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The High Water Line as Shoreline Indicator

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ABSTRACT

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Beach erosion rates are often determined by delineating historical shoreline positions from maps and aerial photographs and more recently global positioning systems (GPS). The high water line is usually selected as the shoreline indicator for mapping purposes; it is defined as the wetted bound and by "markings left on the beach by the last high tide." The high water line that is acquired from field determination or photogrammetric means is assumed to represent the mean shoreline position for that year, but field studies have shown that its position is variable because of changes in water level due to waves, wind, tides, and other factors. This study investigated the short-term variability in the high water line location over tidal cycles, days, and months through field observations and interpretation of videotape data. Studies, undertaken at Assateague Island National Seashore in Maryland and at the Field Research Facility at Duck, North Carolina, indicated that the high water line is a useful shoreline indicator within certain limits. GPS-acquired shorelines based on actual identification of the high water line in the field are deemed more accurate than photo-interpreted shorelines for coastal erosion mapping and management.

ADDITIONAL INDEX WORDS: *Shoreline indicators, high water line, beach erosion rates, Assateague Island, MD, Duck, NC, shoreline change.*

INTRODUCTION

Beachfront property along the U. S. coasts is subject to a variety of natural hazards. These include flooding from storm surges, wind damage from hurricanes, and short- and long-term coastal erosion. The severity of the impact of these natural hazards generally decreases as one moves inland from the land/sea boundary. Thus, insurance rates and building code regulations, both of which relate to a property's exposure to natural hazards, vary significantly based on a structure's location relative to the shoreline. Accurate, consistent identification of the shoreline as a physical feature and its movement over time result in more accurate identification of the extent of coastal hazard threats. This coastal hazard information is used by individuals, businesses, and governments to make decisions about investments, development, and land use.

Although the specific extent of all natural hazards is not precisely defined, flooding due to coastal storm surges has been mapped by the Federal Emergency Management Agency (FEMA) for coastal communities throughout the United States. Wind hazards have been reflected in building codes for many years, and the inland extent of hurricane winds are beginning to be identified and mapped in some areas through state and federal programs. Erosion hazard mapping has been conducted typically on a locality or state-by-state basis.

Of the three coastal hazards mentioned above, the erosion hazard relies most heavily on the use and accuracy of shoreline mapping. Long-term erosion rates are determined by the use of historical shoreline positions. The United States is fortunate to have a source of accurate historical shoreline mapping undertaken by the National Ocean Survey (NOS) and its predecessor, the U. S. Coast and Geodetic Survey (USC&GS). These maps were constructed in the field, and the surveys identified the mean high water line as the shoreline indicator (SHALOWITZ, 1964).

Beginning in the 1940s aerial photography began to be available for many areas of the coast. Aerial photography has many advantages over the time-consuming and labor intensive method of field surveying. It was suggested at the time that the best indicator of the land/water boundary in aerial photographs was the high water line (MCCURDY, 1947). The use of this indicator for photo interpretation of the shoreline has been widely used in coastal mapping studies (DOLAN *et al.,* 1980; LEATHERMAN, 1983; STAFFORD, 1971).

More recently, the availability of the global positioning system (GPS) has revolutionized field surveying techniques. Highly accurate coordinate points can be obtained easily by driving a vehicle containing a GPS receiver along the shoreline (MORTON, *et al.,* 1993). This new surveying technique requires field identification of shoreline position.

A map, aerial photograph, or field survey performed on any given day and used to locate a shoreline reflects one instant in time. However, shorelines are dynamic, constantly chang-

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ing in response to forces acting upon them. The uncertainties and the natural variability of shoreline indicators, specifically the high water line, need to be quantified.

