters wide. Large cobbles and boulders are located in the nearshore influencing wave action. Bank heights and exposed formations vary along the reach.

Site Photos:

Shoreline

Reach

Bruun Profile Study 2008 Site Description

Site Name:	Pleasure Island
Site Position:	4343481.4N 379605.3E
Location:	Pleasure Island, Baltimore County
Date Collected:	7.10.08
Shoreline Type:	graded beach
Extent of Reach:	175 Meters
Bank Elevation above water (ft.):	graded shoreline
Land use/cover along reach:	mixed forest/beach

Site and Reach Description: The site is a gently graded sandy beach, approximately 18 meters in width, with no bluff. The site is located down shore from the original 2001 survey site due to revetment at the original site, as well as concrete slabs underwater in the near shore zone. There is a dilapidated wooden groin located north of the site which is still productive, but approaching failure. There is a two foot elevation difference between the easterly side vs. westerly side of this groin with the easterly side being higher in elevation. The reach is halted approximately 75 meters to the west as the island bends northward. To the east, the reach extends approximately 100 meters where it becomes dominated by the concrete from an old road bed.

Site Photos:

Shoreline

Reach

Bruun Profile Study 2008 Site Description

Site Name: Cheston Point, Rhode River
Site Position: 4302781N 368124E
Location: Anne Arundel County
Date Collected: 6.30.08
Shoreline Type: Bluff with adjacent beach
Extent of Reach: 200 Meters
Bank Elevation above water (ft.): ~3 meters (9 feet)
Land use/cover along reach: Deciduous forest

Site and Reach Description: Site is an eroding bluff in the Nanjemoy Formation composed primarily of sand, silt, and silty clay. Beach fronting bluff is only a thin sand layer overlying compacted sediments with a width of approximately 6 meters. The reach is a fairly regular, eroding shoreline fronted by a beach or directly at waterline without a fronting beach. Site is directly across the Rhode River from Dutchman Point with exposure to fetch from both the river and the open channel of the bay.

Site Photos:

Shoreline

Reach

Bruun Profile Study 2008 Site Description

Site Name:	Richland Point
Site Position:	4234310N 397254E
Location:	Middle Hooper's Island, Dorchester County
Date Collected:	7.16.08
Shoreline Type:	Eroding Marsh
Extent of Reach:	~500 Meters
Bank Elevation above water (ft.):	1 foot
Land use/cover along reach:	Open marsh

Site and Reach Description: Site is an eroding marsh with an underlying clay layer. It is a convoluted marsh face with an actively undercut bank. The bank is a direct drop into approximately 2 feet of water. Approximately 20 m of shoreline loss is noted since the last survey of this site in 2001. The marsh extends to the south and wraps around the point of Southern Hooper Island. No significant change in the marsh is observed in that stretch. To the north of the sampled site is the same type of marsh for approx. 1/4 mile, and then the shoreline is revetted.

Site Photos:

Shoreline

Reach

Bruun Profile Study 2008 Site Description

Site Name:	Scientist Cliffs
Site Position:	4264203N 368244E
Location:	Scientist Cliffs, Calvert County
Date Collected:	7.2.08
Shoreline Type:	Bluff fronted by beach
Extent of Reach:	100 Meters
Bank Elevation above water (ft.):	50-60 feet
Land use/cover along reach:	Light residential

Site and Reach Description: The site is an exposed bluff cut by intermittent streams and gullies. It has a highly vegetated, moderately eroding shoreline. The beach is poorly sorted fine to coarse sand with some gravel. The bluff is partially rip-rapped along the base and has gabions. The gabions all are partially deteriorated and appear to have reached the full extent of their capacity. The beach is 3 meters in width.

Site Photos:

Shoreline

Reach

Bruun Profile Study 2008 Site Description

Site Name:	Todd's Point
Site Position:	4275777.6N 391156.2E
Location:	Todd's Point, Dorchester County
Date Collected:	6.25.08
Shoreline Type:	Low bank/pocket beach
Extent of Reach:	200 Meters
Bank Elevation above water (ft.):	~3/4 feet
Land use/cover along reach:	Agriculture/Residential

Site and Reach Description: The site is a low bank fronted by a pocket beach with a thin sand layer overlying compacted sediments that are exposed due to erosion. There are offshore sandbars possibly due to the revetment to the north. The beach is of a very shallow slope and ranges from 0 to 3 meters in width. Reach is exposed to the NW and is reveted to the east and west of the site.

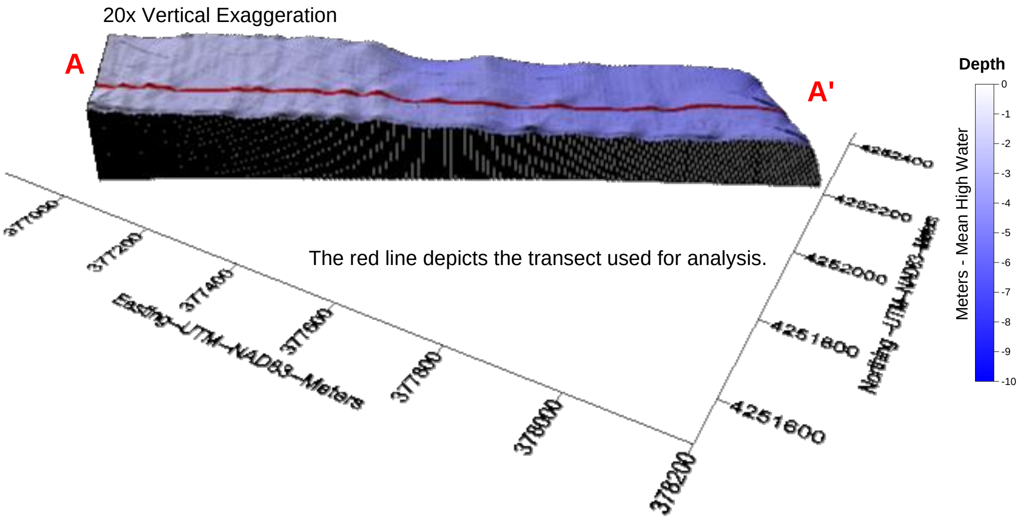
Site Photos:

Shoreline

Reach

Appendix 2. Bathymetric Profiles

Bruun Profile
Calvert Cliffs



The red line depicts the transect used for analysis.

Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.

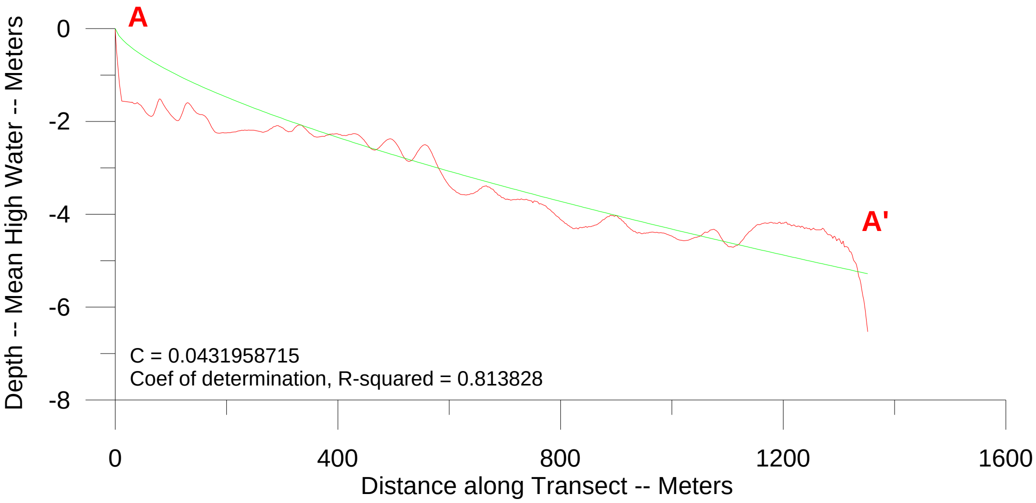
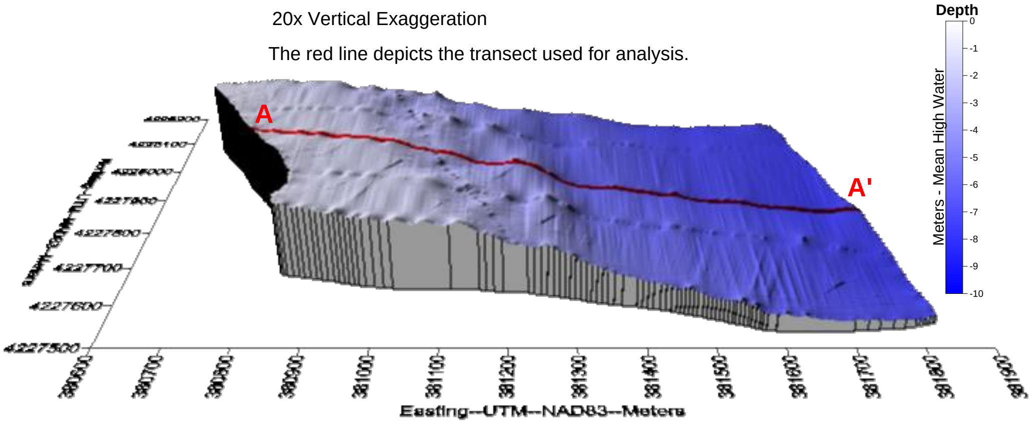


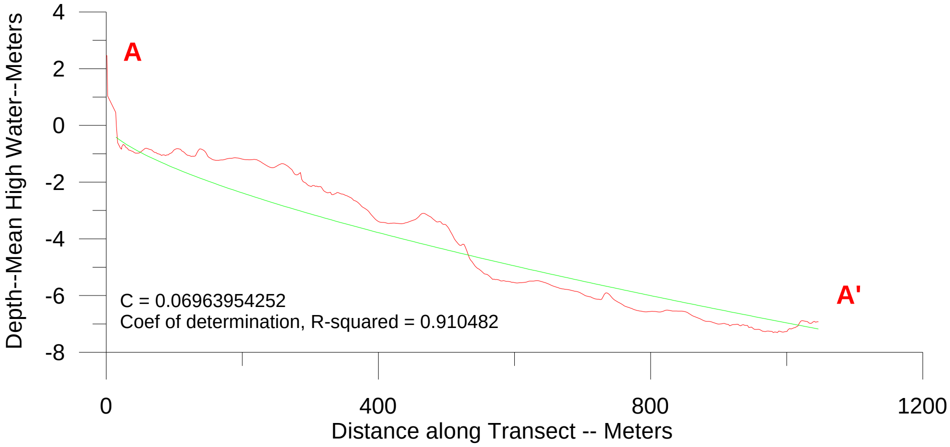
Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

Bruun Profile
Elms


20x Vertical Exaggeration

The red line depicts the transect used for analysis.

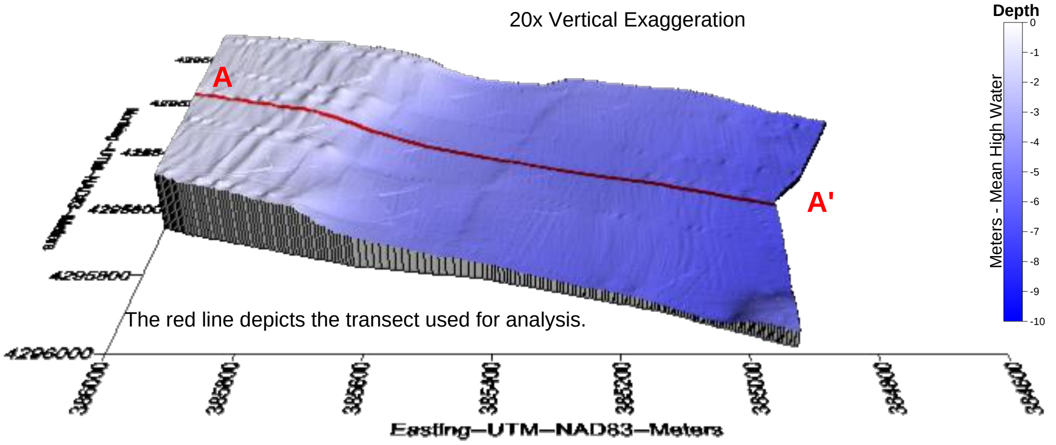
Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.


C = 0.06963954252

Coef of determination, R-squared = 0.910482

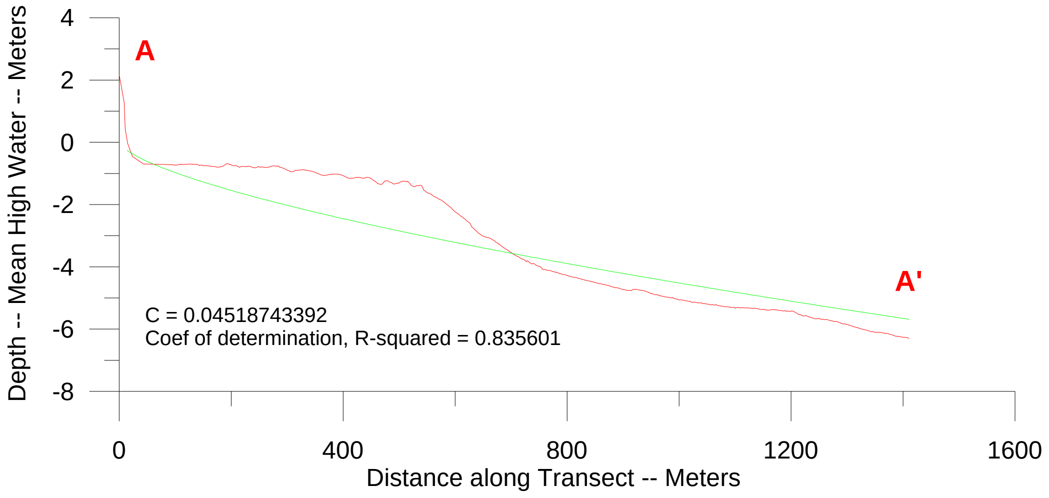
Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

Bruun Profile
Long Point



The red line depicts the transect used for analysis.

Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.



