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Comparing Mean High Water and High Water Line Shorelines: Should Proxy-Datum Offsets be Incorporated into Shoreline Change Analysis?

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ABSTRACT

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More than one type of shoreline indicator can be used in shoreline change analyses, and quantifying the effects of this practice on the resulting shoreline change rates is important. Comparison of three high water line (proxy-based) shorelines and a mean high water intercept (datum-based) shoreline collected from simultaneous aerial photographic and lidar surveys of a relatively steep reflective beach (tan $\beta = 0.07$), which experiences a moderately energetic wave climate (annual average $H_s = 1.2$ m), reveals an average horizontal offset of 18.8 m between the two types of shoreline indicators. Vertical offsets are also substantial and are correlated with foreshore beach slope and corresponding variations in wave runup. Incorporating the average horizontal offset into both a short-term, endpoint shoreline change analysis and a long-term, linear regression analysis causes rates to be shifted an average of -0.5 m/y and -0.1 m/y, respectively. The rate shift increases with increasing horizontal offset and decreasing measurement intervals and, depending on the rapidity of shoreline change rates, is responsible for varying degrees of analysis error. Our results demonstrate that under many circumstances, the error attributable to proxy-datum offsets is small relative to shoreline change rates and thus not important. Furthermore, we find that when the error associated with proxy-datum offsets is large enough to be important, the shoreline change rates themselves are not likely to be significant.

A total water level model reveals that the high water line digitized by three independent coastal labs for this study was generated by a combination of large waves and a high tide several days before the collection of aerial photography. This illustrates the complexity of the high water line as a shoreline indicator and calls into question traditional definitions, which consider the high water line a wetted bound or "marks left by the previous high tide."

ADDITIONAL INDEX WORDS: *Coastal erosion, lidar, coastal mapping, shoreline change.*

INTRODUCTION

Many coastal areas are populated heavily and change continually because of storm events, seasonal fluctuations in wave energy, and changes in sea level. For these reasons, shoreline change analysis has evolved beyond an academic and scientific exercise to become a common objective of most coastal management programs. Numerous techniques have been developed to analyze shoreline change. These techniques range from point measurements of low accuracy made by hand on unrectified aerial photographs to closely spaced, higher accuracy, computer-derived measurements from orthophotographs (MOORE, 2000). Common to all techniques is the need to identify at least two shoreline positions that can be used to calculate an average rate of shoreline change for the time period of interest. A particular study might use shoreline positions derived from a variety of historic and recent sources, including National Ocean Service Topographic Sheets (NOS T-sheets), USGS quadrangles, aerial photographs, global positioning system (GPS) surveys, and laser altimetry data. The inherent accuracy of these data sources, as well as the degree to which techniques correct for these errors in data sources, is critical in determining the significance of shoreline change rates resulting from a temporal analysis of shoreline change (ANDERS and BYRNES, 1991; MOORE, 2000).

A second crucial, though often overlooked, source of error in shoreline change analysis lies in defining the shoreline itself. Because beaches are dynamic, changing not only with season, storm events, and the tide but also with the runup of every wave, identification of a "line" on the beach that is a repeatable, consistent, and meaningful indicator of sediment transport on the foreshore throughout time is a topic of renewed interest and debate in the coastal scientific community (*e.g.,* MORTON and SPEED, 1998; PAJACK and LEATHERMAN, 2002; ROBERTSON *et al.,* 2004; RUGGIERO, KAMINSKY, and GELFENBAUM, 2003). Traditionally, the most commonly used proxy for shoreline position is the high water line (HWL) (ANDERS and BYRNES, 1991; CROWELL, LEATHERMAN, and BUCKLEY, 1991; DOLAN *et al.,* 1980; LEATHERMAN, 1983; MORTON, 1991; STAFFORD, 1971). The HWL, often identifi-

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able in aerial photographs, is typically assumed to represent the landward extent of the last high tide and is recognized as a tonal contrast between the wet intertidal beach and the dry supratidal beach (DOLAN and HAYDEN, 1983; MORTON, 1979; STAFFORD, 1971). This feature has been considered especially useful in shoreline change studies because the HWL can be ". . . approximated by noting the vegetation, driftwood, discoloration of rocks, or other visible signs of high tides" (SHALOWITZ, 1964, p. 172) and because the HWL was the preferred boundary for separating land and sea on NOS T-sheets.

In contrast to visual, proxy-based shorelines, datum-based shorelines derived from topographic surveys (LIST and FARRIS, 1999; RUGGIERO *et al.,* 2005; SMITH and ZARILLO, 1990) or laser altimetry data (*e.g.,* lidar; LEATHERMAN, DOUGLAS, and LABRECQUE, 2003; ROBERTSON *et al.,* 2004; STOCKDON *et al.,* 2002) are not based on visual cues, but rather on the cross-shore position of an elevation contour extracted from topographic data. The elevation of interest is often a tidal datum—for example, mean high water (MHW)—determined from local tide gauges. Such datum-based shorelines provide a more repeatable alternative to visual shoreline proxies, thus eliminating not only the effect of varying oceanographic conditions but also the likelihood of variations in interpretation. Unlike the HWL, the position of MHW varies only with sediment transport gradients and associated morphological changes. The technique presented by STOCKDON *et al.* (2002) allows for the rapid generation of a MHW-datum shoreline at synoptic scales via automated extraction from lidar beach profiles.

Although a datum-based shoreline has some clear advantages over a visually interpreted shoreline for the purpose of shoreline change analysis, RUGGIERO, KAMINSKY, and GELFENBAUM (2003) demonstrate that the MHW-datum intercept falls much lower on the beach than typical HWL shorelines on coasts subject to wave runup. Results presented by RUGGIERO, KAMINSKY, and GELFENBAUM (2003) further suggest that for a high-energy low-sloping beach in Washington State, the offset between MHW and an average HWL can be as much as 50 m, with an average offset of approximately 30 m over several experiments, although they hypothesize that the offset will be smaller on steeper beaches and under lower wave energy conditions. These findings have potentially serious implications for shoreline change studies that use both HWL and MHW shorelines. The fact that many modern shoreline change studies merge historical and recent shoreline position data, and thus might use both HWL and MHW shorelines, provides a primary motivation for the work presented here. The overarching goals of this paper are to quantify and explain the offset between HWL and MHW shorelines for a steeper, lower energy coast than that considered by RUGGIERO, KAMINSKY, and GELFENBAUM (2003) and to consider the implications of such an offset on shoreline change analyses. We first compare the position of the HWL shoreline derived from orthorectified aerial photographs with the MHW shoreline derived from lidar data collected simultaneously near the time of low tide along Assateague Island National Seashore on May 6, 2002. After quantifying the horizontal (cross-shore) and vertical offsets between the HWL and MHW shorelines, we employ a total water level (TWL) model to examine the physical processes that account for the offsets. Finally, we consider the implications of such an offset on shoreline change analyses and demonstrate the utility of quantifying shoreline offsets by directly applying our results to long-term (1849–2000) and short-term (1962–2000) shoreline change analyses for the study area.

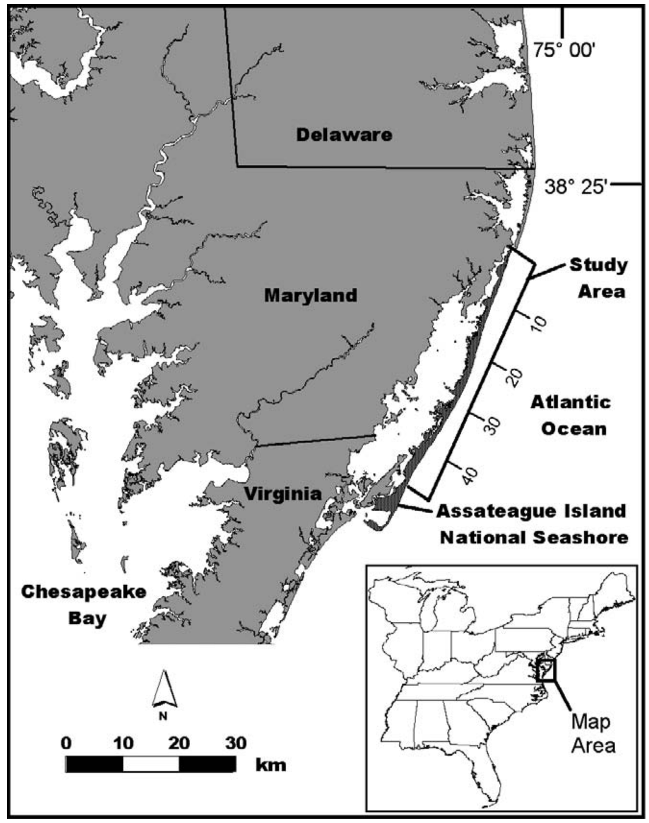


Figure 1. A map showing most of the Delaware, Maryland, and Virginia coastline. Our study area covers the northern 47 km of the Assateague Island National Seashore located in the states of Maryland and Virginia.