Shoreline Indicators

An initial consideration in the collection or use of shoreline data is the identification of the shoreline indicator. Several basic criteria must be met for a given physical feature to be considered a satisfactory shoreline indicator. The shoreline is a line on a map representing the physical feature where the land and water meet. Physical features that are reflected on maps are typically represented in a way consistent for that feature. For example, a single line representing a road on a small-scale map usually denotes the centerline of that road, and not one of the pavement edges. Similarly, when delineating a stream by single line, the thalweg would probably be used, not the right or left channel bank. The centerline of a road or the thalweg of a watercourse is easily defined. However, because of the natural variability of sandy beaches both in their individual nature and at one location over different time periods, the single line representing the shoreline on a sandy beach is not easily defined.

A satisfactory shoreline indicator must be practical. That is, the feature must exist consistently at all locations where a shoreline is to be identified. The feature must also be repeatable. It must be defined well enough that different individuals knowledgeable of coastal processes and skilled in coastal mapping would select the same location to represent the shoreline when using the same shoreline indicator. Consistent interpretation is also important if different remote sensing techniques are used to identify the feature. The same physical location should be chosen by an observer's eye in the field as the location chosen when interpreting an aerial photograph of the same location taken at the same time. Finally, the feature must be reliable in that it provides a consistent representation of shoreline position.

There are many physical features that could be used as shoreline indicators. These features include the berm crest, scarp edge, vegetation line, dune toe, dune crest, and cliff or bluff crest and toe. Figure 1 shows these shoreline indicators based on physical features. Several shoreline indicators associated with water levels also exist. Many terms have been used to describe shoreline indicators associated with water levels, including the high water line, mean high water line, wetted bound or wetted boundary, wet/dry boundary, wet sand line, and water line (PAJAK, 1997).

The High Water Line

Of all the shoreline indicators, the high water line (HWL) is considered the best shoreline indicator by many, but not all, researchers because it is easily field-located and photo-interpreted (CROWELL, LEATHERMAN and BUCKLEY, 1991). MORTON and SPEED (1998) pointed out that the HWL is not a morphologic feature, but it is generally located just seaward of the berm during normal tidal (not spring or neap) and wave (*e.g.,* not storm or big swell) conditions. The high water line links historical shoreline maps to more recent shoreline data because the same shoreline indicator is used (LEATHERMAN, 1983). In the 1830s the U.S. Coast Survey (known as the U.S. Coast and Geodetic Survey after 1947) began surveying the nation's shorelines by locating the high water line in the field (SHALOWITZ, 1964). The intention was to delineate without recourse to leveling the line of mean high water, but what the topographer actually delineates are the markings left on the beach by the last preceding high water (SHALOWITZ, 1964). Even though the aim of the historical surveys was to map the mean high water line, the mean high water line can only be precisely located by leveling along the coast, and locating points along the line corresponding to the tidal datum. The horizontal location of the mean high water line on a gently sloping sandy beach, although precisely defined with respect to elevation, is highly variable because the beach and foreshore are dynamic. Thus, the use of the high water line is a practical solution to locating the land/sea boundary in a dynamic environment.

It has been stated that the horizontal position of the high water line and mean high water line are nearly equivalent, assuming moderate weather conditions (CROWELL, LEATHERMAN and BUCKLEY, 1991). This may be true in some circumstances, but little quantitative information exists regarding this relationship. Since about 1940, aerial photographs have been used to locate the high water line. Using the high water line to determine shoreline position enables use of the longest possible record of shoreline position for determining erosion rates as opposed to any other indicator. Longer periods of record of shoreline position result in more reliable predictions of erosion rates (CROWELL, LEATHERMAN and BUCKLEY, 1993; NATIONAL RESEARCH COUNCIL, 1990).

The position of the high water line is affected by astronomical tides, seasonal beach changes, storm events, and wind tides. Along the U. S. West Coast, climatic variability, such as El Nino events, have an important effect on water levels. Differences in one of these factors, with all other factors remaining constant, can result in a much different shoreline position, as indicated by the high water line. Some factors have a greater influence than others depending on the sandy beach location. All of these factors can contribute to apparent differences in shoreline position, which are a measure of its variability (MORTON and SPEED, 1998; HOLMAN and SALLENGER, 1985).