C = 0.04518743392
Coef of determination, R-squared = 0.835601

Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

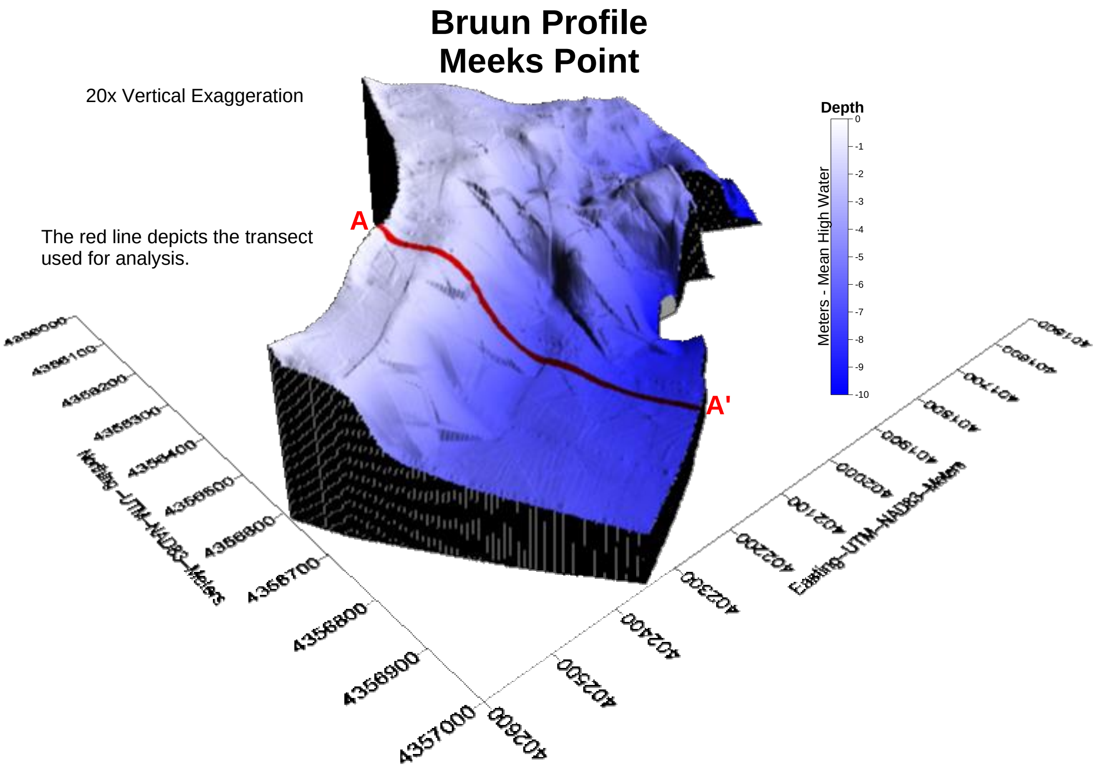


Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.

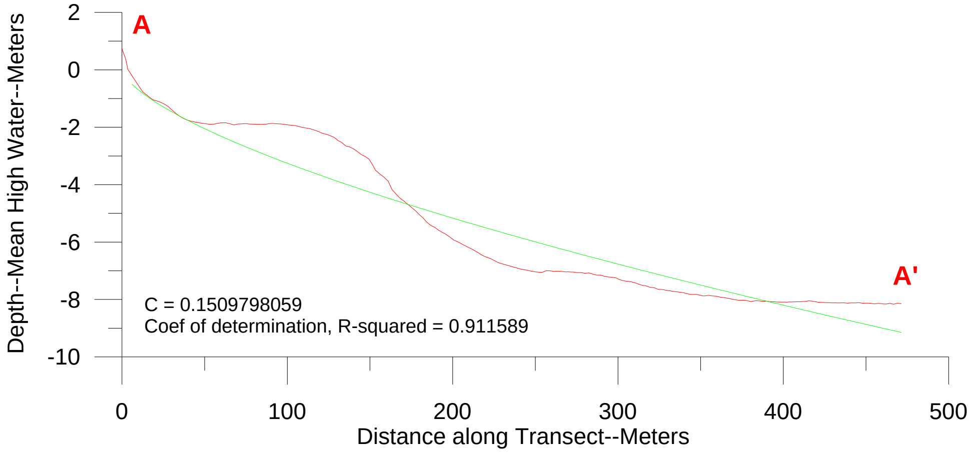


Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

Bruun Profile
Pleasure Island

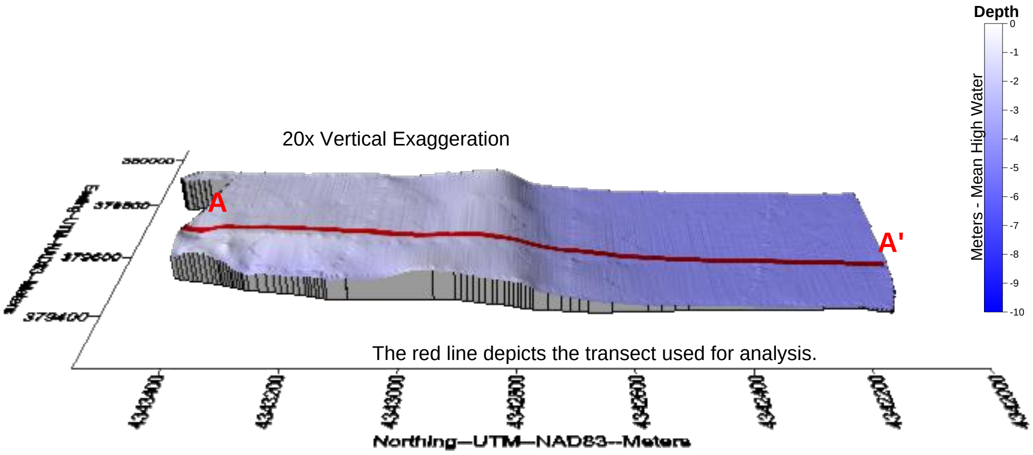


Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.

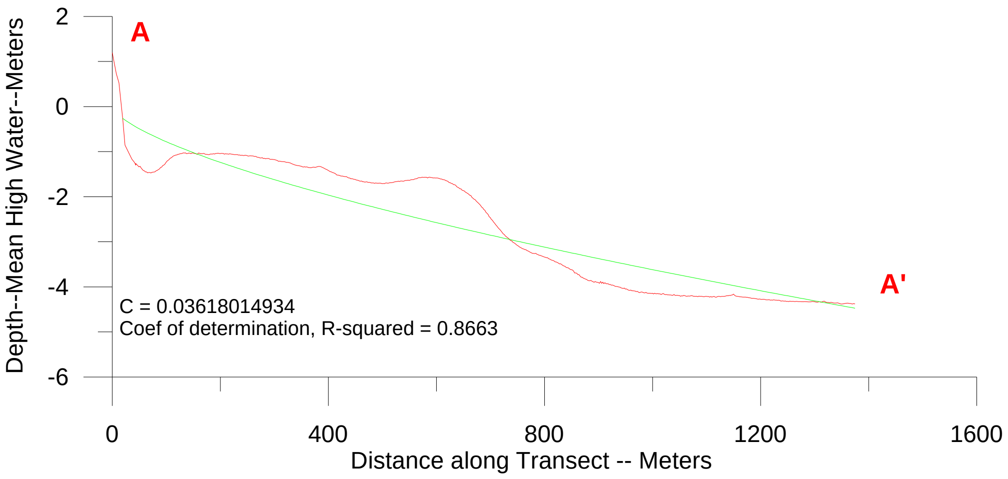
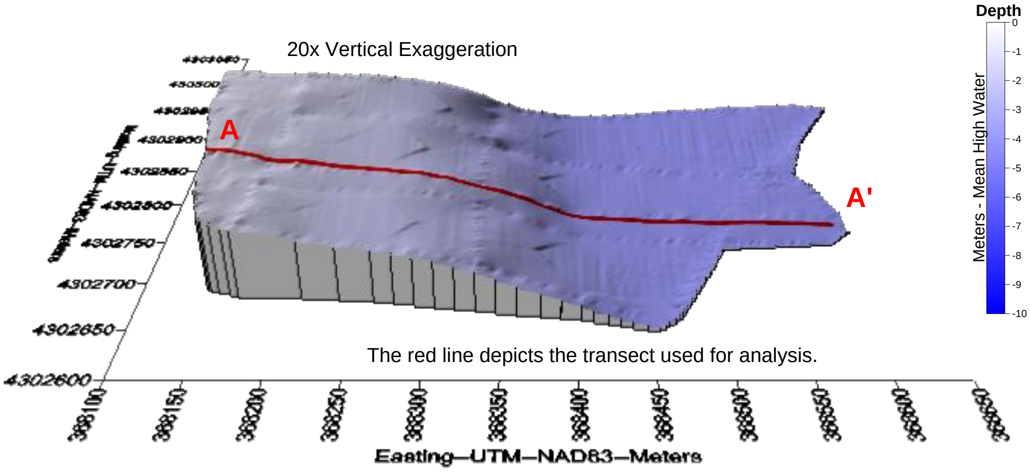


Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

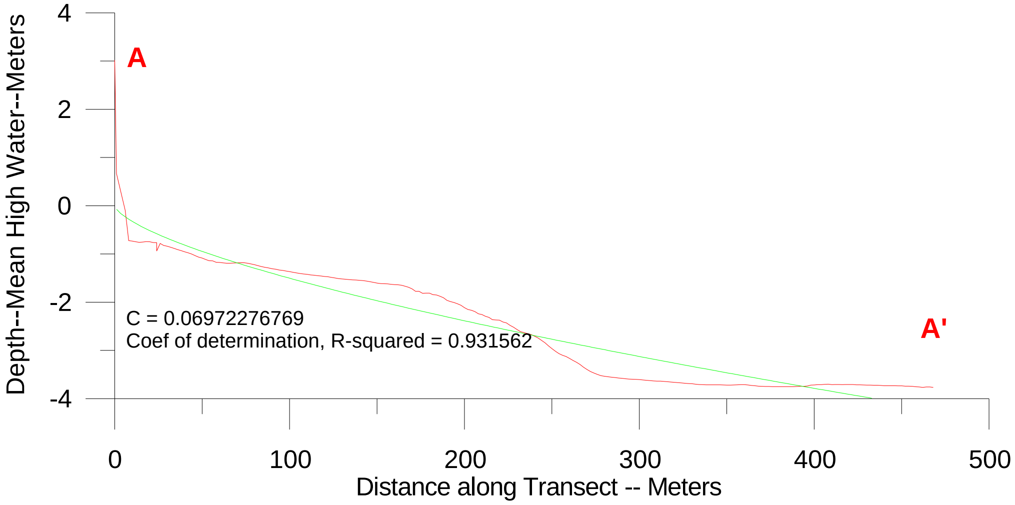
Bruun Profile
Rhodes River



20x Vertical Exaggeration

The red line depicts the transect used for analysis.

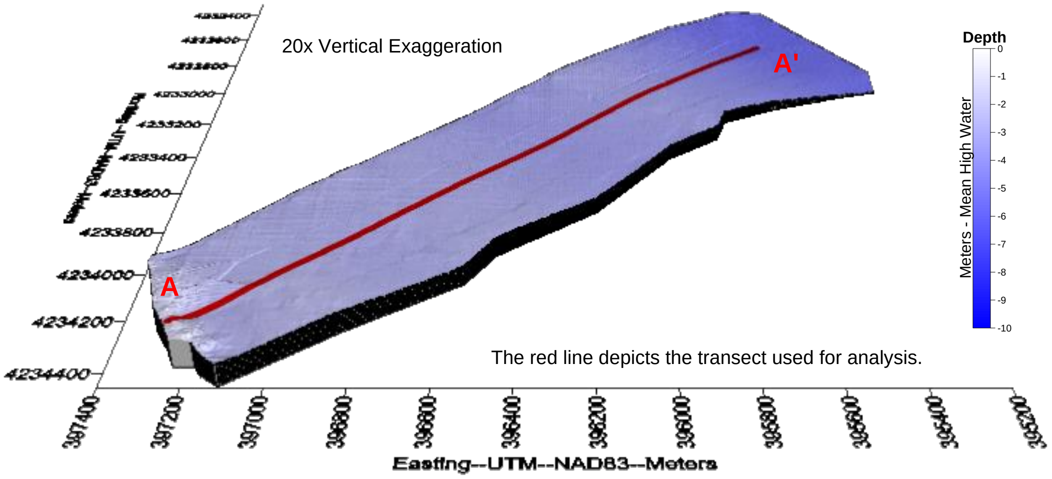
Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.



C = 0.06972276769
Coef of determination, R-squared = 0.931562

Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

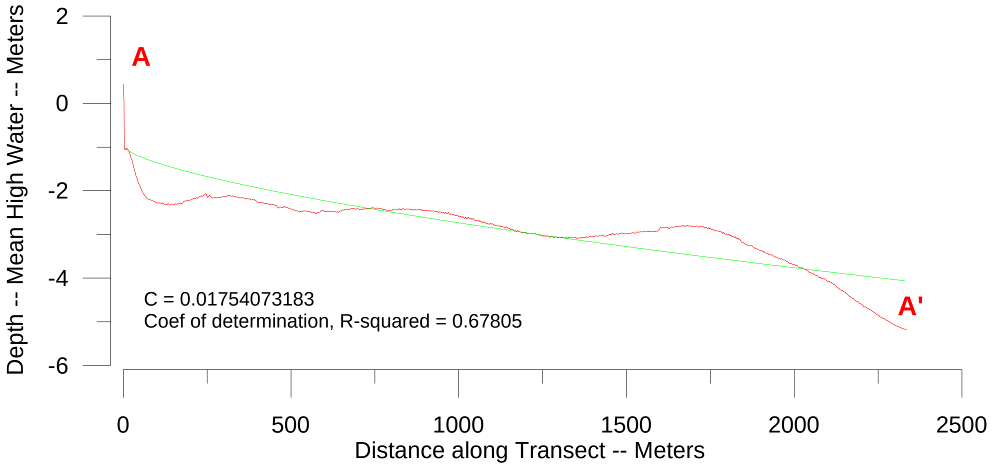
Bruun Profile
Richland Point



20x Vertical Exaggeration

The red line depicts the transect used for analysis.