PROJECT DESIGN

To investigate the offset between HWL and MHW shorelines on a steeper and lower energy coast than previously investigated by RUGGIERO, KAMINSKY, and GELFENBAUM (2003), as well as to encompass a longer section of coast, we arranged for simultaneous low-tide collection of lidar data and digital aerial photography along a 47-km stretch of Assateague Island National Seashore (Figure 1) in May 2002. Assateague Island is a 60-km-long barrier island located immediately south of Ocean City, Maryland. Its northern half lies in Maryland, whereas its southern half is located in Virginia. The tides are semidiurnal, with a spring tidal range of approximately 1.7 m (on the basis of tidal station at the Ocean City Fishing Pier), and the beach has a mean foreshore slope of 4° (tan $\beta \approx 0.07$), measured from lidar data. The wave climate is generally moderate with a mean deep-water

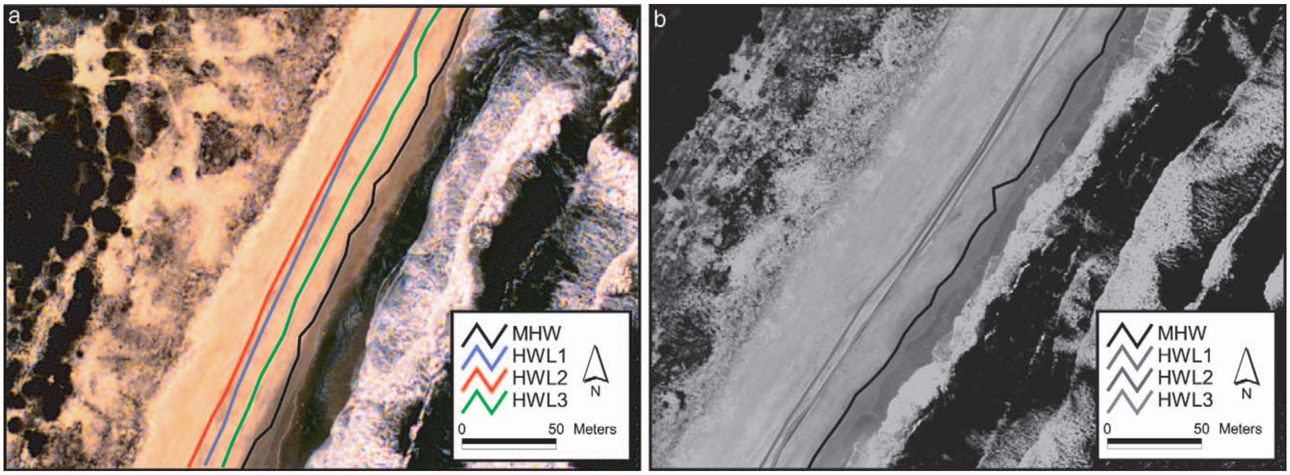


Figure 2. The position of MHW and the HWL1, HWL2, and HWL3 shorelines are shown superimposed on a section of a digital orthophotograph located at approximately 47 km (a) and 44 km (b) on the reference line shown in Figure 1.

significant wave height of 1.2 m (determined from an 18-year record of NDBC station 44009, Delaware Bay). Hurricanes and extratropical storms, however, can produce local wave heights in excess of 8 m, and from the 18-year Delaware Bay record, we estimate that the 50-year return wave height is approximately 10 m in this region.

During the morning low tide (predicted minimum water level, 1015 EDT) on May 6, 2002, Assateague Island was surveyed from 1055 to 1158 with NASA's Airborne Topographic Mapper (ATM). The ATM, initially developed to map the Greenland ice sheet (KRABILL *et al.,* 1995), is mounted on a Twin Otter aircraft and is used for mapping coastal change

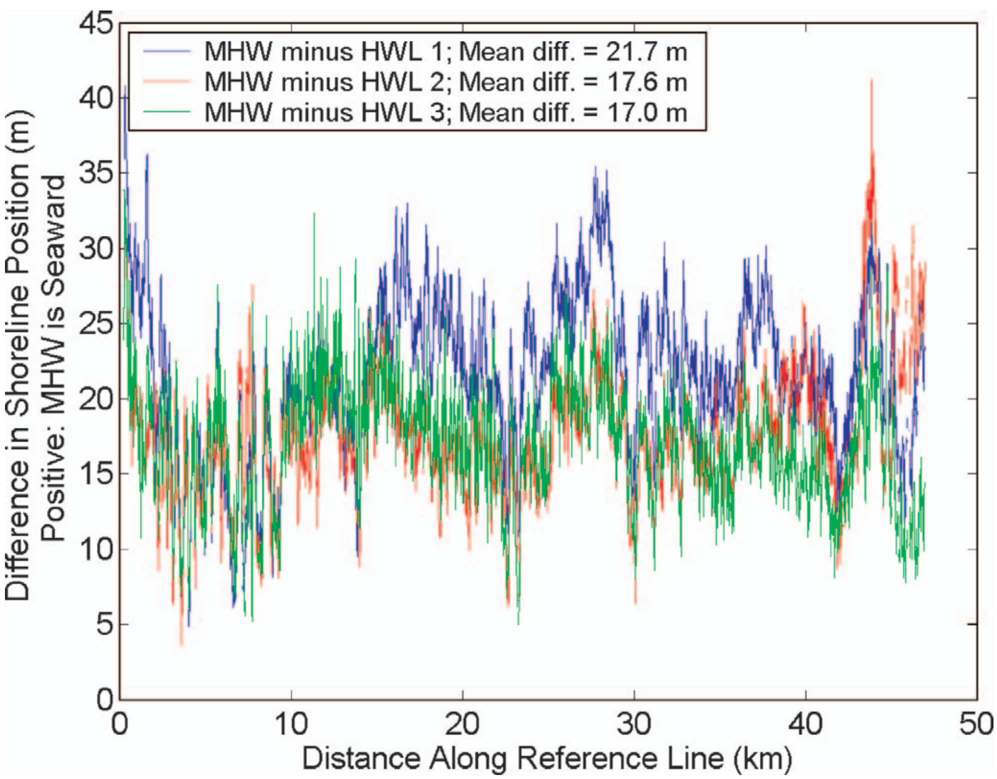


Figure 3. The cross-shore difference between the MHW and HWL shorelines as a function of distance along the reference line shown in Figure 1. Larger positive values indicate a HWL that is more landward of the MHW shoreline derived from the lidar data.

and studying the effect of coastal storms (KRABILL *et al.,* 2000; SALLENGER *et al.,* 1999). Testing of the ATM has demonstrated a total root mean square (RMS) vertical error estimate of ±15 cm (SALLENGER *et al.,* 2003). This accounts for all known sources of error and bias in the lidar system. Given the vertical error estimate and the mean Assateague Island foreshore slope of 4°, the method for estimating lidar-derived shoreline position accuracy reported in STOCKDON *et al.* (2002) indicates that we can expect our MHW shorelines to have a horizontal accuracy of ±2.2 m. On the basis of nearby NOAA tide gauges, the local MHW elevation is 0.34 m NAVD88 (North American Vertical Datum of 1988; WEBER, LIST, and MORGAN, 2005). With the use of an automated method similar to that of STOCKDON *et al.* (2002), in which an alongshore series of cross-shore beach profiles (spacing = 10 m) are constructed and the intersection of the MHW elevation with each profile is extracted, a MHW shoreline was generated from the lidar data.

Concurrent with the lidar survey, aerial photography with a ground cell resolution of 0.45 m was collected in the study area between 0902 and 0951 (Emerge Inc., Andover, Massachusetts) with a Cessna 172 equipped with a digital camera, an onboard GPS, and an inertial measurement unit. A digital elevation model (DEM) from an August 2000 ATM survey, along with the inflight GPS and inertial measurements, was used by Emerge personnel to orthorectify the aerial imagery to National Map Accuracy Standards for imagery at scale 1 : 13,600. The August 2000 DEM was used because postprocessing requirements prevented a DEM from the 2002 lidar survey from being prepared before orthorectification. We confirmed the reported accuracy of the orthophotographs using seven primary and eight secondary stable ground control points, having a total horizontal RMS error of approximately ±1 m (M. DUFFY, personal communication), located in the northern and southern sections of the study area where parking lots and structures are found. The primary and secondary points, surveyed by National Park Service personnel with GPS, were selected from a larger database of control points and categorized according to the certainty with which written location descriptions allowed identification of the points on the aerial photographs in a geographic information system. This accuracy analysis reveals that the primary and secondary points are located an average of 0.7 and 1.0 m, respectively, from their surveyed location, indicating that points identified on the orthophotographs are within at least ±1.4 m of their true ground position. This error estimate includes any errors that might occur because an older DEM was used in the orthorectification process.