Previous Investigations

Use of the high water line as the shoreline indicator requires quantification of its variability over varying time scales, as well as assurances that it can consistently and accurately be identified. Little published research exists in this regard. SMITH and ZARILLO (1990) investigated the long-term vs. short-term shoreline position for a barrier beach fronting Mecox Bay on Long Island, New York. They concluded that short-term fluctuations in shoreline position can be quite large, but the aerial photographic data used were limited, and the short-term changes were measured monthly, providing limited insight into variations of the high water line position. DOLAN, *et al.* (1980) obtained measurements of the variability of the high water line over a tidal cycle at four locations in North Carolina and Virginia. Data from this study

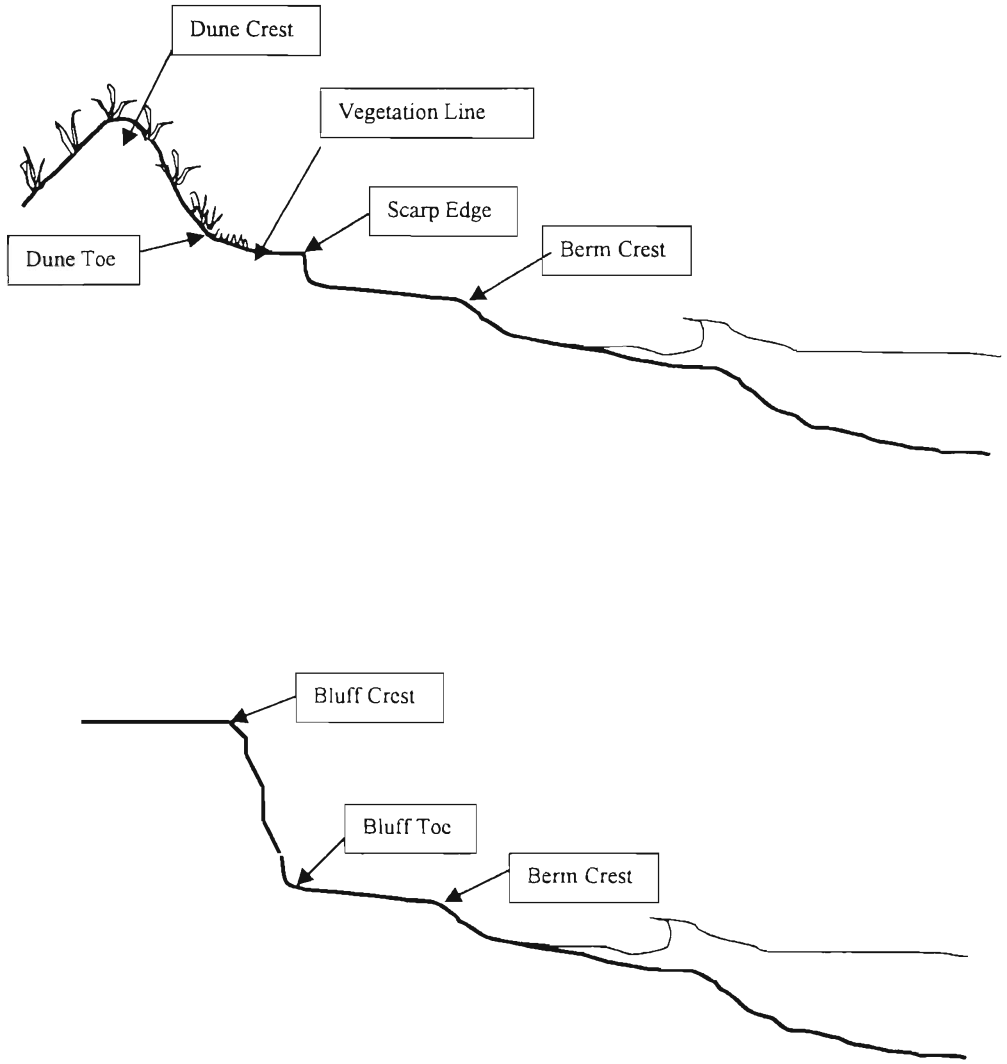

Figure 1. Shoreline indicators based on physical features.

indicated that the difference in high water line position from one high tide to the next, 12 hours and 25 minutes later, ranged from a minimum of 0.12 m to 5.8 m. These data are a measure of the short-term variability of the high water line, but these findings are extremely limited because the high water line position was monitored over only one tidal cycle at each site.