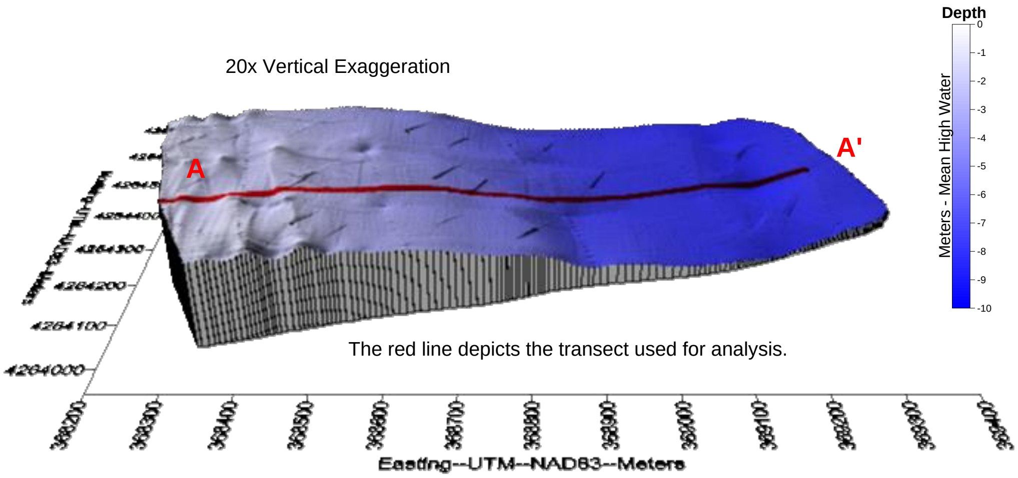
Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.



C = 0.01754073183
Coef of determination, R-squared = 0.67805

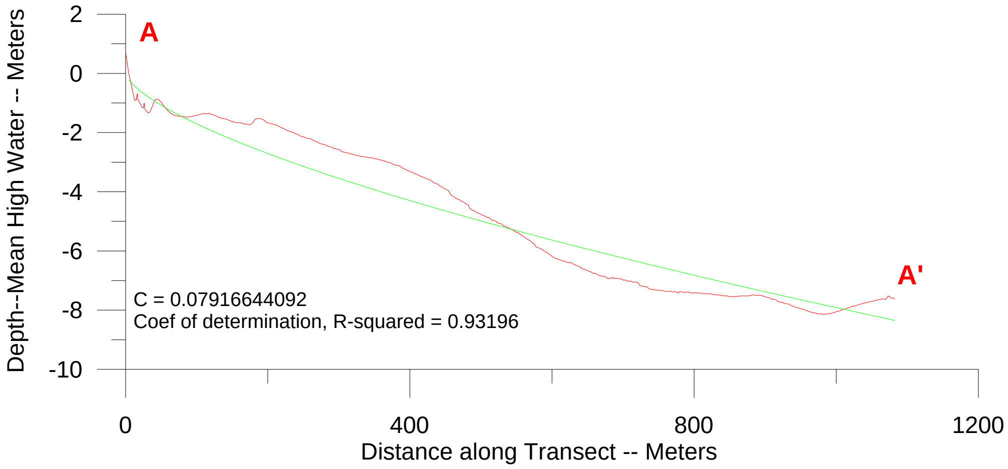
Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

Bruun Profile
Scientist's Cliffs



The red line depicts the transect used for analysis.

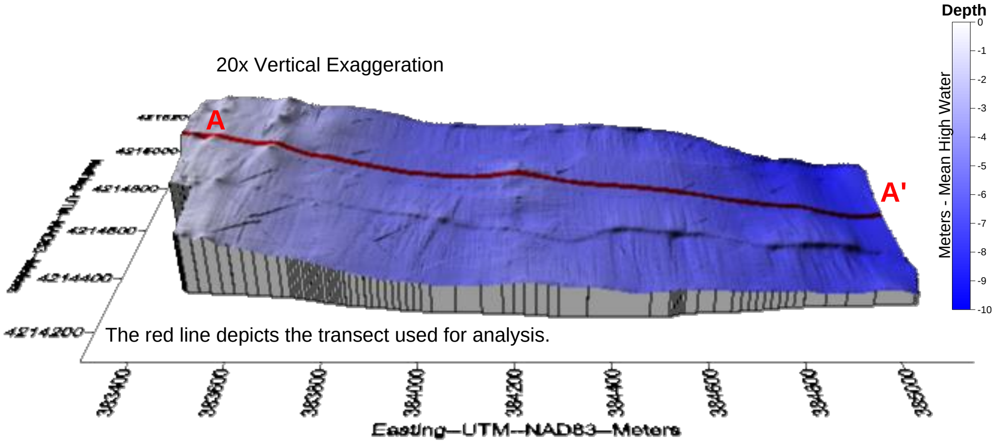
Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.



C = 0.07916644092
Coef of determination, R-squared = 0.93196

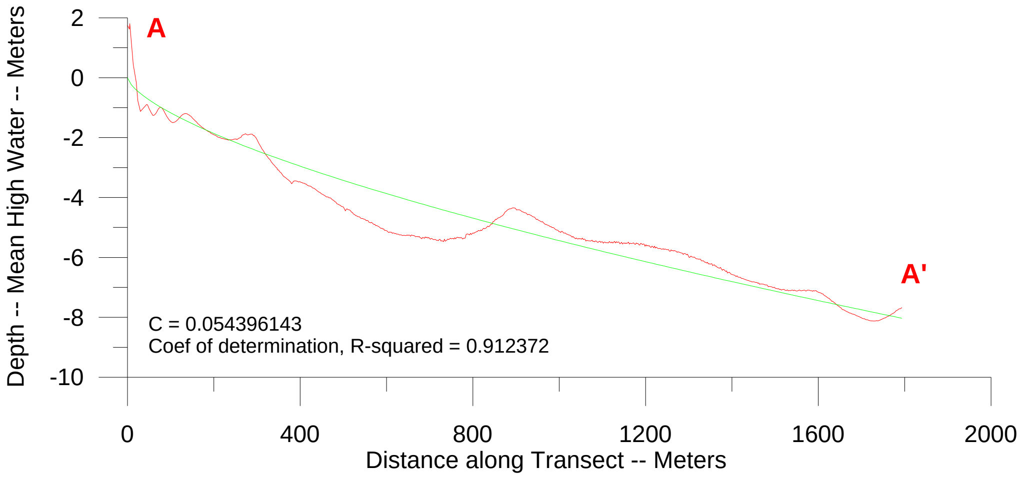
Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

Bruun Profile
Scotland Beach


20x Vertical Exaggeration

The red line depicts the transect used for analysis.

Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.


C = 0.054396143

Coef of determination, R-squared = 0.912372

Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

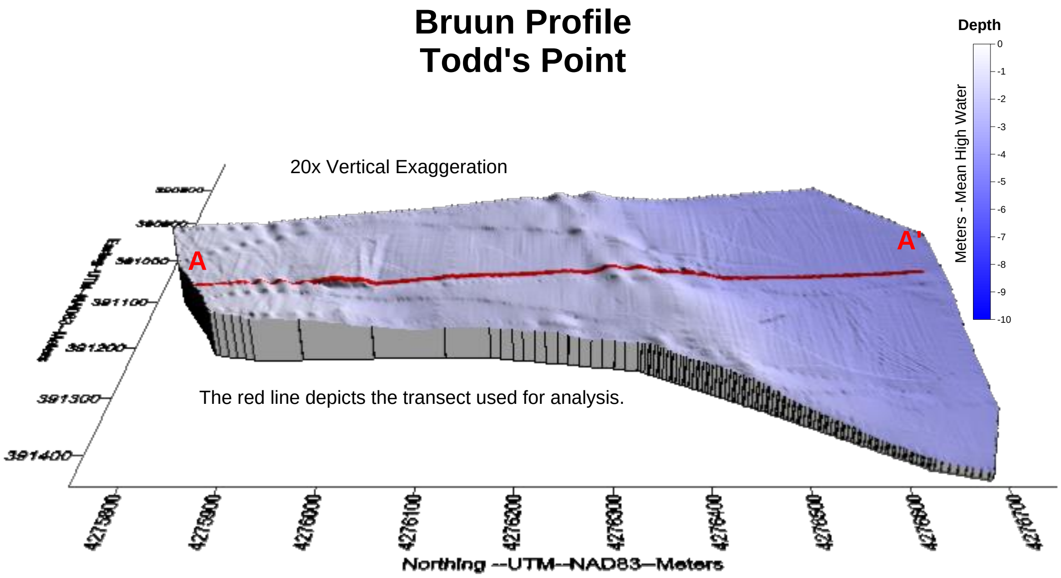


Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.

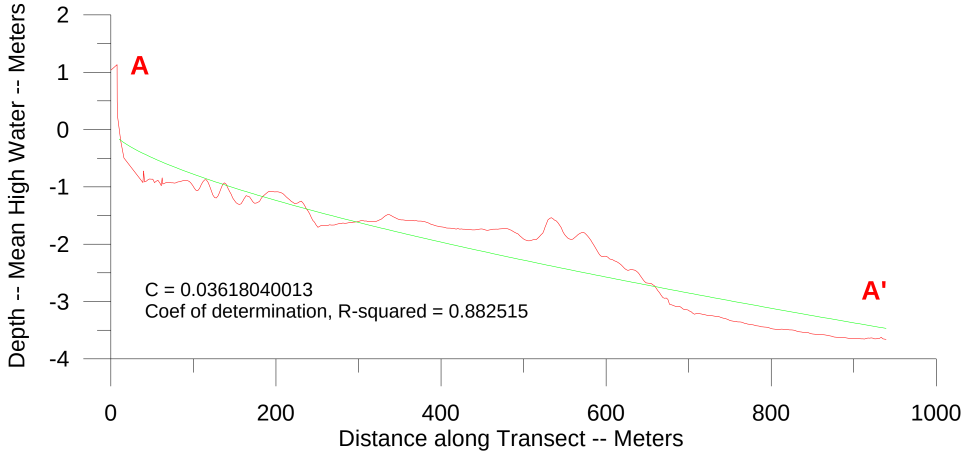


Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

Appendix 3. Core Descriptions and Photos

Calvert Cliffs at Shore, Core 1 Total length – 24 cm
Location: Northing 4251635 Easting 376943

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 12	10 YR 5/4	moderate yellowish brown very coarse sand with pebbles and shell fragments and fossils
	12-24	5GY 4/1	dark greenish gray mud. Very platy, heavy clay content

Calvert Cliffs at 1.0m depth, Core 2 Total length – 40 cm Location: Northing 4251648 Easting 376959			
Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 6	air/water	
	6-16	5Y 3/2	olive gray sand with some mud/clay content several large whole shells at 16 cm
	16-40	5Y 5/6	light olive brown sand with some mud/clay content

Calvert Cliffs at 2m depth, Core 3 Total length – 44 cm Location: Northing 4251778 Easting 377142			
Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 5	10YR 5/4	moderate yellowish brown sand with anoxic sand mottling
	5-44	N1	black anoxic sand

Calvert Cliffs at plateau, Core 4 Total length – 34 cm
Location: Northing 4252068 Easting 377605

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 6	air/water	
	6-12	10 YR 5/4	moderate yellowish brown sand with anoxic sand mottling with shells
	12-32	N3	dark gray anoxic sand with shells
	32-34	5Y 4/1	olive gray sand with shells

Richland Point at Marsh, Core 1 Total length – 23 cm
Location: Northing 4234329 Easting 397238

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0-23	5Y 4/1	olive gray heavy clay mud, glayed, with iron deposits

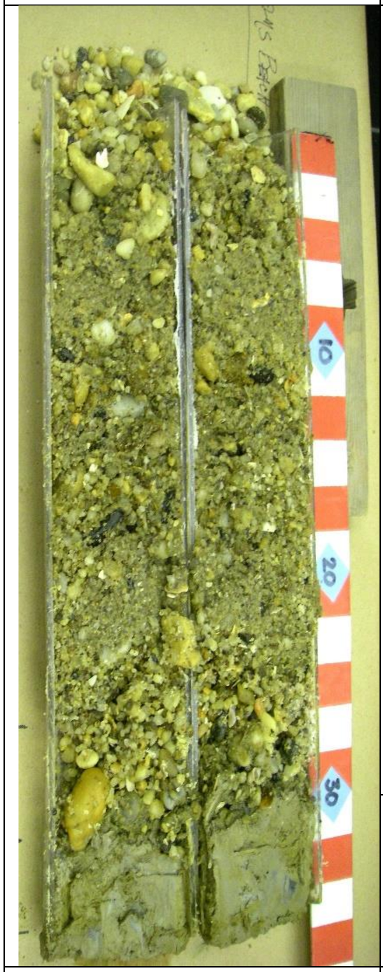
Richland Point at 1.9m, Core 2 Total length – 25 cm
Location: Northing 4234271 Easting397118

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0-3	5Y 4/4	moderate olive brown sand cap with lenses prograding down into next layer
	3-25	N3	anoxic dark gray sand with large shells

Richland Point at 2.2m depth, Core 3 Total length – 15 cm
Location: Northing 4233612 Easting 396430

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0-4	5Y 4/4 with N3	moderate olive brown sand with anoxic dark grey sand interbedded
	4-15	N3	anoxic dark gray sand

Elms Beach South Beach, Core 1 Total length – 34.0 cm
Location: Northing 4227918 Easting 380755

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 30	10YR 5/4	Moderate yellowish brown beach sand grading from coarse to medium to coarse again with large pebbles and shell fragments
	30-34	5Y61	Light olive gray mud

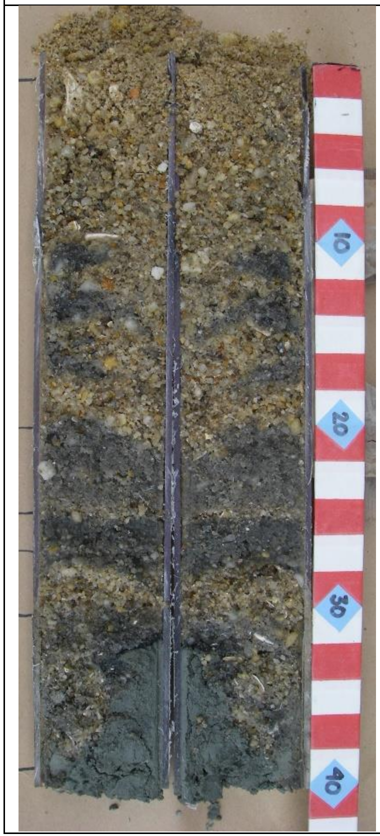
Elms Beach Sandwave Ridge @ 2.8' depth, Core 2 Total length – 38cm
Location: Northing 4227910 Easting 380877