Because visual shoreline proxies are subject to variations in interpretation, especially when digitized in aerial photographs, we solicited the assistance of three coastal scientists, experienced with HWL shoreline interpretation. The digital orthophotographs were delivered in Geotiff format (NAD83, UTM, meters) for digitizing in ArcView Geographic Information System. The coastal scientists were provided with instructions for digitizing in ArcView and asked to produce an estimate of the HWL, interpreting it as they would for their own research. The resulting HWL shorelines are shown in Figures 2 and 3.

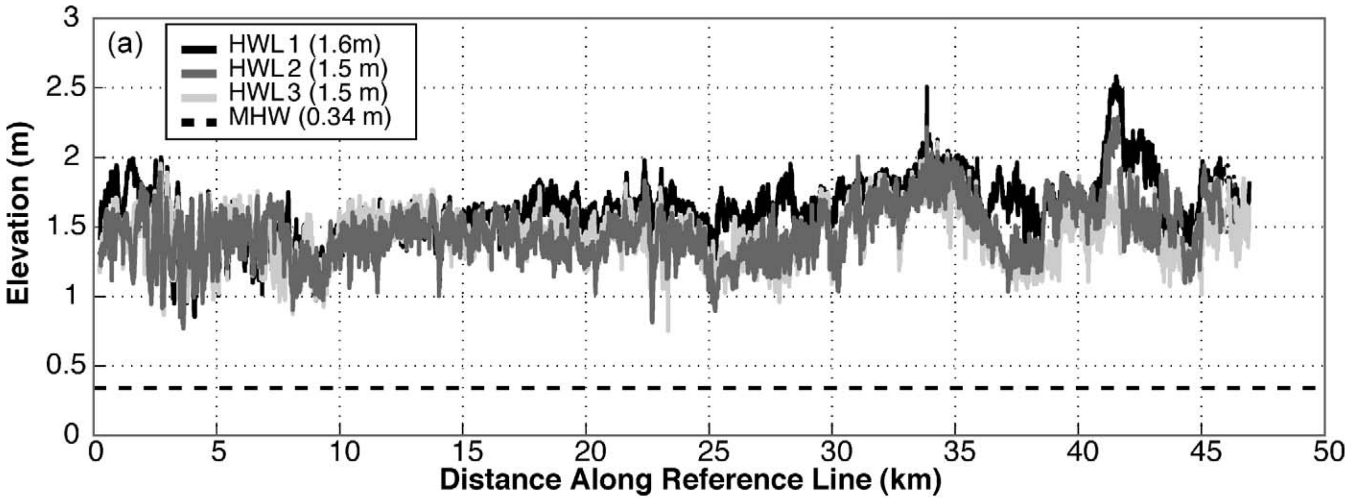
COMPARISON OF HWL AND MHW SHORELINES

HWL *vs.* MHW Shorelines

As illustrated by RUGGIERO, KAMINSKY, and GELFENBAUM (2003) and as demonstrated in a representative close-up aerial view from the southern section of the study area, the MHW datum-based shoreline for Assateague Island falls consistently seaward of all three visually interpreted (proxy-based) HWL shorelines (Figures 2a, 2b). Although the MHW shoreline is always seaward of the HWL shorelines (hereafter referred to as HWL1, HWL2, and HWL3), the degree of offset from each is not consistent alongshore (*e.g.,* compare Figures 2a and 2b). The considerable alongshore variability in the offset between the MHW shoreline and each HWL shoreline for the entire study area is shown in Figure 3, in which cross-shore offsets range from 4 to 41 m. Also listed in Figure 3 are the mean offsets between the MHW shoreline and HWL1, HWL2, and HWL3 of 21.7 m (standard deviation [SD] = 5.3 m), 17.6 m (SD = 4.3 m), and 17.0 m (SD = 4.0 m), respectively. The range of offset values is indicative of variations in interpretation of the HWL that result even when using high-resolution aerial photography. The basis for such variations in interpretation is important and of interest but beyond the scope of this paper.

Before exploring potential physical explanations for the offset between the MHW shoreline and the HWL shorelines, it is useful to consider that the horizontal offsets also manifest vertically. Superimposing the HWL shorelines on the May 6, 2002, lidar topography allows determination of the elevation of each HWL shoreline (Figure 4). Figure 4 reveals that MHW (0.34 m NAVD88) is consistently lower in elevation than all three HWL shorelines with HWL1, HWL2, and HWL3 having mean elevations of 1.6 m (SD = 0.22 m), 1.5 m (SD = 0.20 m), and 1.5 m (SD = 0.19 m), respectively. Given the differences in both horizontal and vertical position, we turn to identifying the physical site characteristics and processes responsible for generating these offsets with the eventual goal of predicting the offset between the MHW and HWL shoreline for other beaches without the need for in-depth analysis. We begin with an exploration of the relationship between the MHW/HWL offset and foreshore slope at the time of data collection. Foreshore beach slope is derived from the May 6 lidar survey using the same lidar profiles used to obtain the MHW shoreline. A linear regression is fit through elevation data defining the beach foreshore, and the slope of the resulting line (*i.e.,* the foreshore slope) is calculated. The slopes for all profiles, spaced at 10 m alongshore, are shown in the bottom panel of Figure 4 along with the elevations of MHW, HWL1, HWL2, and HWL3 in the top panel. Visually, it is apparent that a relationship exists between the beach slope and the elevation of the HWLs, particularly between 25 and 47 km where there is considerable alongshore variability in beach slope. The correlation between the elevation of the HWL shorelines and the foreshore slope is significant, with correlation coefficients of 0.3, 0.45, and 0.6 for HWL1, HWL2, and HWL3, respectively, for which a correlation coefficient of approximately 0.2 is significant at the 95% confidence interval.

We hypothesize that beach slope is a good predictor of the



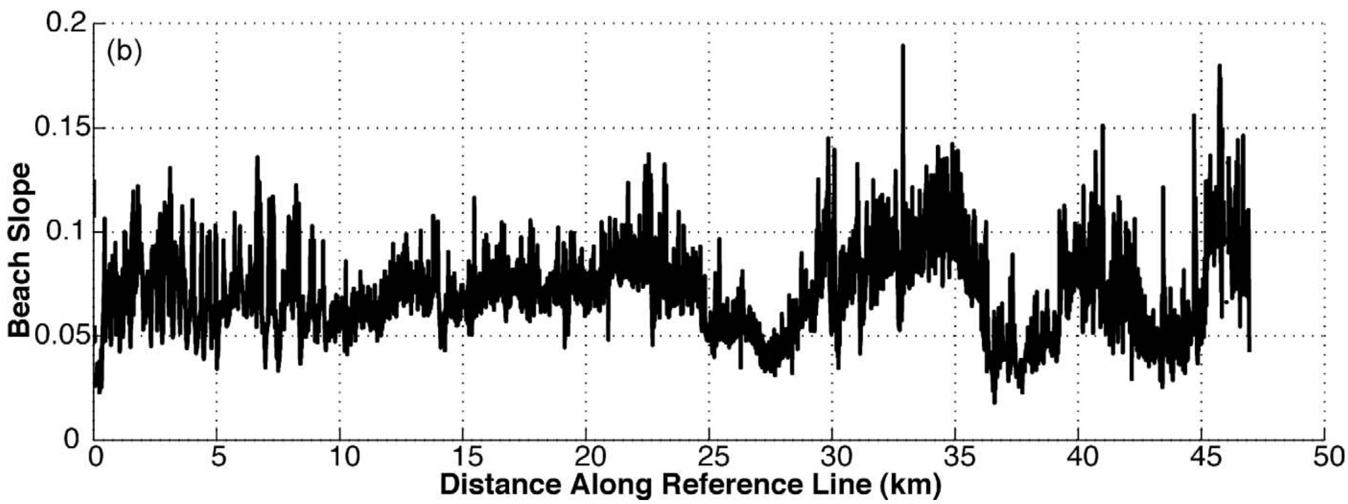


Figure 4. (a) Elevation of each HWL shoreline and the MHW shoreline (constant elevation = 0.34 m) as a function of distance along the reference line shown in Figure 1. (b) Variation of foreshore slope in gradient along the reference line. All elevations are reported relative to NAVD88. Average elevations are shown in parentheses.

elevation of the HWL because of the relationship between wave runup and beach slope. The elevation of the HWL, expected to represent the maximum elevation of water on the beach during the last high tide or high water event (*e.g.,* a storm), varies directly with the elevation achieved by wave runup, which has been shown by many researches to be proportional to beach slope (*e.g.,* HOLMAN, 1986). Wave runup is less where the beach is flatter, resulting in formation of a HWL at a lower elevation on the beach, whereas wave runup is greater where the beach is steeper, resulting in a HWL at a relatively higher elevation on the beach. This relationship between beach slope and wave runup, and its role in determining the alongshore variability of the vertical elevation of the MHW shoreline and the HWL shorelines, is explored further in the following section with a TWL model.