SHALOWITZ (1964) discussed the accuracy of the surveyed mean high water line and identified potential errors resulting from locating the line at the time of a particular survey, assuming normal horizontal control. SHALOWITZ's estimate of error due to the identification of the actual mean high water line on the ground is 3–4 m. This error estimate is the difference between the high water line position identified in the field and the true mean high water line location. CROWELL, LEATHERMAN and BUCKLEY (1991) focused on the measurement errors inherent in the raw data used to map the high water line, including delineating, mapping, or rectifying the line identified or interpreted as the high water line (survey errors, air photo distortions) and processing or transferring the delineated line into digital format (digitizer errors). Their worst-case estimate of the measurement errors is 6.1–8.9 m.

There are a number of issues that are not generally considered in the use of the high water line as a shoreline indicator. First is the inherent variability of this physical feature over various time scales. Additionally, it is usually assumed that the high water line position obtained by interpreting an aerial photograph and by field identification results in an identical position. Another untested assumption is that the high water line position is nearly equivalent to the location of mean high water assuming moderate weather conditions.

METHODS

Data were collected at two principal sites along the U.S. mid-Atlantic coast: Assateague Island, Maryland and Duck,

North Carolina. The Assateague Island site is a medium fine-grained beach (d_{50} = 0.33 mm) with a typical foreshore slope of 5–6° (U.S. Army Corps of Engineers 1997). The average tide range at Assateague is approximately 0.7 m. The beach at Duck, North Carolina is coarse-grained (d_{50} = 1.0 mm) and steep, with a typical foreshore slope of 8–10° (BIRKEMEIER *et al.*, 1985). The average tide range at Duck is approximately 1.1 m.

Observation of the High Water Line

The following high tides were videotaped at Assateague Island in 1996: 16:23 July 26, 17:26 July 27, 18:23 July 28, 06:50 July 29, 16:00 August 24, 17:06 August 25, 06:03 and 19:00 August 26, and 07:29 August 27. Taping began approximately 30 minutes prior to the high tide and continued until approximately 30 minutes there-after. The video camera was mounted on a tripod placed near the high water line and positioned looking north up the beach. After observing the imprint of the high water line for the high tide, its position along the transect was marked with a 1.2 m plastic stake.

Field Location vs. Photo Interpretation of the High Water Line

Aerial photographs were taken from a small plane rented at the Ocean City Airport, Maryland. The flights occurred near low tide on July 27 and August 25, 1996. Markers were placed on the high water line, and photographs were taken of the marked beach. The markers were then removed and photographs were taken of the unmarked beach. The pilot circled over the shoreline near the National Park Service (NPS) 5.25 benchmark and tilted the plane so that nearly vertical photographs were obtained. The plane was flying at an altitude of approximately 305 m. A 35-mm Olympus Infinity Zoom 230 camera was used with ASA 200 color slide film. All camera settings were adjusted automatically. The maximum extent of the zoom lens (90 mm) was used to shoot the slides.

Monitoring of the High Water Line

Black and white video images of the nearshore area and swash zone have been collected at the U. S. Army Corps of Engineers Field Research Facility (FRF) at Duck, North Carolina over the period 1986 to present (LIPPMAN, HOLMAN and HATHAWAY, 1993). We utilized data from the Argus station video camera installed on the tower at the FRF at 43 m above sea level. The view of the camera looking north along the beach contains ground control points in the image, and the hourly snapshot video images were used to observe movement of the high water line. These images can be viewed using the Internet at the following address: http://www.frf.usace.army.mil/video.html.