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 2		Air/H20
	thin cap	10YR 5/4	very thin layer of moderate yellowish-brown sand
	2-6 cm	5GY2/1	greenish black fine-grained sand
	6-9 cm	10YR5/4	stripe of mod. yellowish brown sand
	9-30 cm	5GY 2/1	greenish black fine-grained sand
	30-38 cm	5GY 2/1	same sediment as 9-30 cm, with the addition of a thick shell layer

Elms Beach Sandwave Trough @ 4.0' depth ,Core 3 Total length – 60cm
Location: Northing 4227900 Easting 380938

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 54	5GY 2/1 to N2	Greenish black sand with shell fragments and a few whole mollusk shells (at 20cm and 30 cm), as well as a large cobble (40-50 cm). Grades to Grayish Black Sand
	54-60	10YR 6/6 to 5Y6/1	Dark yellowish orange sandy mud grading into a light olive gray mud at the very base of the core

Elms Beach @ 11' depth ,Core 4 Total length – 44cm Location: Northing 4227901 Easting 381177			
Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 4	5Y 4/1	Olive gray sand with heavy shell fragments
	4-22	N3	Dark gray sand with some mottling of the olive gray 5Y 4/1 sediments. Large cobble from 15-22 cm.
	22-44 cm	5Y 6/1 mottled with 10YR 6/6	Light olive gray mud mottled with dark yellowish orange sandy mud

Scientist Cliffs Beach at Tideline, Core 1 Total length – 40cm Location: Northing 4264202.1 Easting 368250.3			
Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 10	10YR 6/6	Very coarse sands with pebbles and shells
	10-32	10YR 6/6 with N5	10-20: Interbedded sand and mud with pebbles and shells. 20-24: N5 mud with pebbles and shells. 25-32: interbedded sand and mud with pebbles and shells.
	32-40	N4	Lense of N4 mud, no pebbles and shells

Scientist Cliffs Sandwave Peak at 2.5 depth, Core 2 Total length – 53 cm
Location: Northing 4264230 Easting 368286

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 6	10 YR 6/6 to 5/4	Fine yellowish brown-orange sand
	6-11	N4	Medium dark grey sand
	11-20	N2	Grayish black sand
	20-22	N1	Dark band of black sand
	22-30	N4-N5	Parallel lamination medium to medium dark gray sands
	30-53	N2	Grayish black sand

Scientist Cliffs at Plateau, 10 ft depth, Core 4 Total length – 60 cm
Location: Northing 4264360 Easting 368512

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 12	5Y 5/2	Pale brown fine sand
	12-22	5Y 5/2 with N4	Interbedded pale brown and gray sands
	22-40	N4 to N5	Gray sands
	40-55	5Y 5/2 with N4 and N5	Interbedded pale brown with medium dark grey sands
	55-60	5GY 2/1	Greenish black silty marsh mud, very platy

Long Point N at Tide Line, Core 1 Total length – 50 cm
Location: Northing 4295312.8 Easting 386270.9

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 40	10 YR 6/6	dark yellowish orange medium grained beach sand, with small pebbles and black minerals (magnesium)
	40-50	N4	topped with a pebble/shell interface with medium dark gray sand below

Long Point N Core at Sandwave Peak, 0.7m depth, Core 2 Total length – 74 cm
Location: Northing 4295393 Easting 385864

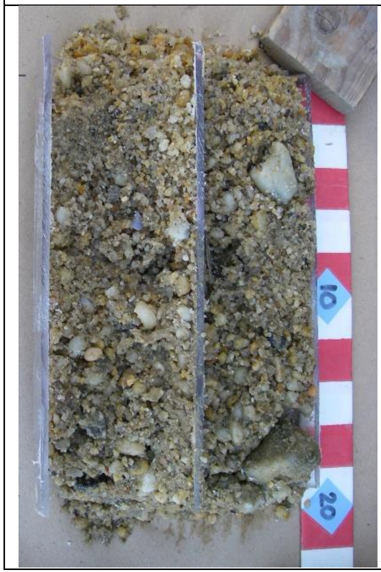
Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 5	air	air/water
	5-33	10Y 6/2	pale olive fine grained sand
	33-74	N3 with N6	Mottled dark gray and medium light grey anoxic sand with odor

Long Point N at Sandwave Trough 1.0m depth, Core 3 Total length – 56 cm
Location: Northing 4295388 Easting 385877

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 2	air/water	
	2-22	5Y 5/2	light olive gray sand with a slight shade gradation down the core
	22-56	N5 mottled with N4	Medium gray sand mottled with medium dark gray sand grading back to medium gray sand

Long Point N at 1.6m depth, Core 4 Total length – 66 cm
Location: Northing 4295386 Easting 385667

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 2	air/water	
	2-16	5Y 5/2	light olive gray sand with mottled interface with the sediments below
	16-66	N3	dark gray anoxic sand

Scotland Beach at Beach, Core 1 Total length – 18 cm Location: Northing 4214819 Easting 383334			
Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 18	10 YR 6/6	dark yellowish orange very coarse sand with pebbles

Scotland Beach at Sandwave Peak, Core 2 Total length – 66 cm
Location: Northing 4214796 Easting 383592

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0-10	10 YR 6/6	dark yellowish orange fine grained sand
	10-66	N2 mottled with N4	grayish black anoxic sand mottled with medium dark gray anoxic sand. Some pebbles, small amounts of iron deposits

Scotland Beach at Sandwave Trough, Core 3 Total length – 22 cm
Location: Northing 4214794 Easting 383570

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0-10	10 YR 4/2	dark yellowish brown sand with shells
	10-22	N1	black anoxic sand with large shells, iron deposits

Scotland Beach at 11 ft depth, Core 4 Total length – 36 cm

Location: Northing 4214767 Easting 383694

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0-6	air/water	
			capped with a very thin layer of sand
	10-36	5Y 6/1	light olive gray clay-rich mud heavily glayed with iron deposits throughout. A pocket of black anoxic mud located from 10 to 20 cm.

Meeks Pt Beach Core, Core 1 Total length – 30 cm
Location: Northing 4356451 Easting 402343

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 18	10YR 6/6	dark yellowish orange medium to coarse grained beach sand 18 cm – band of dark minerals
	18-28	10 YR 6/6	layers of large pebbles

Meeks Pt at Tideline, Core 2 Total length – 36 cm Location: Northing 4356457 Easting 402343			
Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 6	10 YR 6/6	dark yellowish orange very coarse sand and pebbles
	6-36	10 YR 6/2	pale yellowish brown muddy sand with distinct silver luster/sheen from minerals with a texture of fine grained mud some iron mottling

Meeks Pt. at 3 ft depth, Core 3 Total length – 24 cm
Location: Northing 4356468 Easting 402339

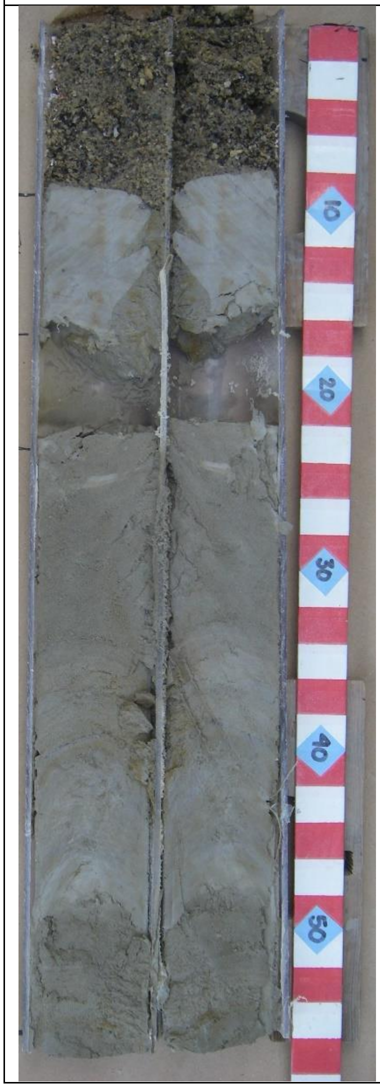
Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 5	5Y 6/1	light olive gray mud with large pebbles and interbedded sand
	5-24	5Y 6/1	light olive gray heavy clay mud

Meeks Pt at 8 ft depth, Core 4 Total length – 42cm Location: Northing 4356541 Easting 402250			
Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 20	5YR 2/1	brownish black sand with large shells around 20 cm, some lighter brown mottling
	20-27	N5	layer of anoxic black sand
	27-42	10 YR 4/2	dark yellowish brown sand

Meeks Pt at 2.9m depth, Core 5 Total length – 56 cm
Location: Northing 4356560 Easting 402229

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 7	5Y 4/1 with 10YR 5/4	olive gray muddy sand with moderate yellowish brown sand interbedded
	7-56	10YR 5/4 with 10YR 4/2	moderate yellowish brown sand mottled with anoxic gray-black sand and dark yellowish brown sand

Todds Point at Beach/Bank Toe, Core 1 Total length – 56 cm
Location: Northing 4275793.0 Easting 391159.5

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 10	10 YR 6/2 to 5/4	Pale yellowish brown to moderate yellowish brown coarse sand with pebbles
	10-18	5Y 5/2	Light olive gray muddy sand with higher clay content than 22-56
	18-22		Air pocket in core
	22-56	5Y 5/2	Light olive gray muddy sand

Todds Point Sandbar 50 m offshore, Core 2 Total length – 40 cm Location: Northing 4275855.4 Easting 391149.2			
Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0-15	5Y 5/2 mottled with N1	Light olive gray sand mottled with black anoxic sand
	15-20	5Y 6/1	Light olive gray mud, high clay content
	20-33	10 YR 5/4 with 5Y 6/1	Moderate yellowish-brown sand, mottled with light olive gray mud/clay
	33-40	5 GY 6/1	Greenish gray sand

Todds Point Offshore Sandbar, Core 4 Total length – 46 cm
Location: Northing 4276319 Easting 391099

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0-5	10 YR 5/4	Moderate yellowish brown sand mottled with anoxic black sand
	5-46	N2	Grayish black anoxic sand with heavy shell content (mollusks)

Pleasure Island Beach Core Total length – 39 cm
Location: Northing 4343469 Easting 379605

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 39	10 YR 5/4	Homogenous medium to coarse grained moderate yellowish brown beach sand with shells in the top layer to 19 cm

Pleasure Island Core at Tide Line, Core 1 Total length – 26 cm Location: Northing 4343462 Easting 379606			
Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 26	10 YR 5/4	Homogenous coarse grained moderate yellowish brown sand, shells and pebbles throughout

Pleasure Island Core @ 5’ depth, Core 2 Total length – 70.0 cm

Location: Northing 4343423 Easting 379605

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 1.0	5Y 3/2	thin cap of olive gray sand
	1.0 -24.0	5Y 6/1	light olive-gray sandy mud with high clay content mottled with organic plant matter with an odor
	24.0-40.0	5Y 6/1 with 5Y 4/4	interbedding of above sediment with light tan-orange brown sand
	40.0-66.0	5Y 4/4	Light tan-orange brown sand
	66.0-70.0	10 YR 5/4	base of compacted, more orange, more clay content sand

Pleasure Island Core @ 3.5'depth, Core 3 Total length – 90.0 cm
Location: Northing 4343250 Easting 379627

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 4	5Y 3/2	olive gray sand
	4-40	5Y 6/1	light olive gray sandy mud with high clay content. Organic plant matter throughout. Odor present
	40-80	5Y 6/1 with 5Y 4/4	above sediment interbedded with light tan orange brown sand
	80-90	5Y 4/4 with 5Y 6/1	light tan orange brown sand interbedded with light olive gray sandy mud

Pleasure Island Core at Plateau, Core 4 Total length – 62 cm
Location: Northing 4342787 Easting 379616

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0 – 8	5Y 3/2	Olive gray sand with and orangish tinge
	8-13	5Y 3/2 with 5Y 4/1 and N4	above sediment interbedded with 5Y 4/1 and N4 anoxic black grey sand. Pocket of clam shells present.
	13-62	N4	Anoxic (black/grey) olive gray sand

Rhode River Bank Toe, Core 1 Total length – 20 cm
Location: Northing 4302777 Easting 368125

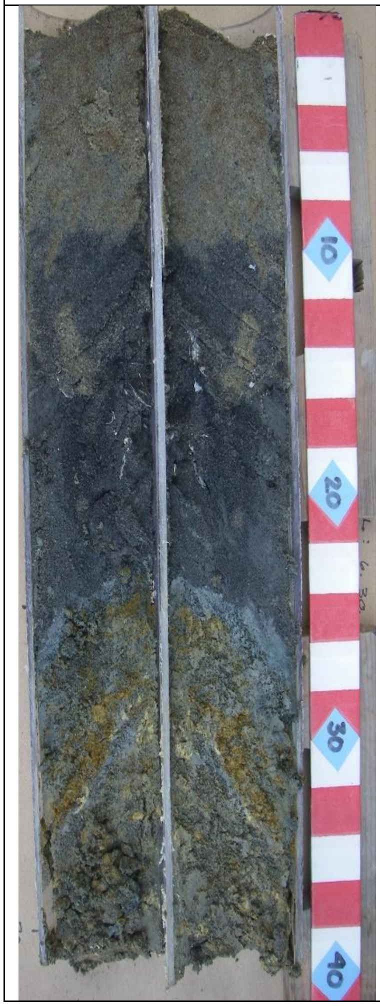
Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0-6	5Y 6/1	Light olive gray muddy sand
	6-20	10Y 4/2	Grayish olive coarse grained sand

Rhode River at Tideline, Core 2 Total length – 35 cm
Location: Northing 4302776 Easting 368134

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0-16	5Y 6/1	Light olive gray very coarse sand with dark minerals
	16-30	5Y 4/1	Olive gray very coarse sand with dark minerals
	30-35	5Y 4/1	Olive gray finer grained sand with mud

Rhode River at 4 ft depth, Core 3 Total length – 22 cm Location: Northing 4302778 Easting 368170			
Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0-11	5G 4/1	Dark greenish gray sand with dark minerals, some iron deposits
	11-22	5Y 4/1	Olive gray muddier sand