Water Level Modeling

Developing an understanding of the processes responsible for the offset between the MHW shoreline and the HWL shorelines as shown in Figures 3 and 4 requires consideration of the processes by which a HWL forms. Because the HWL is a feature thought to represent the recent extent of high water on the beach, we must consider the factors that determine the total elevation of water on a beach.

Total water level on a beach at any time is the sum of the tide level (E_T), and the elevation reached by wave runup, including wave setup (RUGGIERO *et al.,* 1996, 2001; RUGGIERO, KAMINSKY, and GELFENBAUM, 2003; Figure 5). Typically, measured tides are used when computing TWLs, but unfortunately, the tide gage in the vicinity of Assateague Island was not working during the May 6 experiment. Instead, we

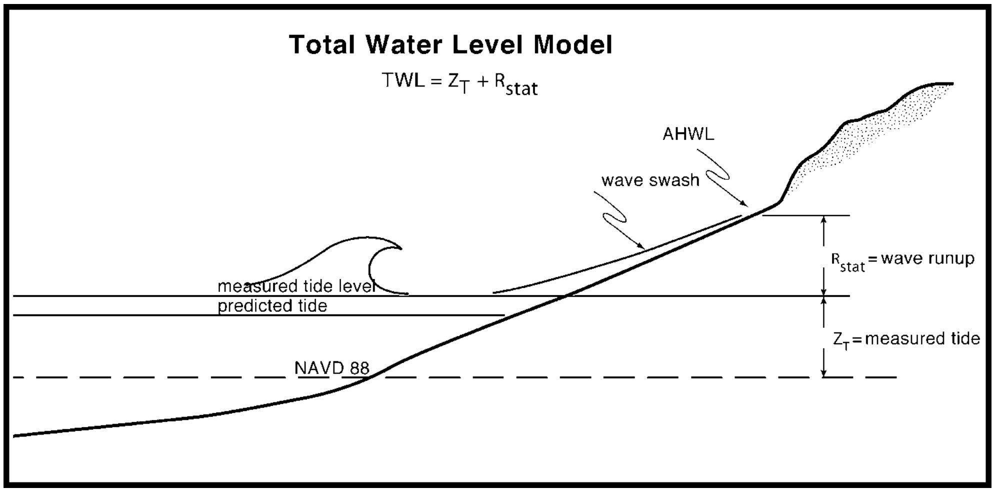


Figure 5. A schematic depicting the total water level model. In this model, the total elevation of the water is equal to the sum of the elevation of the measured tide level and the elevation of wave runup. (after Ruggiero *et al.,* 1996, 2001).

use predicted tides at the NOS tidal station (8570280) at the Ocean City Fishing Pier, an open water tidal station 6 km from the northern end of our study area. Empirical estimates of the elevation achieved by wave runup are necessary to calculate the TWL, and for the case of predicting HWLs, we use an extreme runup elevation, $R_{2\%}$, the elevation that 2% of individual runup maxima reach or exceed (Ruggiero, Kaminsky, and Gelfenbaum, 2003).

Several researchers have demonstrated a relationship between the normalized wave runup elevation and the Iribarren number, ξ_0, using wave runup data from multiple investigations (Holman 1986; Ruggiero *et al.,* 2001; Stockdon *et al.,* 2006), yielding

$$\frac{R_{2\%}}{H_s} = C\xi_0 \tag{1}$$

where H_s is the deep-water significant wave height, C is a dimensionless constant, and the Iribarren number, ξ_0, also known as the "surf similarity" parameter, is defined as

$$\xi_0 = \frac{\tan\beta}{(H_s/L_0)^{1/2}} \tag{2}$$

where $\tan\beta$ is the beach slope and L_0 is the deep-water wave length given by linear theory as $gT^2/2\pi$, where g is acceleration due to gravity and T is the peak wave period. Stockdon *et al.* (in press) have developed relations for extreme wave runup elevations based on video-derived runup measurements that represent a wide range of environmental conditions. With the use of these relations, the coefficient C is found by H.F. Stockdon (personal communication) to be 0.77, with an intercept value of 0.34 for the dimensional form of Equation (1).

Following on the assumption that HWLs form during times of maximum water level, we employ a TWL model and input both measured (wave height and period from the Delaware Bay NDBC gage [44009]) and predicted (tide) hydrodynamic conditions (Figures 6a and 6b), and measured beach slope for the Assateague Island study area (Figure 4) to predict the elevation of the HWL for the time period of the survey. We generate a TWL time series according to

$$TWL = Z_T + 0.77\tan\beta(H_sL_0)^{1/2} + 0.34H_s \tag{3}$$

where Z_T is the tide level. Figure 6c is a time series of predicted TWLs between April 21 and May 20 generated by the TWL model. The elevation of local maximum high water elevation peaks, indicated by black asterisks, are the times when HWL shorelines, such as those interpreted on the digital aerial photographs of Assateague Island in this study, are assumed to have formed. Using the time of the TWL peak corresponding to the last high tide before aerial photo collection on May 6 (Figure 6, black open circle), we calculate the alongshore variability of the estimated HWL (EHWL) using the measured alongshore variability of the beach slope as an estimate of the elevation at which a HWL would be interpreted from the aerial photography. This is shown in Figure 7 along with alongshore elevations of HWL3 determined by intersecting the digitized HWL3 of May 6 with the lidar data. The EHWL for May 6 (photo date) is an average of 0.7 m lower in elevation than HWL1 and an average of 0.5 m lower in elevation than HWL2 and HWL3. Assuming that TWL and the HWL are coincident at the time of HWL formation, these differences indicate that the feature interpreted as the HWL was probably not generated by the peak in EHWL associated with the high tide immediately preceding the time of the photography.

To find the total high water level responsible for generating the HWL feature digitized in the aerial photographs requires us to look farther back in the hydrodynamic record to a small storm on May 3 (Figure 6, black closed circle), which nearly coincided with a high tide. Calculation of the EHWL generated by the TWL of May 3 reveals an EHWL elevation (average $\approx$ 1.5 m) that is much closer to the HWL shoreline