To ensure that the proper feature was being identified on the video images, site visits were made to the FRF to place markers on the beach and observe the images in real time, ensuring that the proper interpretation of the high water line was being made. It became apparent that the hourly record of images would be helpful in ensuring confidence in the high water line identification. The hourly record was used to track the position of the wet/dry sand line during the day and verify the limit of the high tide and the high water line's location.

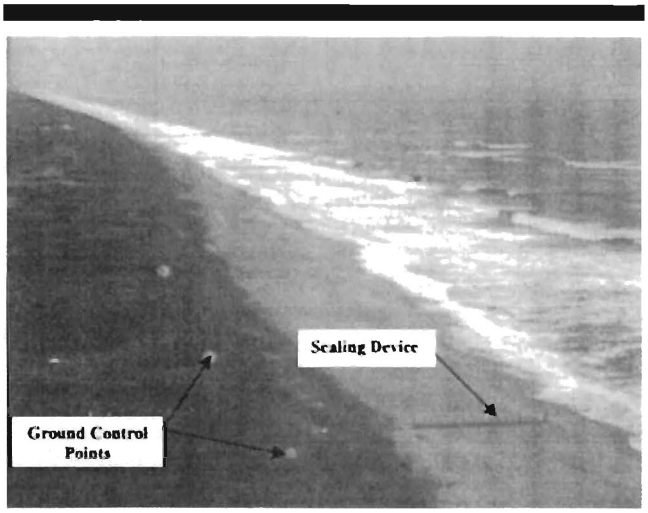

Figure 2. Video image from Field Research Facility tower with scaling device, February 4, 1997, 1600 EST.

The video camera produces high oblique images, resulting in varying scale across the image (Figure 2). An image rectification procedure exists for these data (LIPPMAN, HOLMAN and HATHAWAY, 1993). However, the rectification procedure is designed primarily for the time-exposure images, and the detail to interpret the high water line from tonal variations in the sand is effectively washed out. Therefore, another method of scaling the video image was developed (PAJAK, 1997). In order to determine a scale for one area of the image, black plastic sheets were placed on the beach, field-measured, and then measured in the image (Figure 2). The line used to measure the high water line position was referenced from a control line connecting the two ground control points closest to the tower at the FRF. The measurement was taken along a line drawn over the scaling device. The control points are white wooden disks located on the dunes, seen as white circles in the video image. The wooden disks were not installed at the FRF until November of 1993. Therefore, images taken prior to that date were not useable for this research.

Image usability depended on many factors, mainly weather conditions and timing of high tide. Bright sunny days provide the best images. Rain or fog obscures the image and renders them useless for this work. Images taken close to solar noon provide the best contrast for determining the location of the high water line. High tide occurring in the late morning to mid afternoon was preferable, aiding in identification of the high water line position. Once it was determined that images from a specific day were usable, the hourly images were viewed and usually two were printed. One image was selected immediately after the high tide and another, later image was selected. These images were then used to delineate the high water line, and measurements were made along the line of known scale to locate the high water line position relative to the control line.

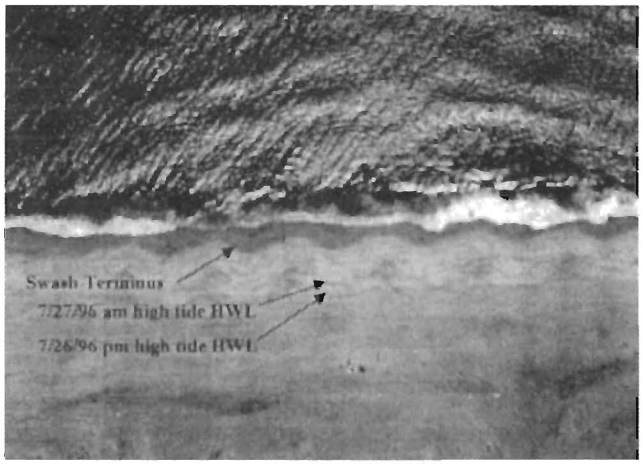

Figure 3. Assateague Island airphoto with beach markers, July 27, 1996.