Rhode River at Slope, Core 4 Total length – 39 cm
Location: Northing 4302730 Easting 368305

Photograph	Interval (cm)	Color (Munsell Color Standard, GSA, 1991)	Description
	0-10	5Y 4/1	Olive gray sand with iron deposits
	10-24	N2	Anoxic grayish black sand
	24-39	N4	Medium dark gray muddy sand with high iron content shown as yellow to bright yellow deposits

Appendix 4

SUMMARY OUTPUT : A bathy vs A RSA sand

Regression Statistics	
Multiple R	0.182025683
R Square	0.033133349
Adjusted R Square	-0.104990458
Standard Error	0.040827419
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.000399853	0.000399853	0.239881523	0.639267016
Residual	7	0.011668147	0.001666878		
Total	8	0.012068			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.029727663	0.067282619	0.441832735	0.671937621	-0.129370448	0.188825775	-0.129370448	0.188825775
0.114	0.297288668	0.606987793	0.489777014	0.639267016	-1.138009386	1.732586723	-1.138009386	1.732586723

RESIDUAL OUTPUT

Observation	*Predicted 0.043*	*Residuals*
1	0.060348396	0.009651604
2	0.06629417	-0.02129417
3	0.061240262	0.089759738
4	0.065996881	-0.029996881
5	0.061537551	0.008462449
6	0.046673118	-0.029673118
7	0.069267056	0.009732944
8	0.05737551	-0.00337551
9	0.069267056	-0.033267056

Regression Analysis: Estimates of Equilibrium Parameter *A* (Bathymetry vs. RSA sand)

SUMMARY OUTPUT: A bathy vs A RSA total sample

Regression Statistics	
Multiple R	0.232432696
R Square	0.054024958
Adjusted R Square	-0.081114334
Standard Error	0.04038392
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.000651973	0.000651973	0.399772394	0.5472948
Residual	7	0.011416027	0.001630861		
Total	8	0.012068			

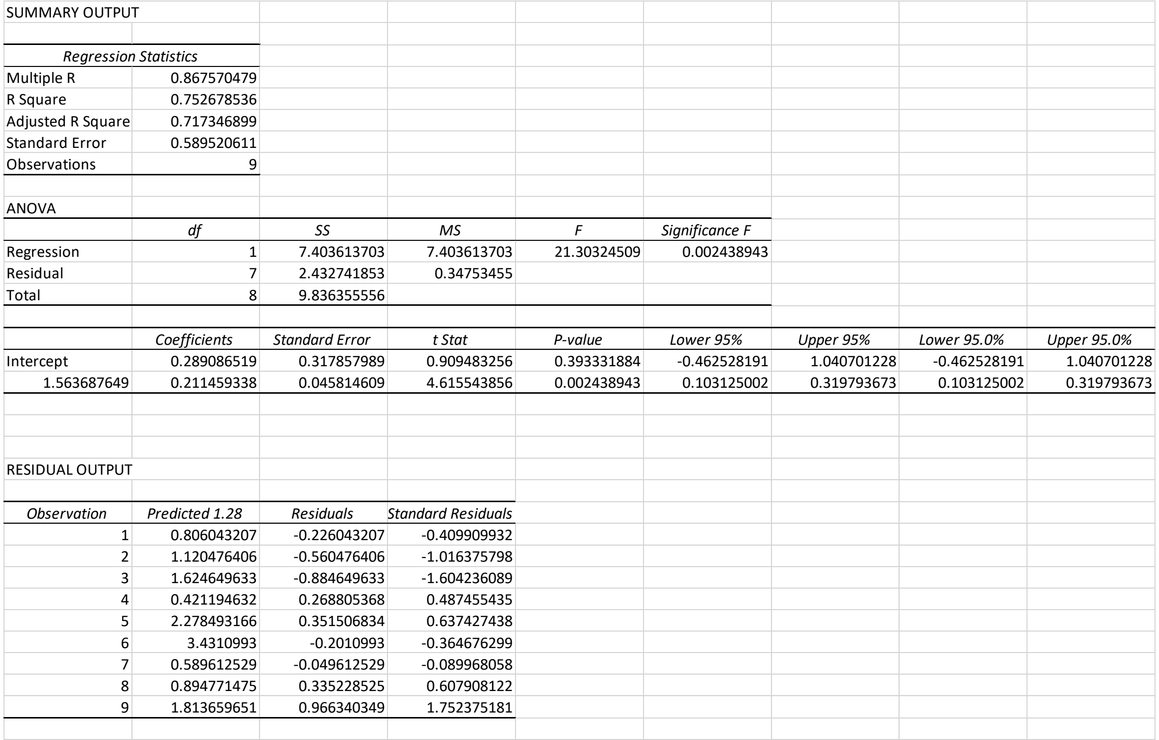
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.051156316	0.021802244	2.346378441	0.051360498	-0.0003978	0.102710431	-0.0003978	0.102710431
0.217	0.019884506	0.031449114	0.632275568	0.5472948	-0.054480831	0.094249844	-0.054480831	0.094249844

RESIDUAL OUTPUT

Observation	*Predicted 0.043*	*Residuals*
1	0.059945268	0.010054732
2	0.057400051	-0.012400051
3	0.066387848	0.084612152
4	0.05563033	-0.01963033
5	0.054099223	0.015900777
6	0.051911927	-0.034911927
7	0.062132563	0.016867437
8	0.080326887	-0.026326887
9	0.070165904	-0.034165904

Regression Analysis: Estimates of Equilibrium Parameter *A* (Bathymetry vs. Total Sample)

Appendix 5



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.867570479
R Square	0.752678536
Adjusted R Square	0.717346899
Standard Error	0.589520611
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	7.403613703	7.403613703	21.30324509	0.002438943
Residual	7	2.432741853	0.34753455		
Total	8	9.836355556			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.289086519	0.317857989	0.909483256	0.393331884	-0.462528191	1.040701228	-0.462528191	1.040701228
1.563687649	0.211459338	0.045814609	4.615543856	0.002438943	0.103125002	0.319793673	0.103125002	0.319793673

RESIDUAL OUTPUT

Observation	*Predicted 1.28*	*Residuals*	*Standard Residuals*
1	0.806043207	-0.226043207	-0.409909932
2	1.120476406	-0.560476406	-1.016375798
3	1.624649633	-0.884649633	-1.604236089
4	0.421194632	0.268805368	0.487455435
5	2.278493166	0.351506834	0.637427438
6	3.4310993	-0.2010993	-0.364676299
7	0.589612529	-0.049612529	-0.089968058
8	0.894771475	0.335228525	0.607908122
9	1.813659651	0.966340349	1.752375181

Bruun Model Analysis. Statistical Summary.

TABLES

Site Name	*Site Number*	*Location*	*GPS Position (UTC)*	*Shoreline Type*	*Bank Elev. above water*	*Extent Reach*
Meeks Point	11	Kent County	4356452N 402345E	Eroded bluff fronted by beach	7-15m	400m
Pleasure Island	15	Baltimore County	4343481N 379605E	Graded beach	Graded shoreline	175m
Rhode River	18	Anne Arundel County	4302781N 368124E	Bluff with adjacent beach	3m	200m
Long Point	7	Dorchester County	4295313N 386287E	Eroded bluff fronted by beach	0.6-1.5m	150m
Todd's Point	33	Dorchester County	4275778N 391156E	Low bank; pocket beach	0.9-1.2m	200m
Scientist's Cliffs	21	Calvert County	4264203N 368244E	Bluff fronted by beach	15-18m	100m
Calvert Cliffs	22	Calvert County	4251633N 376940E	Eroding bluff	20-25m	500m
Richland Point	3	Dorchester County	4234310N 397254E	Eroding marsh	0.3m	500m
Elms Beach	23	St. Mary's County	422791N 380739E	Bluff fronted by beach	2 m	100m
Scotland Beach	25	St. Mary's County	4214826N 383312E	Bluff with beach	0.3-1.2m	350m

Table 1. Site Descriptions (N to S)

Site Name	Calculated Constant (*A*)	R^2
Todd's Point	0.036	0.882
Calvert Cliffs	0.043	0.814
Long Point	0.045	0.836
Richland Point	0.017	0.678
Elms	0.069	0.910
Scotland Beach	0.054	0.912
Scientist's Cliffs	0.079	0.932
Rhodes River	0.069	0.932
Pleasure Island	0.036	0.866
Meeks Point	0.150	0.912

Table 2. Calculated Equilibrium Profile Constant (A) values with R^2 *; 2008 Bruun Profile Survey, from Bathymetric Data (Maryland Geological Survey, R. Ortt)*

Site	*Profile Par. A (RSA)*	
	Sand Only	*Total Sample*
Calvert	0.114	0.217
Elms	0.103	0.442
Long	0.123	0.314
Meeks	0.106	0.766
Pl. Isl.	0.122	0.225
Rhode R.	0.107	0.148
Richland	0.057	0.038
S. Cliffs	0.133	0.552
Scotland	0.093	1.467
Todd's Point	0.133	0.956

Table 3. Core top grain size analysis results from the Rapid Sediment Analyzer (estimates of mean grain diameter D(mm) – sand portion only as well as the total sample) used to calculate the Equilibrium Profile Constant (A) using Equation (1.4) $A = 20 \cdot D^{0.63}$ *for* $0.1 \times 10^{-3}m \le D \le 0.2 \times 10^{-3}m$ *[Maryland Geological Survey, 2008 Bruun Profile Survey]*

Site	*Core #*	*Distance(m)*	*%Sand*
Pleasure Island	Beach	12.40	99.36
	Core1	19.38	76.17
	Core2	58.39	93.73
	Core3	230.83	97.64
	Core4	693.96	98.01
Richland Point	Core1	6.89	13.91
	Core2	119.31	98.47
	Core3	1071.92	96.47
Todd's Point	Core 1	14.80	96.32
	Core 2	78.02	97.86
	Core 3	544.12	90.72
	Core 4	762.52	97.80
Meeks Point	Core 1	0.17	92.23
	Core 2	5.32	45.34
	Core 3	16.80	10.34
	Core 4	125.22	99.74
	Core 5	152.33	90.82
Scientist Cliffs	Core1	5.74	53.86
	Core 2	48.15	99.08
	Core 3	70.04	93.54
	Core4	302.71	99.39
Calvert Cliffs	Core1	3.60	92.68
	Core 2	23.99	79.57
	Core 3	247.66	99.41
	Core 4	793.80	99.76
Scotland Beach	Core1	93.73	47.95
	Core 2	259.93	82.79
	Core 3	281.60	98.14
	Core 4	386.07	88.12
Rhode River	Core 1	1.08	57.80
	Core 2	10.09	99.57
	Core 3	46.05	98.49
	Core 4	181.95	97.64
Long Point	Core 1	19.37	99.30
	Core 2	58.39	98.60
	Core 3	230.83	99.19
	Core 4	693.96	99.19
Elms Beach	Core 1	15.92	40.65
	Core 2	138.18	98.71
	Core 3	199.63	98.92
	Core 4	438.22	79.78

Table 4. Mobile Sand Unit Characteristics. Percent Sand (%Sand) calculated from grain size analysis of core samples from the 2008 survey.
Distance = distance along transect in meters from beginning of 2008 bathymetry transect for each sampled core position

Site	A *(m/yr)* *	B* *(m)*	C* *(m)*	D* *(m)*	X_{calc} *(m/yr)*	X_{hist} *(m/yr)*
Calvert	0.034 S	22.86	1351.67	6.53	1.56	1.28
Rhode	0.034 A	2.74	468.09	3.77	2.44	0.58
Elms	0.034 S	2.13	1046.52	6.92	3.93	0.56
Long Pt	0.035 C	1.52	1411.16	6.3	6.32	0.74
Meeks	0.031 B	15.24	471.38	8.15	0.62	0.69
Pl Island	0.031 B	0.15	1374.78	4.38	9.41	2.63
Richland	0.035 C	0.31	2334.94	5.19	14.86	3.23
Sc Cliffs	0.034 S	18.29	1082.62	7.61	1.42	0.54
Scotland	0.034 S	1.22	1802.83	20.18	2.86	1.23
Todd's Pt	0.035 C	0.90	939.33	3.66	7.21	2.78

Table 5. Bruun Model Analysis, Input Data

**Sources:*

A = *NOAA Tides and Currents, Sea Level Rise in the Chesapeake Bay, MD.*
Tide Gauges: S: Solomon's Island 1937-2006
A: Annapolis 1928-2006
B: Baltimore 1902-2006
C: Cambridge 1943-2006
B = *Berm Height from MGS SedNuts Survey*
C = *Transect Length from 2008 Bruun Survey Bathymetry Data where transect length = GPS Position A_{NE} – GPS Position A'_{NE}. Assumption that C, as defined in the Bruun model to be the distance offshore to the limiting depth or the end of the mobile sand unit is the same as the measured transect length. Bathymetry collected along a transect assumed to end near the end of the mobile sand unit based on sonar, bottom shape, and grain size analysis of cores collected along the transect.*
D = *Depth at Location C (assumed to be the end of the transect, point A'_{NE}) measured with Bathymetry and Sonar*
$X_{calc} = A \cdot C / B+D$ = *Shoreline Change*
X_{hist}= *Maryland Geological Survey's MD Coastal Atlas data for historic shoreline change, L. Hennessey, MGS*