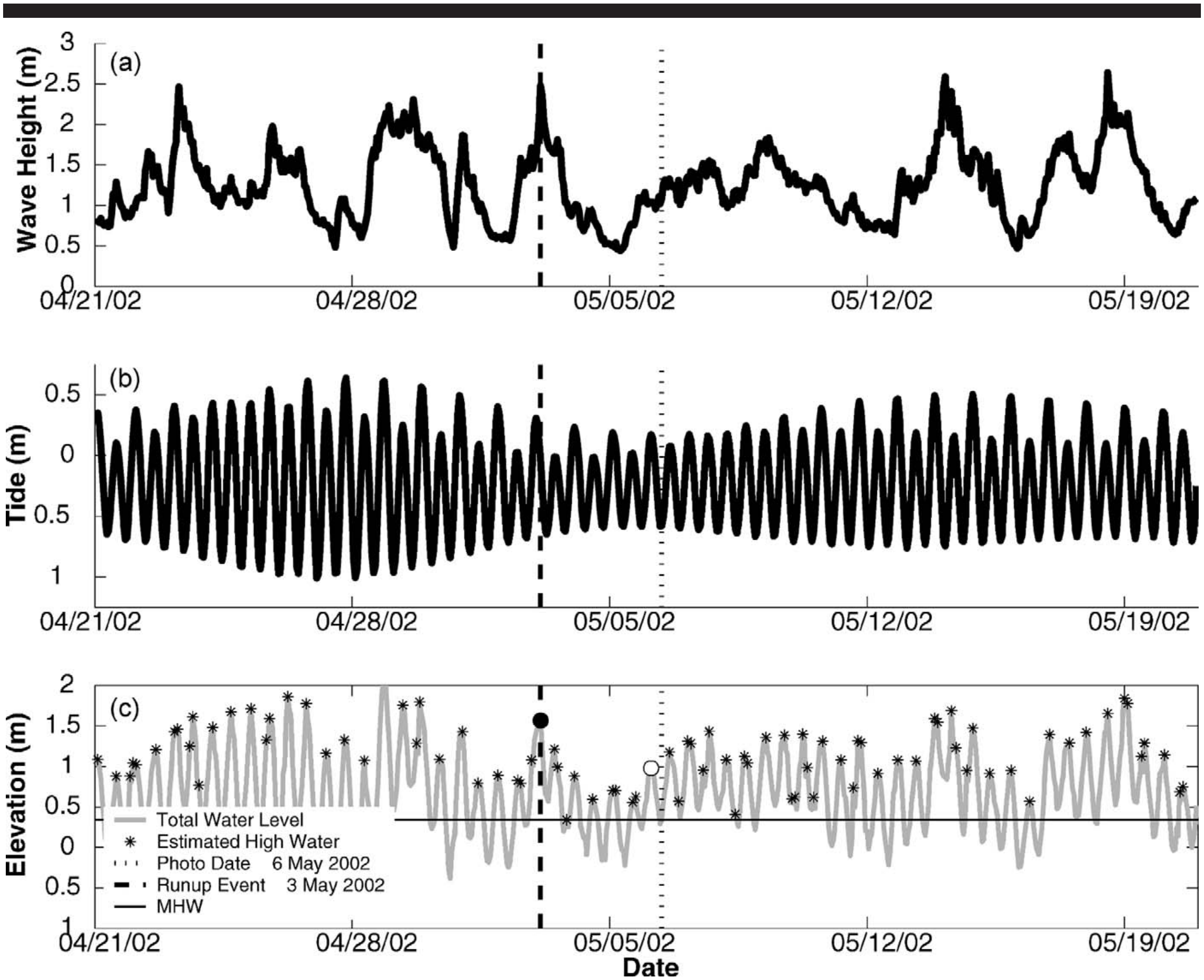


Figure 6. (a) Record of wave height (m) for the time period April 21 through May 20 from the Delaware Bay NDBC gauge (44009). (b) Record of predicted tidal elevations (m) for the same time period from the Ocean City Fishing Pier Gage (857280). (c) Estimated total water level found as the sum of the predicted tide height and the runup elevation estimated from Equation 1. Black asterisks indicate instantaneous high water level maxima when a HWL can form. The dotted vertical line indicates the time of both the lidar and aerial photo surveys, and the dashed vertical lines indicates the time of the small storm of May 3. The black open circle indicates the high water maxima immediately preceding the May 6 surveys, and the black closed circle indicates the high water maxima from a small storm 4 days before the surveys. All elevations are reported relative to NAVD88.

elevations (*e.g.,* average elevation HWL3 $\approx$ 1.5 m; Figure 7) than the EHWL elevation (average 1.9 m) of May 6. There is also a closer match between the alongshore variability of the HWL elevation (resulting from alongshore variations in beach slope) and the May 3 EHWL elevation. From this result, we hypothesize that the storm of May 3 left markings on the beach that were captured by the May 6 aerial photography and interpreted as the HWL during digitizing.

INCORPORATING OFFSETS INTO SHORELINE CHANGE ANALYSIS

Shoreline Change Analyses

Given that the HWL shorelines digitized from the aerial photography of May 6, 2002, are offset both horizontally and vertically from the MHW shoreline, we turn to the effect of this offset on shoreline change analyses. Because shoreline change analyses often entail rate calculation over the longest time period possible, as well as rate calculation over a more recent time period, we perform both a linear regression analysis using four shorelines over more than 100 years and a shorter term endpoint rate analysis using two shorelines.

A linear regression analysis uses the least squares method to calculate a best fit line through a series of shoreline positions. The slope of the resulting line provides an estimate of the shoreline change rate (Dolan, Fenster, and Holme, 1991). The 2002 MHW shoreline and three historical shorelines, two of which consist of multiple segments from different years (1849, 1850, or 1859; 1933; and 1962 or 1976), provide

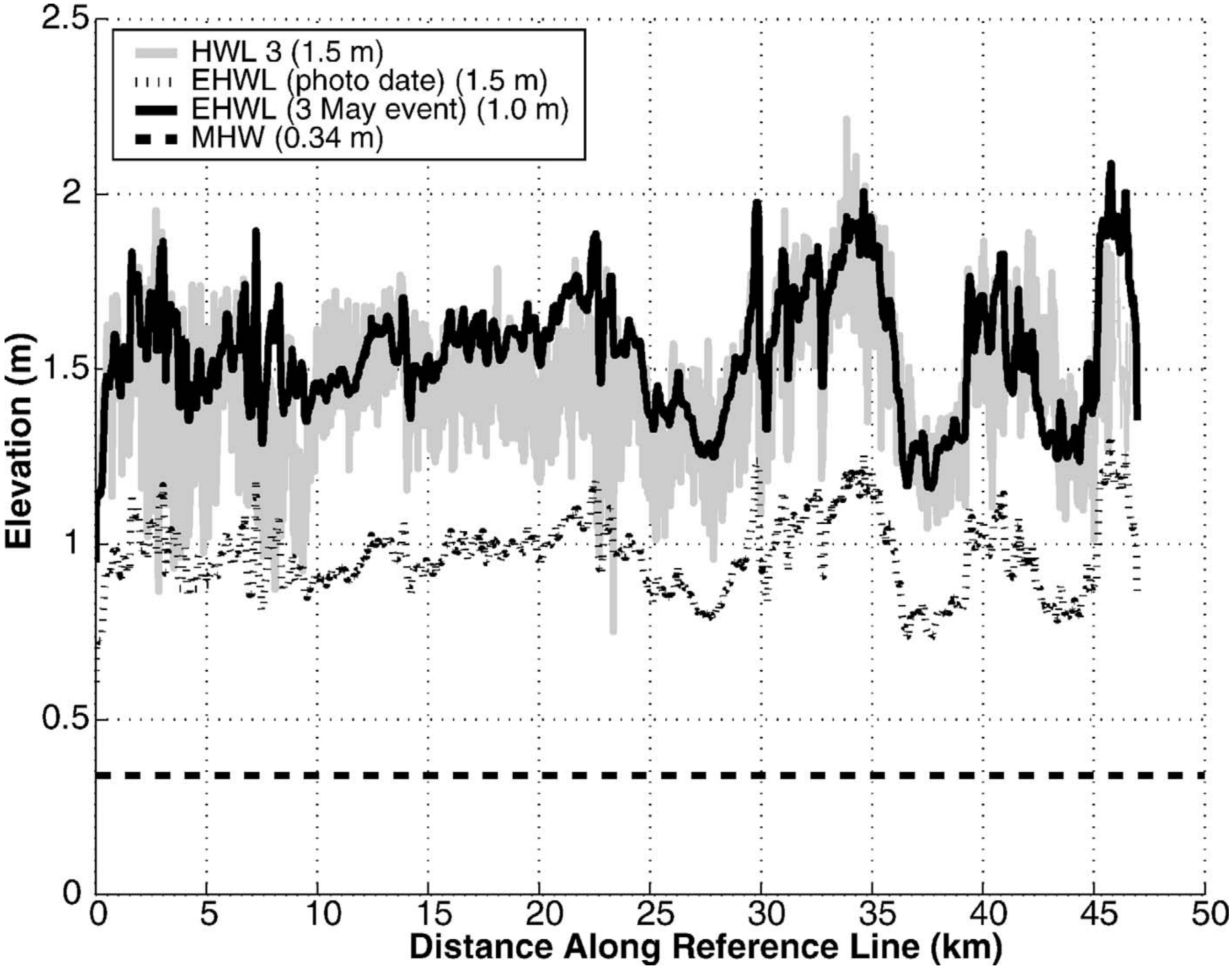


Figure 7. The alongshore variability of the elevation of HWL3, the estimated HWL (EHWL) calculated for the high water maxima immediately preceding the survey on May 6 (open circle, Figure 6c) and the estimated HWL (EHWL) calculated for the high water maxima on May 3 (black circle, Figure 6c). Average elevations for each are shown in parentheses. The elevation of the MHW shoreline is constant alongshore. All elevations are reported relative to NAVD88.

shoreline positions for a linear regression analysis of shoreline change along Assateague Island. The resulting rates are compared with rates resulting from a second linear regression analysis that incorporates the same historical shorelines but replaces the 2002 MHW shoreline with an offset-corrected shoreline (Figure 8a). The offset-corrected shoreline is created by moving the MHW shoreline landward 18.8 m to account for the average offset between the HWL shorelines and the MHW shoreline (Figure 3). The mean difference in shoreline change rates, or the rate shift, calculated by subtracting the results of the first shoreline change analysis from the results of the second shoreline change analysis and calculating an average, is −0.1 m/y. The rate shift is negative because of the landward shift of the MHW shoreline to more closely approximate the location of the digitized HWL shoreline.