FIGURES

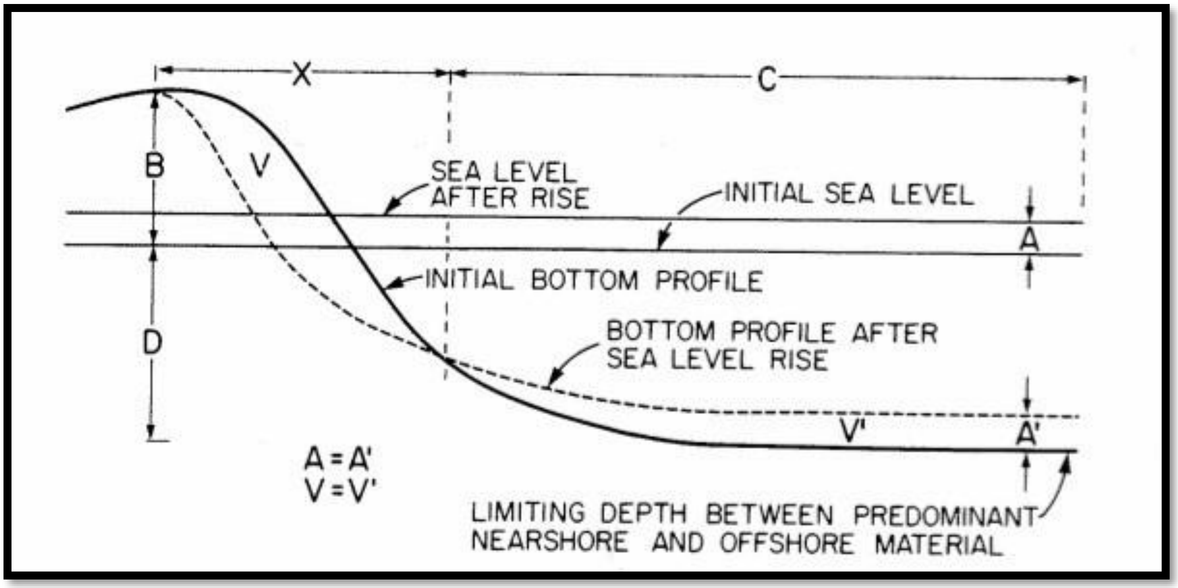


Figure 1. Bruun's Equilibrium Profile [Bruun 1968]

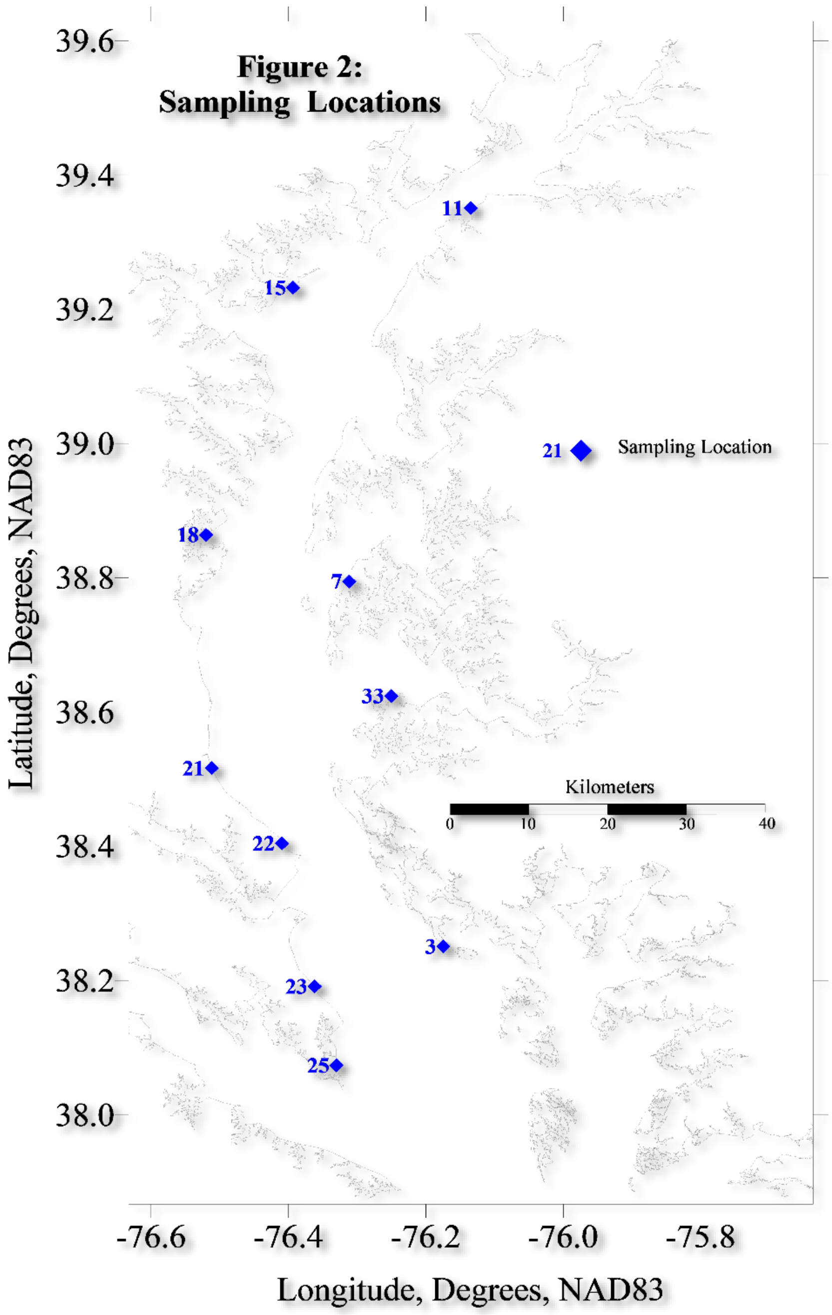


Figure 2. Sampling Locations, 2008 Bruun Profile Survey

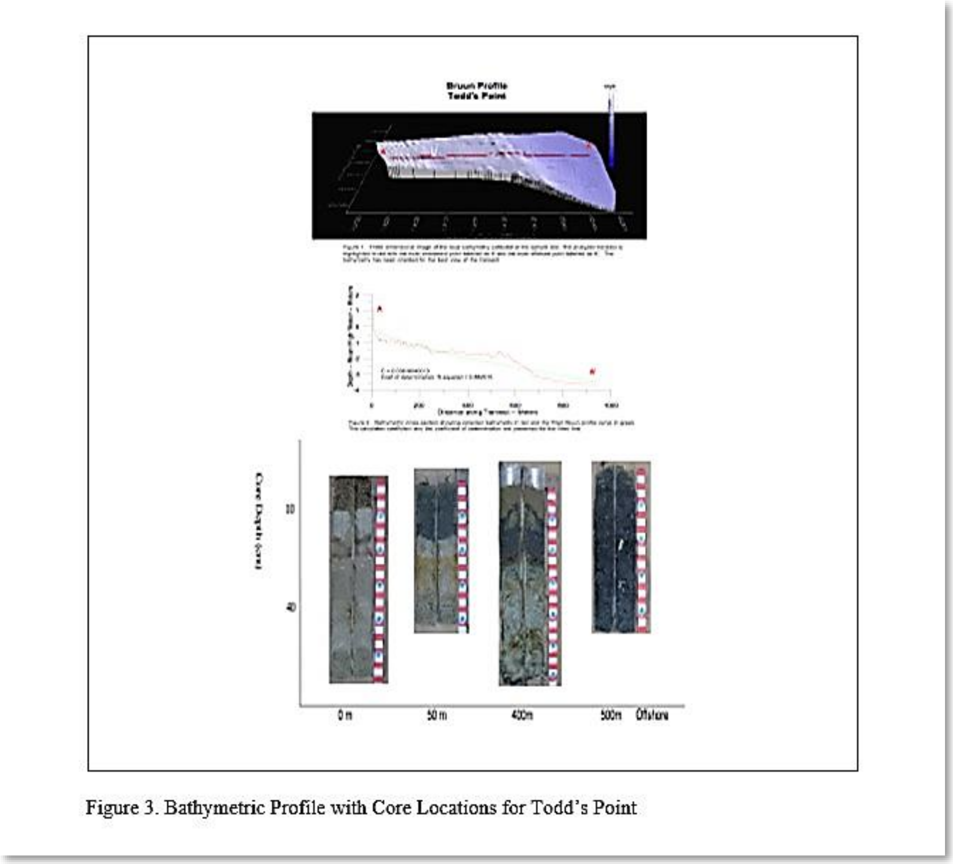


Figure 3. Bathymetric Profile with Core Locations for Todd's Point

Figure 3. 2008 bathymetric example profile with core locations, Todd's Point

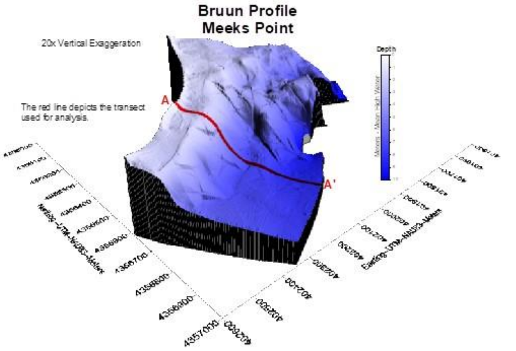


Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.

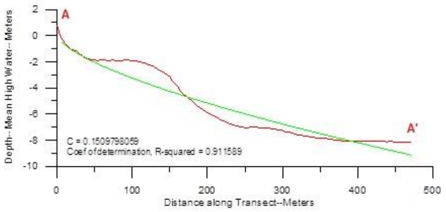


Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

Figure 4. Three-dimensional image of the local bathymetry collected at the Meeks Point sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as **A** *and the most offshore point labelled as* **A'***. The bathymetry has been oriented for the best view of the transect. Secondary plot represents the bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.*

Figure 5. Survey ties using leveling lines and handheld GPS at Meeks Point

Figure 6. All cores collected along the Rhodes River transect (bank toe, surf zone, plateau, and slope). Each core collected is split, labeled, and photographed.

Field Measurement Instructions

Task 1: Identify Site

Purpose: Understand current conditions and fetch which influences erosion.

Step 1. Go to coordinates on site page. Verify site has not been armored or changed to prevent erosion. If site has been armored, see if there is an acceptable site in the near vicinity that appears to be the same structure (bank height, soil type, etc.). Record a short description of site, take some pictures, and describe fetch and shoreline.

Task 2: Conduct a bathymetric survey of site.

Purpose: To develop a profile from the shore to the offshore. The lines surrounding the main profile are used to verify there are no anomalies in the profile.

Execute using Knudsen Echo control software and load config file: D:\bruun\bruunconfig.cfg. Verify GPS coordinates are being read. Record both binary and ascii file with everything selected for the ascii file (this is default and should not need to be changed)

Step 1: Run a line (in either direction) perpendicular to the shoreline using the site coordinates (generally) as one end. The line should run far enough out that you see the depth drop off significantly to a plateau. The goal is to run the line long enough to where the sediment is being lost in the sink rather than active mobility. At Pt. Lookout that looks to be around 14-foot depth, and at Scotland beach that looks to be around 21-foot depth. It was found best to watch Ozi to run this line straight and perpendicular to the beach. Record the ending point of this line as the transect end point on the datasheet. For documentation purposes, try to run this at the same speed and fairly straight.

Step 2: After this profile (in a new file), run two lines to the north of your profile line and two lines to the south of your profile line (all perpendicular to shoreline). This is just to demonstrate that there are no major variations in the profile. If necessary, you can pick one of those lines as your main profile line if there is something in the way or anomalous in the first one. If you move the main profile line to one of these other ones, change the transect end points on the datasheet to match the one you pick.

Step 3: Finally, do two or three cross tracks (new file) just to have some tie-ins for the survey. Try to make one of these as close to shore as possible to help with the bathymetry creation.

Task 3: Differential Leveling at shoreline

Purpose: Tie-in upland topography with bathymetric profile.

Step 1: Setup the tripod and level at high spot (typically on bank). If the bank is unmanageably high (i.e. > 15 feet or so), then just setup at base and provide an estimate of bank height. Record GPS (white Magellan) of tripod and height of instrument (stadia rod measurement from ground to the center of the level objective). Annotate on datasheet.

Step 2: Record several points to generally describe upland topography to near shore bathymetry. Typically, complete a top of bank reading, toe of bank reading, high water mark (rack line), tide level mark (current water level), and two or three readings of the near shore. Each site is different. If there is a bluff with a straight drop to the water, it will not be necessary to survey as many points. At each location record GPS, and level readings (middle most important, top and bottom readings for distance). Annotate on data sheet. Also annotate the time (UTC from the white GPS) for the tide level mark so it is possible to go back and retrieve tide information to tie both the upland and the bathymetry surveys together. For points collected in the near shore, record estimated depths also.

Task 4: Collect cores and grab samples along profile line.

Purpose: Collect and describe the active mobile sediment layer along the profile. Secondary purpose is to attempt to describe the thickness of this layer.

Step 1: Collect a core sample and grab sample at a location near the tide line, but in the water. Typically, this is in water depths of less than a foot. Annotate GPS, depth, and any other data on datasheet. Label core and grab bag with site name, date, and core #. Cores will generally be between 6” and 2 feet in length depending upon substrate.

Step 2: Collect 3-4 more cores and grab samples along the surveyed profile. At each site record depth, GPS location, and obtain a grab sample and core. In general, attempt to core along significant structural changes and before the profile rolls off to depth. This has been more complicated to determine in the field and generally turns into collecting a core at 1 meter of depth along the profile, two meters of depth along the profile, and three meters of depth along the profile. If there are sand waves in the profile attempt to collect a core at a peak and trough of the waves, and then one more before the profile rolls off to depth. With anything deeper than 2.5 meters or so, it is necessary to use the aluminum liners. It was found that simply driving the CABs to refusal and pulling them out with the plumber’s test bob is the best method for obtaining the cores. Twisting the cores rather than just purely pulling them out also seems to help in retrieval.

Figure 7. Field Measurement Instructions

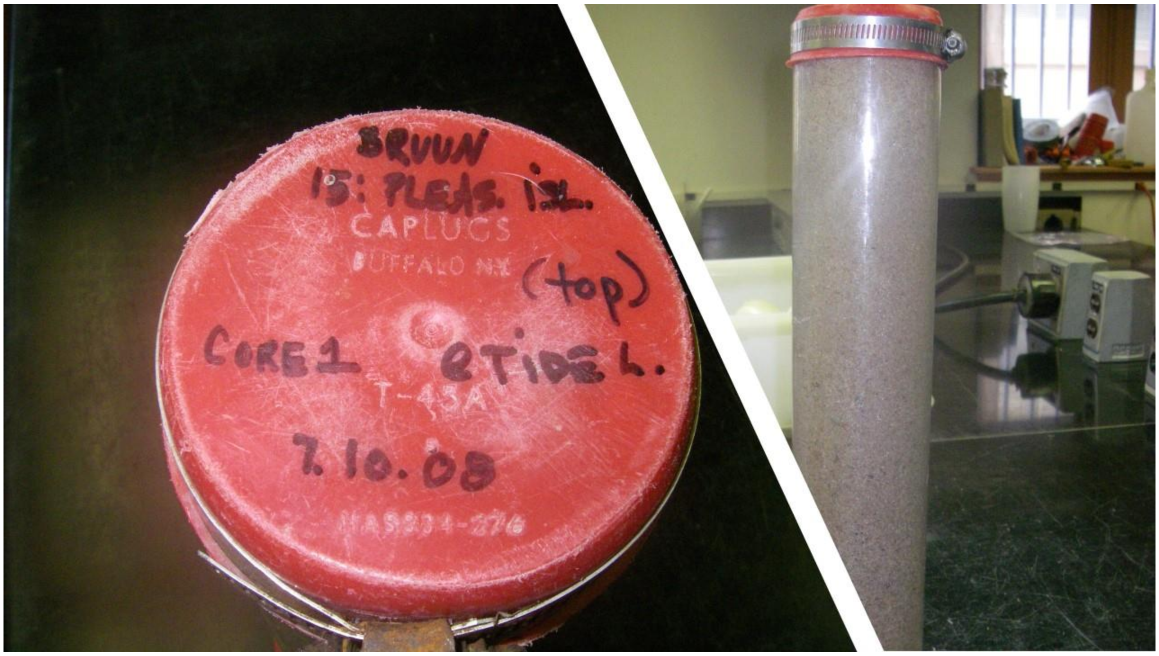


Figure 8. Cored Sediment in Cellulose Acetate Butyrate (CAB) tube capped and labeled, Pleasure Island site. Pictured in the Maryland Geological Survey Sed Lab, Baltimore, Maryland.

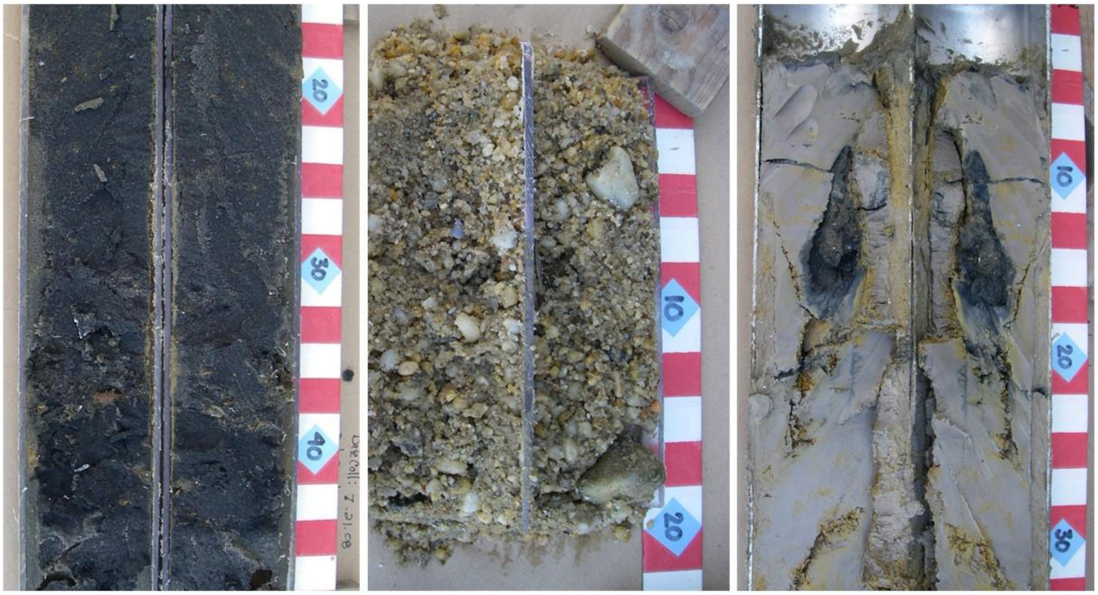
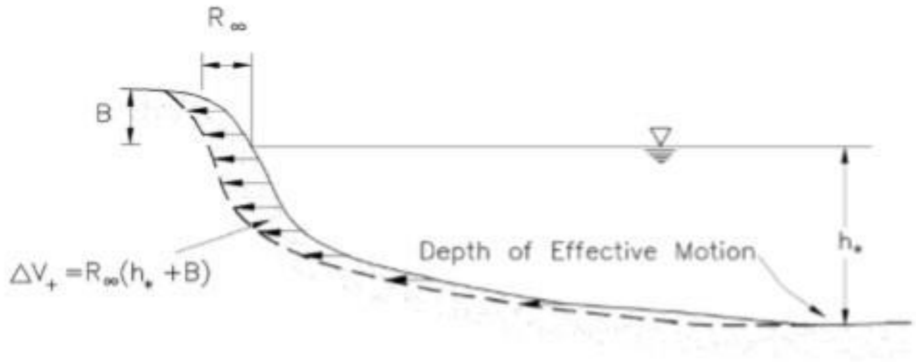


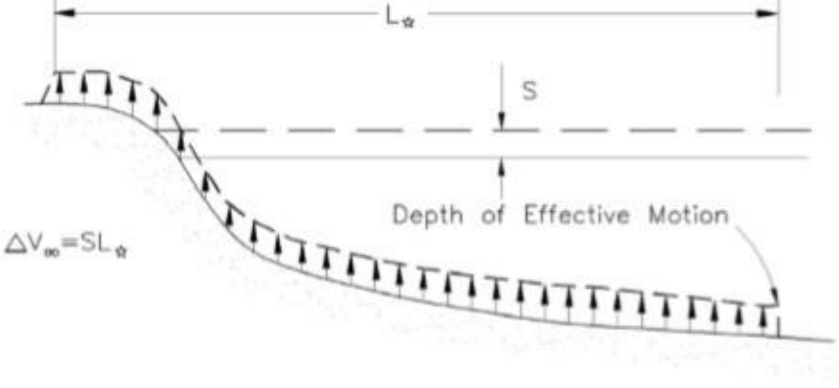
Figure 9. Split, Photographed Cores from Scotland Beach site from tide line, beach, and channel

Figure 10. Research Vessel 2008 Bruun Profile Survey with an onboard perspective of transect distance from shore

Figure 11. Leveling lines run from beach to beginning of measured offshore 2008 bathymetric profile at Calvert Cliffs



a) Volume of Sand "Generated" by Horizontal Retreat, R_∞, of Equilibrium Profile Over Vertical Distance (h_*+B)



b) Volume of Sand Required to Maintain an Equilibrium Profile of Active Width, L_*, Due to a Rise, S, in Mean Water Level

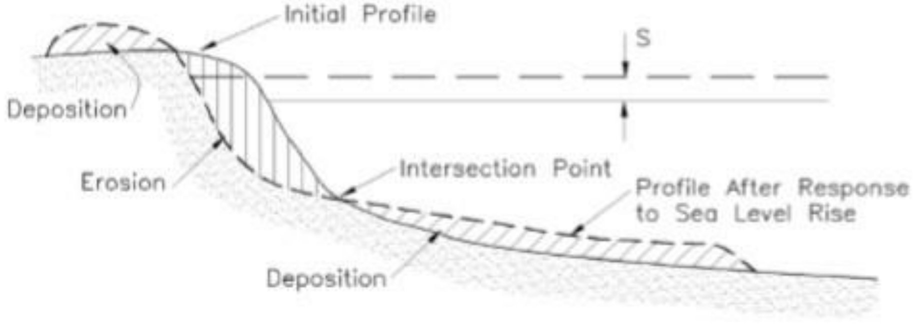
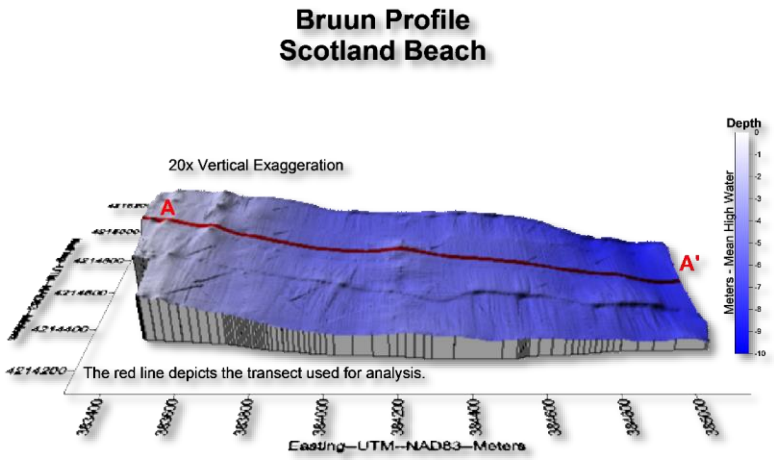
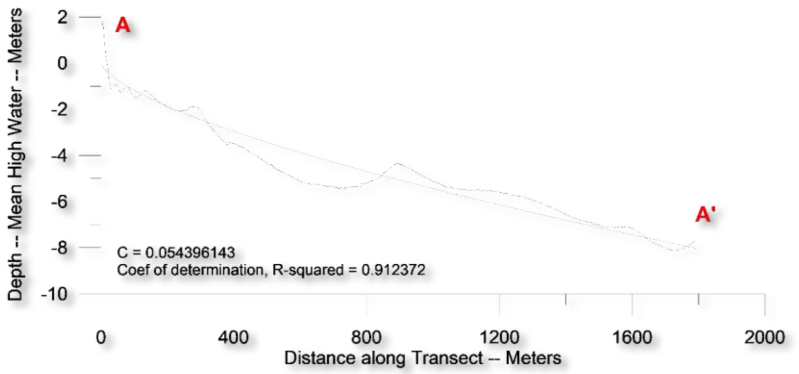


Figure 12. Components of sand volume balance due to sea level rise and associated profile retreat according to the Bruun Rule (Army Corp Manual, Fig. III-3-32)



The red line depicts the transect used for analysis.

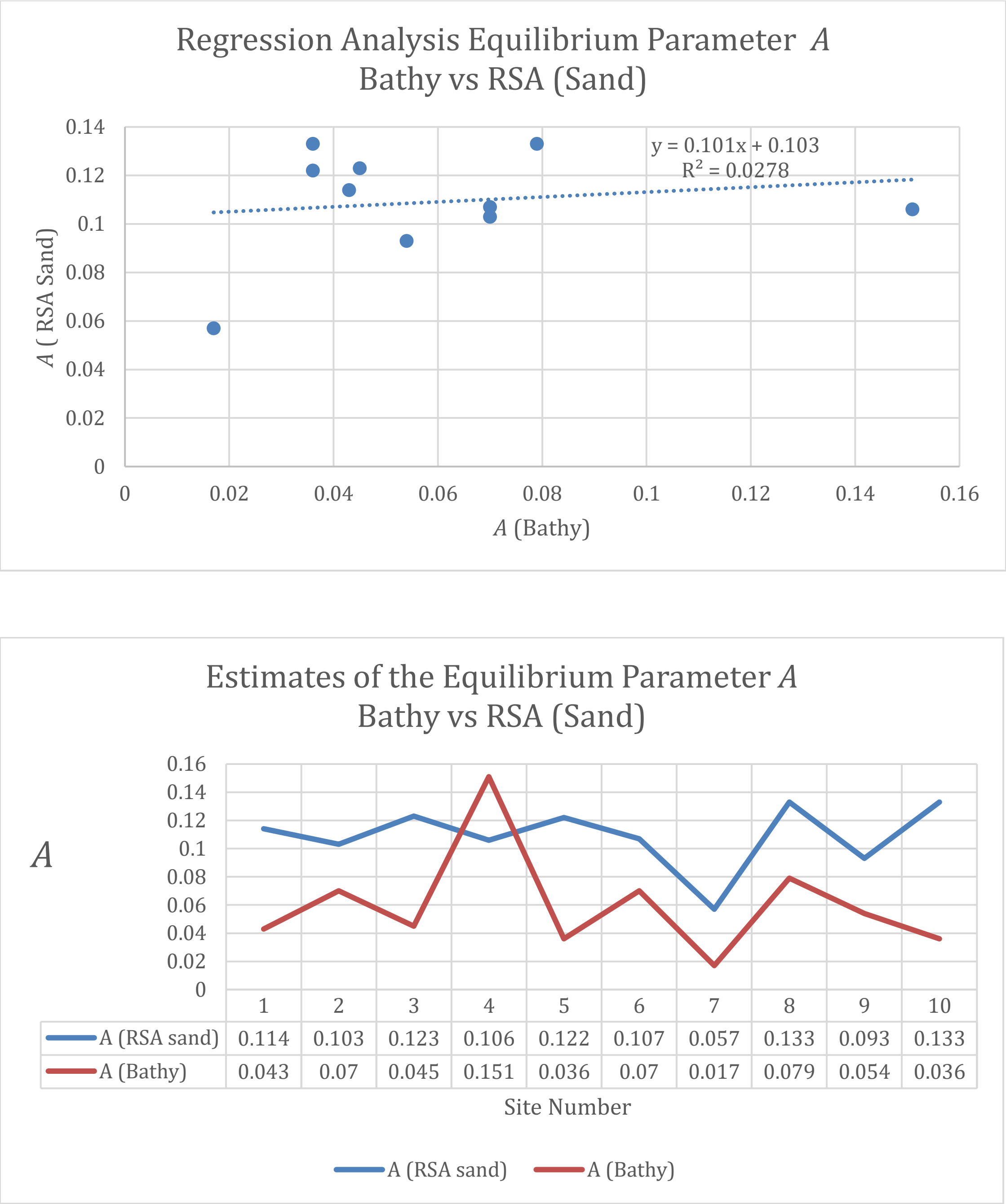
Figure 1. Three dimensional image of the local bathymetry collected at the sample site. The analyzed transect is highlighted in red with the most shoreward point labelled as A and the most offshore point labelled as A'. The bathymetry has been oriented for the best view of the transect.