A similar comparison is shown in Figure 8b for rates calculated by the endpoint method, which is a simple calculation in which the total distance between shoreline positions is divided by the time period between measurements (Dolan, Fenster, and Holme, 1991). Here, rates were again calculated twice: once with a combined 1962/1976 shoreline and the 2002 MHW shoreline and a second time with the combined 1962/1976 shoreline and the 2002 offset-corrected shoreline. The resulting mean rate shift of −0.5 m/y is five times larger than the rate shift resulting from the long-term linear regression example. Although the mean difference is still relatively small, because the range of rates (−3.9 to 5.6 m/y) crosses zero with the use of the uncorrected shoreline, the shift is large enough to change the sign of the rates in some locations.

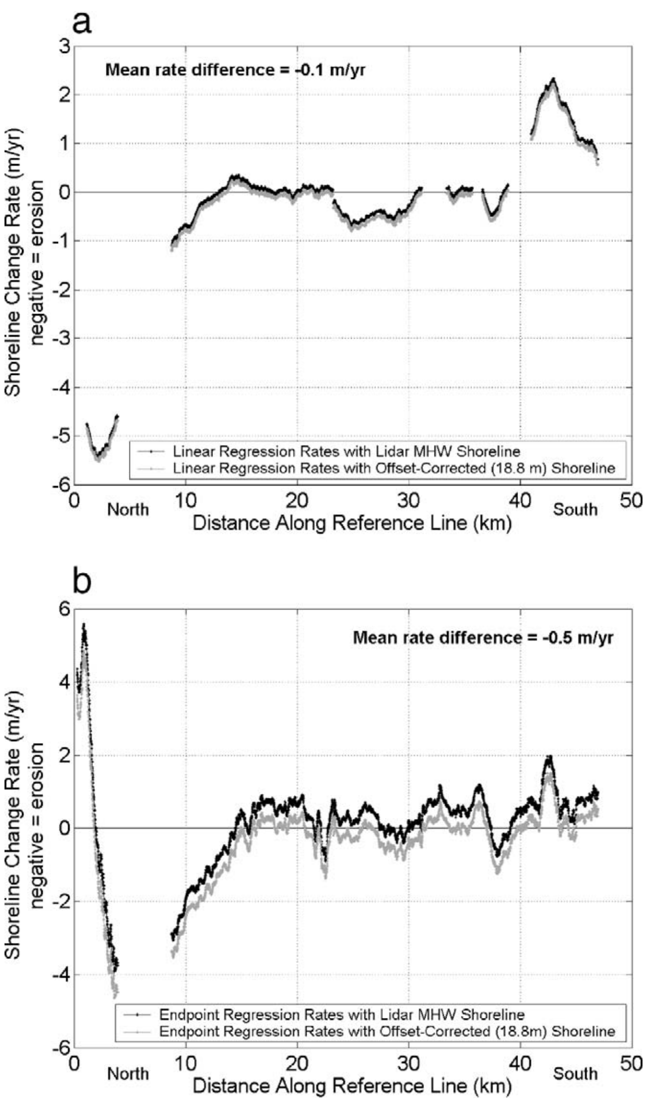


Figure 8. Shoreline change rates for Assateague Island generated with a four-point linear regression (a) and the endpoint method (b). Rates are shown for analyses in which the MHW shoreline and the offset-corrected shoreline are used as the 2002 shoreline.

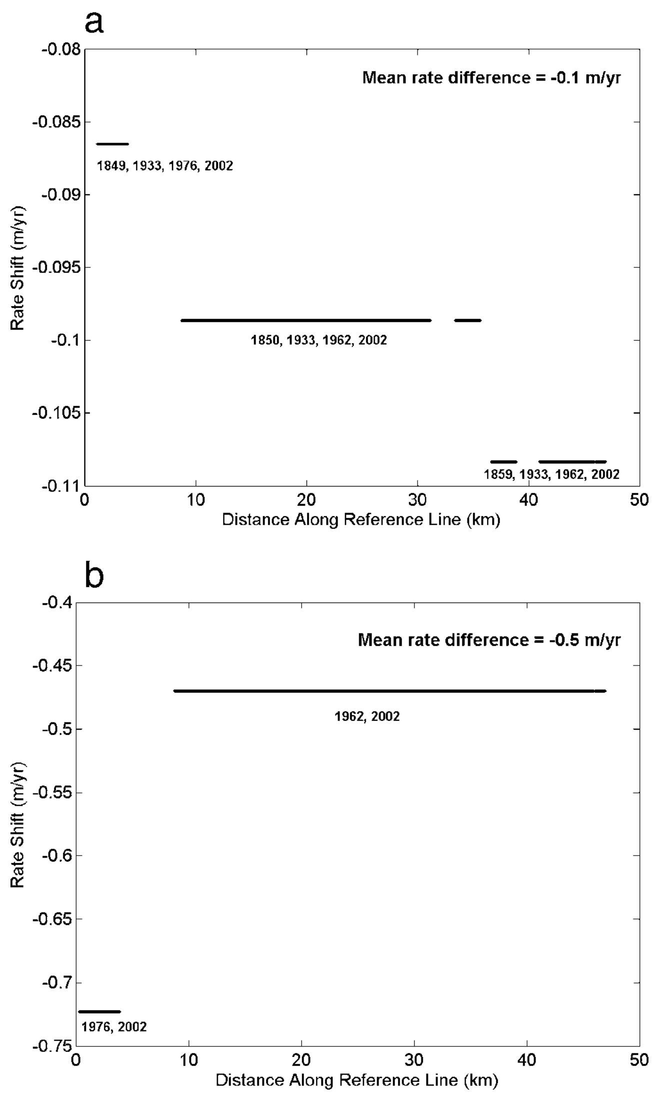


Figure 9. The difference in shoreline change rates for the long-term linear regression analysis (a) and the short-term endpoint analysis (b) determined by subtracting the rates calculated with the MHW shoreline from the rates calculated with the offset-corrected shoreline. Dates shown indicate years used in the shoreline change analyses. Note that the vertical scales are different.

The Rate Shift

Comparison of the rate shifts obtained in the two shoreline analyses above indicates that the effects of the offset between the MHW shoreline and a HWL are considerably greater at shorter measurement intervals. This is demonstrated further in Figure 9, which shows the rate shift as a function of distance along the reference line for the linear regression analysis (Figure 9a) and the endpoint analysis (Figure 9b), both of which were calculatd with the offset-corrected shoreline as described above. In both cases, the rate shift is independent of the shoreline change rate, depending instead on the number of years considered in the analysis (*i.e.,* when a longer time span is considered, the rate shift is smaller). The rate shift resulting from the shorter time period calculation provides the clearest illustration of this (Figure 9b). Where 1976 and 2002 shorelines are used in the analysis (0–4 km), the rate offset is -0.73 m compared with the stretch of coast for which the 1962 and 2002 shorelines are used (7–47 km) and the offset is -0.47 m. Having established this relationship between the parameters involved, if the average alongshore offset between the proxy and datum shorelines is known, the endpoint rate shift, R_{Se}, can be determined according to the simple expression

$$R_{\mathrm{Se}} = \frac{-|\bar{X}_0|}{t} \qquad (4)$$

where $\bar{X}_0$ is the average horizontal offset between the MHW shoreline and the HWL and t is the time elapsed between shoreline measurements. Adding R_{Se} to all rates resulting from an analysis in which a datum-based MHW shoreline provides the modern shoreline position will essentially remove the average effect of the proxy-datum offset from the calculations. Of course, this requires that the horizontal offset is known.

Determining the rate shift for a linear regression analysis is more complicated because the offset between the MHW and HWL shorelines changes the shoreline change rate by altering the slope of the regression line. This prevents use of Equation (4) to determine the rate shift when carrying out linear regression and explains the nonlinear relationship between the rate shift and the time period of analysis (Figure 9a). To determine the rate shift when three or more shorelines are used to calculate rates, it is necessary to perform a linear regression analysis using the proxy shoreline as well as a linear regression analysis using the datum-based shoreline to solve for the value of the regression at the time of the most recent shoreline in both cases. The difference between these values then becomes the true offset between the two best fit lines, which can be divided by the time elapsed between shorelines. The resulting expression for the linear regression rate shift, R_{Sr}, is then given by

$$R_{Sr} = \frac{X_{OC}(t) - X_{MHW}(t)}{t_{total}} \tag{5}$$

where t is the time of the most recent shoreline used in the analysis; $X_{OC}(t)$ and $X_{MHW}(t)$ are values of X solved for time t along the regression line for the analysis with the offset-corrected shoreline and the MHW shoreline, respectively; and t_{total} is the total time elapsed between historical shorelines. Given the complexity of arriving at a solution to Equation (5), it will generally be simpler, when using more than three shorelines, to determine the rate shift by calculating the difference between the two sets of rates.

In addition to producing a predictable shift in the shoreline change rates, the offset between the MHW and HWL shorelines affects the statistical significance of shoreline change rates found through linear regression (DOUGLAS, SANCHEZ, and SCOTT, 1999). Although the effect is small, the percentage of rates identified as exceeding the 95% confidence interval increases slightly from 26.5% of the rates to 31.2% of the rates when the offset-corrected shoreline is used in the linear regression analysis (Figures 10a, 10b).

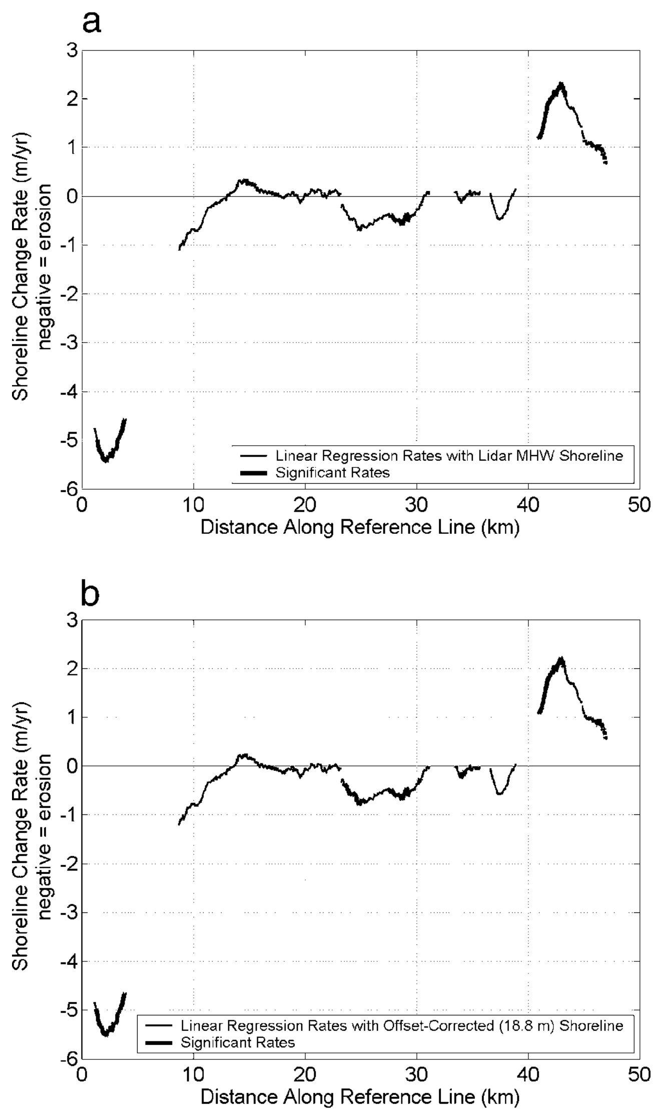


Figure 10. (a) Shoreline change rates for Assateague Island generated with a four-point linear regression and the MHW shoreline. (b) Shoreline change rates for Assateague Island generated with a four-point linear regression and the offset-corrected shoreline. Significant rates (95% confidence interval) are indicated in black.

DISCUSSION

Even for a moderately steep beach, a large offset will typically exist, both horizontally and vertically, between the visual HWL shoreline proxy and the datum-based MHW intercept. As a result, the effect of incorporating a datum-based intercept such as a MHW shoreline into a shoreline change analysis along with historical shorelines of the HWL-proxy type produces a rate shift that is larger for shorter measurement intervals. Because, at least for the endpoint method, the rate shift can be calculated if the offset and dates of shoreline positions used in the change analysis are known, a straightforward method for determining the offset between shoreline indicators would be particularly useful.

Comparing a broadly defined dissipative beach to a reflective beach, we expect beach slope and horizontal proxy offset to be inversely correlated, with steeper beaches having smaller offsets. This is validated by comparing the Assateague Island, Virginia, study area, having an average foreshore beach slope of $\tan \beta = 0.07$ and an average horizontal offset value of 18.8 m, with the Long Beach Peninsula, Washington, study area, having an average foreshore beach slope of $\tan \beta = 0.02$ and an average offset value of 30.6 m (RUGGIERO, KAMINSKY, and GELFENBAUM, 2003). This relationship is evident in Equation (6) if we assume the EHWL predicts the HWL elevation and if we assume a linear beach slope between the location of MHW and the HWL. Here, we subtract the elevation of the MHW shoreline, Z_{MHW}, from the elevation of the HWL shoreline at a single water level maxima (TWL), as given by Equation (3), and divide by slope yielding

$$(X_{HWL} - X_{MHW})_{offset} = \frac{[(Z_T - Z_{MHW}) + 0.77 \tan \beta (H_s L_0)^{1/2} + 0.34 H_s]_{maxima}}{\tan \beta} \tag{6}$$

where X_{HWL} and X_{MHW} are the horizontal positions of the HWL and the MHW shoreline, respectively. Although a steeper sloping beach has higher vertical wave runup for the same wave conditions as a gently sloping beach, Equation (6) suggests that beach slope and the horizontal proxy-datum offset are inversely proportional. Although evident when comparing dissipative and reflective beaches, this inverse relationship is not evident at the scale of the Assateague Island study area because the assumption of a linear slope between MHW and HWL elevations likely does not hold and the foreshore slope varies over a much narrower range. Equation (6) also suggests a direct relationship between vertical proxy-datum offsets and slope, which is confirmed by our observations at Assateague Island.

Unfortunately, because of the difficulties involved in determining which relative maximum in a TWL time series is responsible for generating a HWL, Equation (6) cannot be applied in a straightforward manner to estimate proxy-datum offsets. As PAJACK and LEATHERMAN (2002) point out, the HWL is often defined as a wetted bound or by "markings left on the beach by the last high tide." In addition to exploring the offset between HWL shorelines and a MHW datum intercept shoreline, we clearly demonstrate that the HWL is not simply a mark left on the beach by the most recent high tide; rather, as demonstrated by RUGGIERO, KAMINSKY, and GELFENBAUM (2003) and in this paper with a TWL model and local hydrodynamic conditions, the HWL is a more complex feature produced by a combination of tide levels and wave energy that could represent a high water maxima reached at least several days before the survey date. Although we do not know exactly how long a high water mark such as that generated on May 3 and identified on May 6 photography will remain on the beach, it is clear that the variability of HWL markers, as digitized on aerial photography, is even more complicated than the simple traditional definition the HWL suggests.

Although a rate shift is produced by the offset between proxy and datum intercept shorelines, the importance of this rate shift to the results of shoreline change analyses will depend largely on the magnitude of shoreline change rates. In locations where the proxy-datum offset is not great or when the time period of analysis is long, the rate shift might be small enough to ignore altogether. For example, if shoreline change rates are rapid (*e.g.,* 2 m/y), a constant rate shift of −0.1 m/y, as obtained in our long-term linear regression example above for an average offset of 18.8 m, will be a small percentage (5%) of the total corrected rate. Given the errors involved in shoreline change analyses (*e.g.,* ANDERS and BYRNES, 1991; CROWELL, LEATHERMAN, and BUCKLEY, 1991; MOORE 2000), an additional error from a rate shift on the order of 5% is not likely worth expending significant effort to quantify more precisely. If shoreline change rates are relatively slow (*e.g.,* 0.5 m/y) or the time period of analysis is short, a constant rate shift of −0.1 m/y will be a much larger percentage (20%) of the total corrected rate. However, in this case, the shoreline change rates themselves are not likely to be statistically significant. In this circumstance, uncertainty estimates used in short-term endpoint analyses will likely be equal to or larger than the shoreline change rates themselves, and the confidence intervals used in linear regression analysis will include the possibility that no significant trend exists. An exception to the relative importance of the rate shift associated with the proxy-datum offset occurs when averaging shoreline change rates alongshore. Alongshore averaged shoreline change rates, whether derived from linear regression or endpoint analysis, are more likely to be statistically significant, even if the rates are relatively low, than any single transect because the random and independent errors associated with calculating shoreline change tend to cancel out during the averaging process. Because the proxy-datum offset is a bias, virtually always acting in the same direction, the error associated with the rate shift does not cancel during averaging. Thus, when alongshore averaging will be undertaken, it may be important to quantify the offset between proxy and datum shorelines to account for the rate shift.