C = 0.054396143
Coef of determination, R-squared = 0.912372

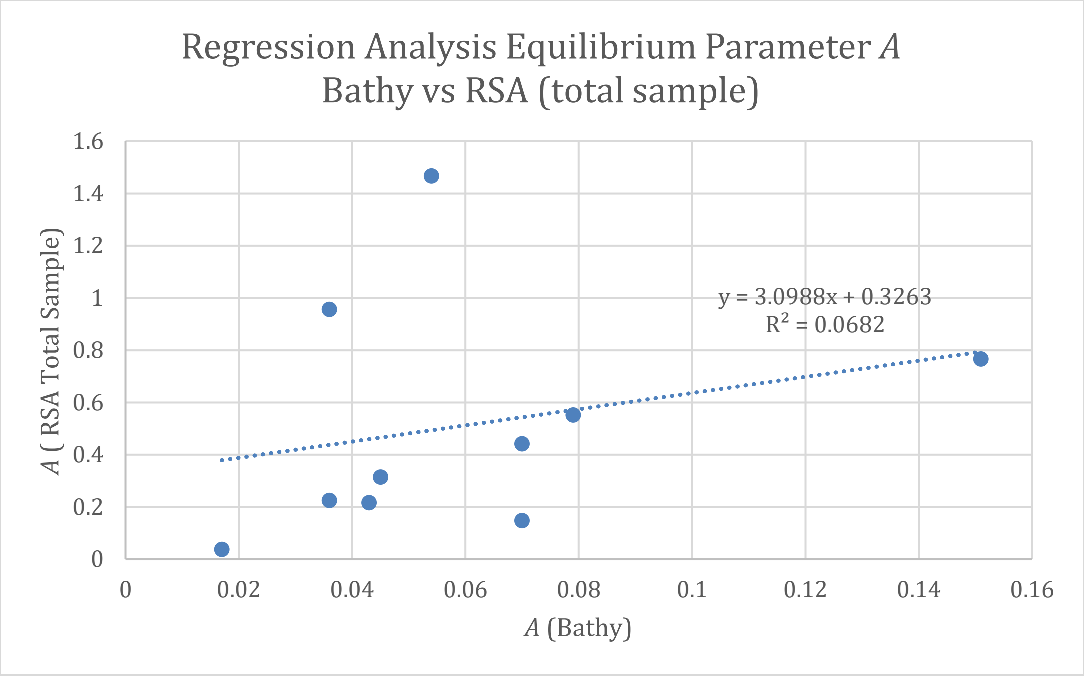
Figure 2. Bathymetric cross-section showing collected bathymetry in red and the fitted Bruun profile curve in green. The calculated coefficient and the coefficient of determination are presented for the fitted line.

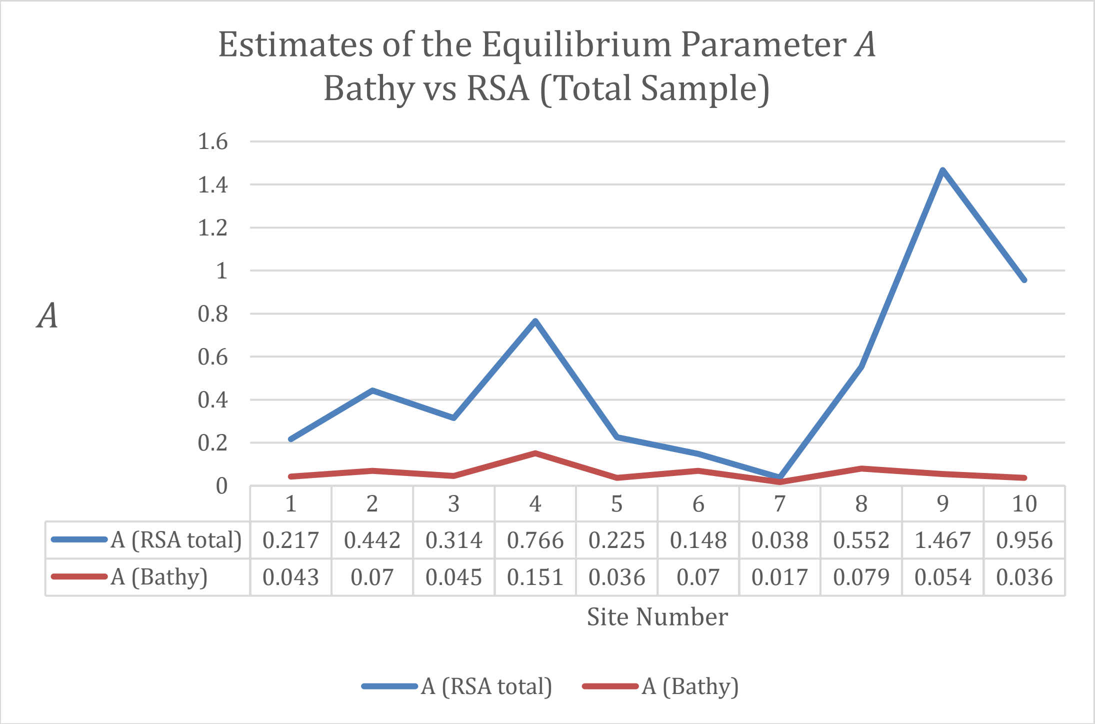
Figure 13. 2008 bathymetric profile example, Scotland Beach



	1	2	3	4	5	6	7	8	9	10
A (RSA sand)	0.114	0.103	0.123	0.106	0.122	0.107	0.057	0.133	0.093	0.133
A (Bathy)	0.043	0.07	0.045	0.151	0.036	0.07	0.017	0.079	0.054	0.036

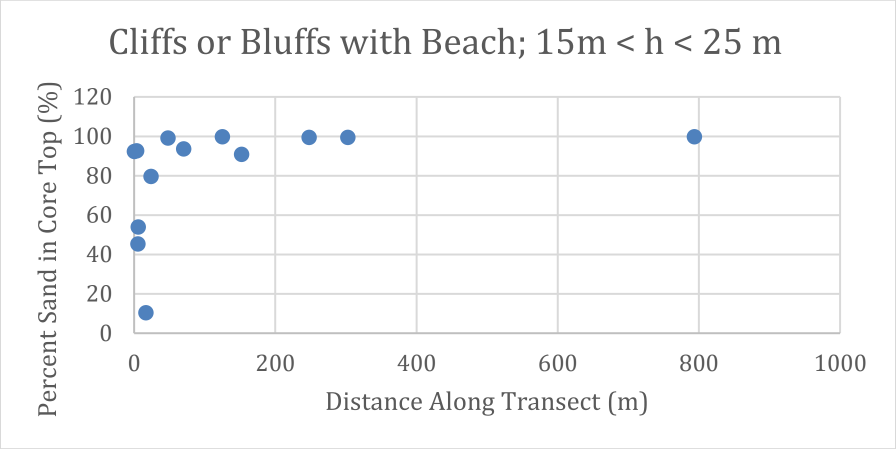
Figure 14a. Equilibrium parameter A calculated using 2008 Bruun Profile Bathymetry Survey transect height and length; correlated with equilibrium parameter A calculated from rapid sediment analyzer core top data, sand only.

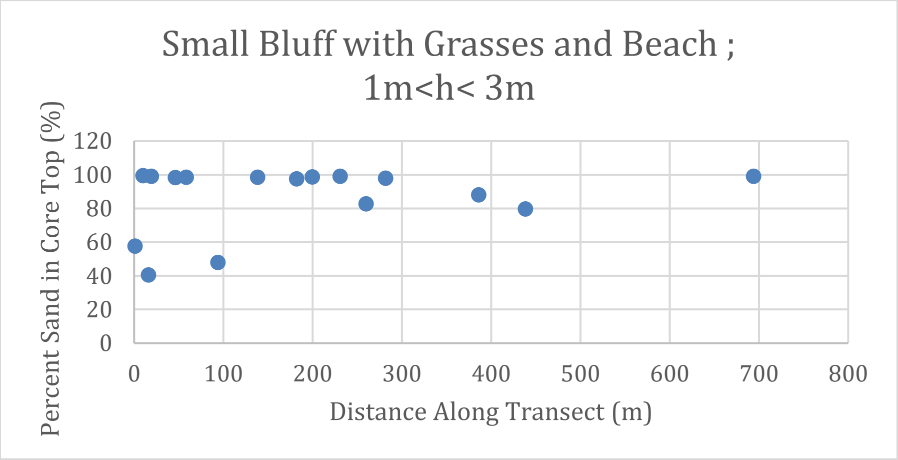




	1	2	3	4	5	6	7	8	9	10
A (RSA total)	0.217	0.442	0.314	0.766	0.225	0.148	0.038	0.552	1.467	0.956
A (Bathy)	0.043	0.07	0.045	0.151	0.036	0.07	0.017	0.079	0.054	0.036

Figure 14b. Equilibrium parameter A calculated using 2008 Bruun Profile Bathymetry Survey transect height and length; correlated with equilibrium parameter A calculated from rapid sediment analyzer core top data, total sample





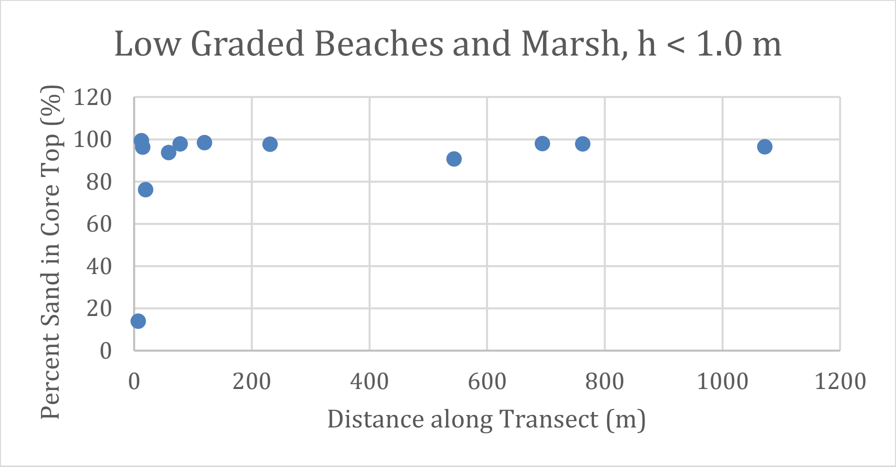


Figure 15. Mobile sand unit characteristics. Percent sand in core top at each core location along the 2008 Bruun Profile Study transect, illustrating mobile sand distribution from beach to end of transect

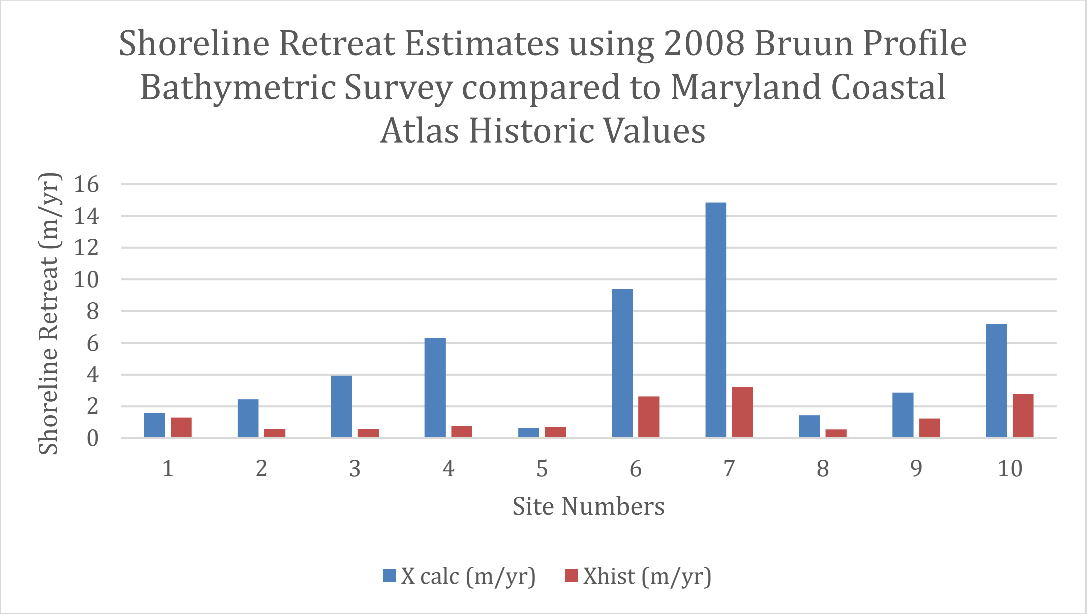
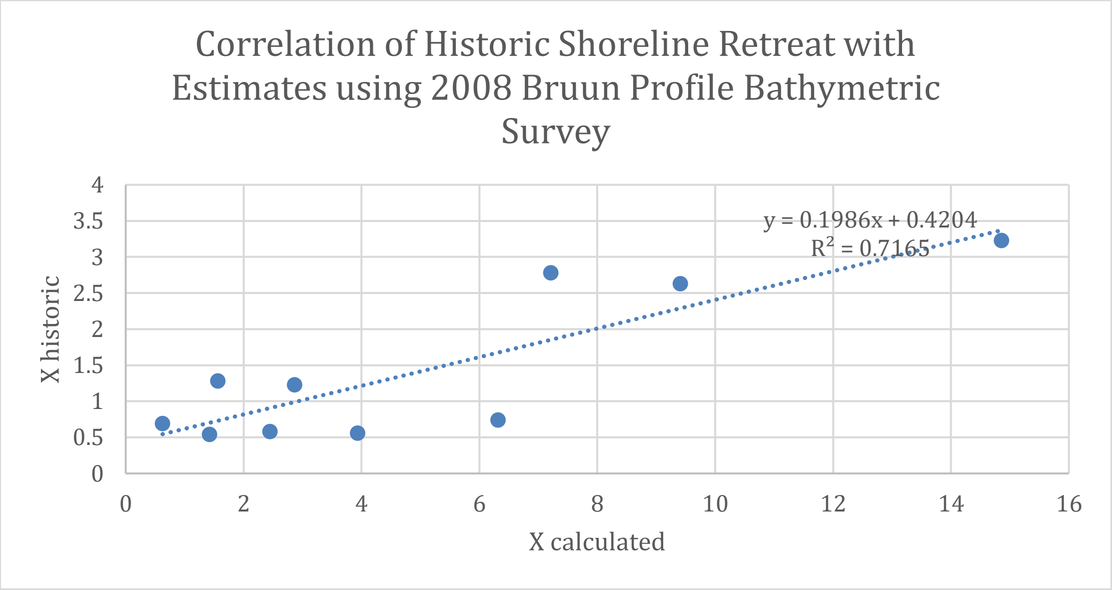


Figure 16. (a)Shoreline retreat estimates using 2008 Bruun Profile Bathymetric Survey compared to Maryland Coastal Atlas historic values.



(b)Correlation of historic shoreline retreat with estimates using the 2008 Bruun Profile bathymetric survey.

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