CONCLUSIONS

The competing needs both to use available historical shoreline positions and to improve the collection of modern shoreline position information to provide more reliable shoreline change analyses in the future must be balanced. To accomplish this, the effect of combining different shoreline indicators into a single shoreline change analysis should be considered. Comparison of HWL shorelines and a MHW datum-based shoreline for a single-day survey on Assateague Island reveals an average horizontal offset between shoreline indicators of 18.8 m. This result is consistent with the hypothesis of RUGGIERO, KAMINSKY, and GELFENBAUM (2003) that offsets will be smaller on steeper beaches with more moderate wave climates than on flatter, higher energy beaches such as those of the Long Beach Peninsula, Washington. At a more local scale, the vertical offset between the same shoreline indicators will correlate directly and more closely with beach slope because wave runup increases with beach slope.

Overall, the importance of incorporating a proxy-datum offset into shoreline change analysis depends on several factors, including the magnitude of the offset, the length of time over which rates are being measured, and the statistical significance of the shoreline change rates. Our results indicate that visual proxy shorelines and datum-based shorelines will be offset; thus, the use of both shoreline indicators in an analysis will result in a rate shift that can be quantified if the offset is known. Under most circumstances, the resulting rate shift will be a small source of error relative to shoreline change rates and will likely not be a major concern. However, we caution that given the convergence of several factors, including a gently sloping beach, a moderately short measurement interval, and a change rate rapid enough to be significant, rate shifts could begin to account for a substantial percentage of error in shoreline change rates. Under these circumstances, and where rates will be averaged alongshore, determining the offset between shoreline indicators would allow for quantification of the rate shift and removal of the associated error.

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LITERATURE CITED

ANDERS, F.J. and BYRNES, M.R., 1991. Accuracy of shorelines change rates as determined from maps and aerial photographs. *Shore & Beach,* 59(1), 17–26.

CROWELL, M.; LEATHERMAN, S.P., and BUCKLEY, M.E., 1991. Historical shoreline change: error analysis and mapping accuracy. *Journal of Coastal Research,* 7(3), 839–852.

DOLAN, R.; FENSTER, M.S., and HOLME, S.J., 1991. Temporal analysis of shoreline recession and accretion. *Journal of Coastal Research,* 7(3), 723–744.

DOLAN, R. and HAYDEN, B., 1983. Patterns and prediction of shoreline change. *In*: KOMAR, P.D. (ed.), *Handbook of Coastal Processes and Erosion.* Boca Raton, Florida: CRC Press, pp. 123–149.

DOLAN, R.; HAYDEN, B.P.; MAY, P., and MAY, S., 1980. The reliability of shoreline change measurements from aerial photographs. *Shore & Beach,* 48(4), 22–29.

DOUGLAS, B.; SANCHEZ, T.A., and SCOTT, J., 1999. Mapping erosion hazard areas in Baldwin County, Alabama and the use of confidence intervals in shoreline change analysis. *Journal of Coastal Research,* SI 28, 95–105.

HOLMAN, R.A., 1986. Extreme value statistics for wave runup on a natural beach. *Coastal Engineering,* 9, 527–544.

KRABILL, W.; THOMAS, R.H.; MARTIN, C.; SWIFT, R.N., and FREDERICK, E.B., 1995. Accuracy of airborne laser altimetry over the Greenland ice sheet. *International Journal of Remote Sensing,* 16, 1211–1222.

KRABILL, W.; WRIGHT, C.W.; SWIFT, R.N.; FREDERICK, E.B.; MANIZADE, S.; YUNGEL, J.; MARTIN, C.; SONTAG, J.; DUFFY, M.; HULSLANDER, W., and BROCK, J., 2000. Airborne laser mapping of Assateague National Seashore Beach. *Photogrammetric Engineering & Remote Sensing,* 66(1), 65–71.

LEATHERMAN, S.P., 1983. Shoreline mapping; a comparison of techniques. *Shore & Beach,* 51(3), 28–33.

LEATHERMAN, S.; DOUGLAS, B.C., and LABRECQUE, J.L., 2003. Sea level and coastal erosion require large-scale monitoring. *Eos, Transactions, American Geophysical Union,* 84(2), 13, 16.

LIST, J.H. and FARRIS, A.S., 1999. Large-scale shoreline response to storms and fair weather. *In*: KRAUS, N.C., and MCDOUGAL, W.G. (eds.), *Coastal Sediments '99.* American Society of Civil Engineers, pp. 1324–1338.

MOORE, L.J., 2000. Shoreline mapping techniques. *Journal of Coastal Research,* 16(1), 111–124.

MORTON, R.A., 1979. Temporal and spatial variations in shoreline changes and their implications, examples from the Texas Gulf Coast. *Journal of Sedimentary Research,* 49(4), 1101–1112.

MORTON, R.A., 1991. Accurate shoreline mapping; past, present, and future. *In*: KRAUS, N.C.; GINGERICH, K.J., and KRIEBEL, D.L. (eds.), *Coastal Sediments '91,* American Society of Civil Engineers, pp. 997–1010.

MORTON, R.A. and SPEED, F.M., 1998. Evaluation of shorelines and legal boundaries controlled by water levels on sandy beaches. *Journal of Coastal Research,* 14(4), 1373–1384.

PAJAK, M.J. and LEATHERMAN, S.P., 2002. The high water line as shoreline indicator. *Journal of Coastal Research,* 18(2), 329–337.

ROBERTSON, W.; WHITMAN, D.; ZHANG, K., and LEATHERMAN, S.P., 2004. Mapping shoreline position using airborne laser altimetry. *Journal of Coastal Research,* 20(3), 884–892.

RUGGIERO, P.; KAMINSKY, G.M., and GELFENBAUM, G., 2003. Linking proxy-based and datum-based shorelines on a high-energy coastline: implications for shoreline change analysis. *Journal of Coastal Research,* Special Issue 38, 57–82.

RUGGIERO, P.; KOMAR, P.D.; MCDOUGAL, W.G., and BEACH, R.A., 1996. Extreme water levels, wave runup and coastal erosion. *In*: EDGE, W. (ed.) *Proceedings of the Coastal Engineering Conference* (American Society of Civil Engineers), pp. 2793–2805.

RUGGIERO, P.; KOMAR, P.D.; MCDOUGAL, W.G.; MARRA, J.J., and BEACH, R.A., 2001. Wave runup, extreme water levels and the erosion of properties backing beaches. *Journal of Coastal Research,* 17(2), 407–419.

RUGGIERO, P.; KAMINSKY, G.M.; GELFENBAUM, G., and VOIGT, B., 2005. Seasonal to interannual morphodynamics along a high-energy dissipative littoral cell. *Journal of Coastal Research,* 21(3), 553–578.

SALLENGER, A.H., JR.; KRABILL, W.; BROCK, J.; SWIFT, R.N.; JANSEN, M.; MANIZADE, S.; RICHMOND, B.; HAMPTON, M., and ESLINGER, D., 1999. Airborne laser study quantifies El Nino-induced coastal change. *Eos, Transactions, American Geophysical Union,* 80(8), 89, 92–93.

SALLENGER, A.H., JR.; KRABILL, W.; SWIFT, R.N.; BROCK, J.; LIST, J.H.; HANSEN, M.; HOLMAN, R.A.; MANIZADE, S.; SONTAG, J.; MEREDITH, A.; MORGAN, K.; YUNKEL, J.K.; FREDERICK, E.B., and STOCKDON, H.F., 2003. Evaluation of airborne topographic lidar for quantifying beach changes. *Journal of Coastal Research,* 19(1), 125–133.

SHALOWITZ, A.L., 1964. Shoreline and Sea Boundaries. VI. U.S. Department of Commerce, Coast and Geodetic Survey, U.S. Government Printing Office, 420p.

SMITH, G.L. and ZARILLO, G.A., 1990. Calculating long-term shoreline recession rates using aerial photographic and beach profiling techniques. *Journal of Coastal Research,* 6(1), 111–120.

STAFFORD, D.B., 1971. An Aerial Photographic Technique for Beach Erosion Surveys in North Carolina. U.S. Army Corps of Engineers, Coastal Engineering Research Center, 115p.

STOCKDON, H.F.; SALLENGER, A.H., JR.; LIST, J.H., and HOLMAN, R.A., 2002. Estimation of shoreline position and change using airborne topographic lidar data. *Journal of Coastal Research,* 18(3), 502–513.

STOCKDON, H.F.; HOLMAN, R.A.; HOWD, P.A., and SALLENGER, A.H., JR., 2006. Empirical parameterization of setup, swash and runup. *Coastal Engineering,* 53(7), 573–588.

WEBER, K.M.; LIST, J.H., and MORGAN, L.M.M., An Operational Mean High Water Datum for Determination of Shoreline Position from Topographic Lidar Data. U.S. Geological Survey Open File Report 2004-1027. [http://pubs.usgs.gov/of/2005/1027/].