Because the use of these data entailed a labor-intensive procedure to interpret and measure the high water line position, selection of images was limited to the months of July, August and September. These three months also include the period when the beach is likely to be the most stable, with the summer berm well established, barring any major storms. Every day of the months of July, August, and September for 1994, 1995, and 1996 was reviewed for usability. Images for 111 days were used for this study.

RESULTS

High Water Line Formation

An interesting question involves the cause of the high water line left on the beach after high tide. Does one swash or do multiple swashes cause it? Based on field investigations and review of the videotapes of ten high tides at Assateague Island, it appears that one swash creates the high water line. In some cases, multiple swashes were observed reaching the same point, but this happens at isolated points along the high water line, not continuously. Spatially, the majority of the high water line on the beach is left by the landward extent of only one swash. Additionally, the high water line is a wet/dry boundary, but it is not necessarily the only one on the beach. Other wet/dry boundaries, with differing contrasts, are apparent from previous high tides, if their extent was landward of the most recent one.

Field Location vs. Photo Interpretation of the High Water Line

Simulated aerial photographs were used to compare high water line identification to that made in the field at Assateague Island, Maryland. It is clear that other shoreline indicators can easily be mistaken for the high water line on aerial photographs. The photographs taken at Assateague include a discontinuous storm/debris line, two high water lines left from two previous high tides, and the wet/dry sand line, or swash terminus. When the sets of unmarked aerial photographs (prints) were shown to scientists experienced in interpreting high water line position, all initially identified the wet/dry sand line, or swash terminus, as the high water line. But when the much higher resolution original color slides were shown to the same researchers, they realized that their initial interpretation was incorrect. In fact, metric-quality airphotos have similar high resolution qualities. Figure 3 is a photograph of the beach with markers on the high water line from the July 27 morning high tide and the July 26 evening high tide. The location of the swash terminus is also denoted on this photography.

Table 1. *Range of data collected at Duck, North Carolina.*

Time Interval	Number of Data Points	Range Of Data (m)	Standard Deviation
1994 (July–Sept)	55	18.0	4.1
Jul 1994	21	9.2	2.8
August 1994	19	5.7	1.9
September 1994	15	13.0	4.1
1995* (July–Sept)	22	27.2	8.3
August 1995	4	N/A	N/A
September	3	N/A	N/A
1996* (July–Sept)	34	24.5	7.0
July 1996	11	8.0	2.5
August 1996	14	11.5	3.4
September	9	N/A	N/A

* Wave energy in 1995 was highest compared to previous 50 years; 1996 wave energy was also above normal.

Monitoring of the High Water Line

Out of 276 possible points from the months of July, August and September over a three-year period, the high water line position was usable only for 111 days. Descriptive statistics were calculated for this data set obtained from Duck, North Carolina. Table 1 shows the data ranges for the years and individual months. Statistics were not calculated for months having less than 10 data points.

The range of the high water line position for the entire data set was 32.6 m with a standard deviation of 8 m. The largest range for any one month was 13.0 m in September 1994, while the smallest range for any one month was 5.7 m in July 1994.

Figures 4 and 5 contain plots of high water line positions for 1994 and 1996. Dates of the spring tides are shown on these plots. The data collected in 1994 (Figure 4) is the most complete set. A cyclical pattern associated with the high water line position appears evident, but the data do not show the expected correlation between spring and neap tides (PAJAK, 1997). The 1996 data are less complete, but the HWL shows more consistency until the advent of a series of tropical storms (Figure 5).

Storm data were obtained from the USACE Field Research Facility website. Storm dates indicate times when the wave height at the seaward end of the Field Research Facility pier exceeded 2 m. Storm effects are evident in the high water line position plots (Figures 4 and 5). These figures demonstrate the dramatic effect storms have on wave action and hence high water line position. The high water line position

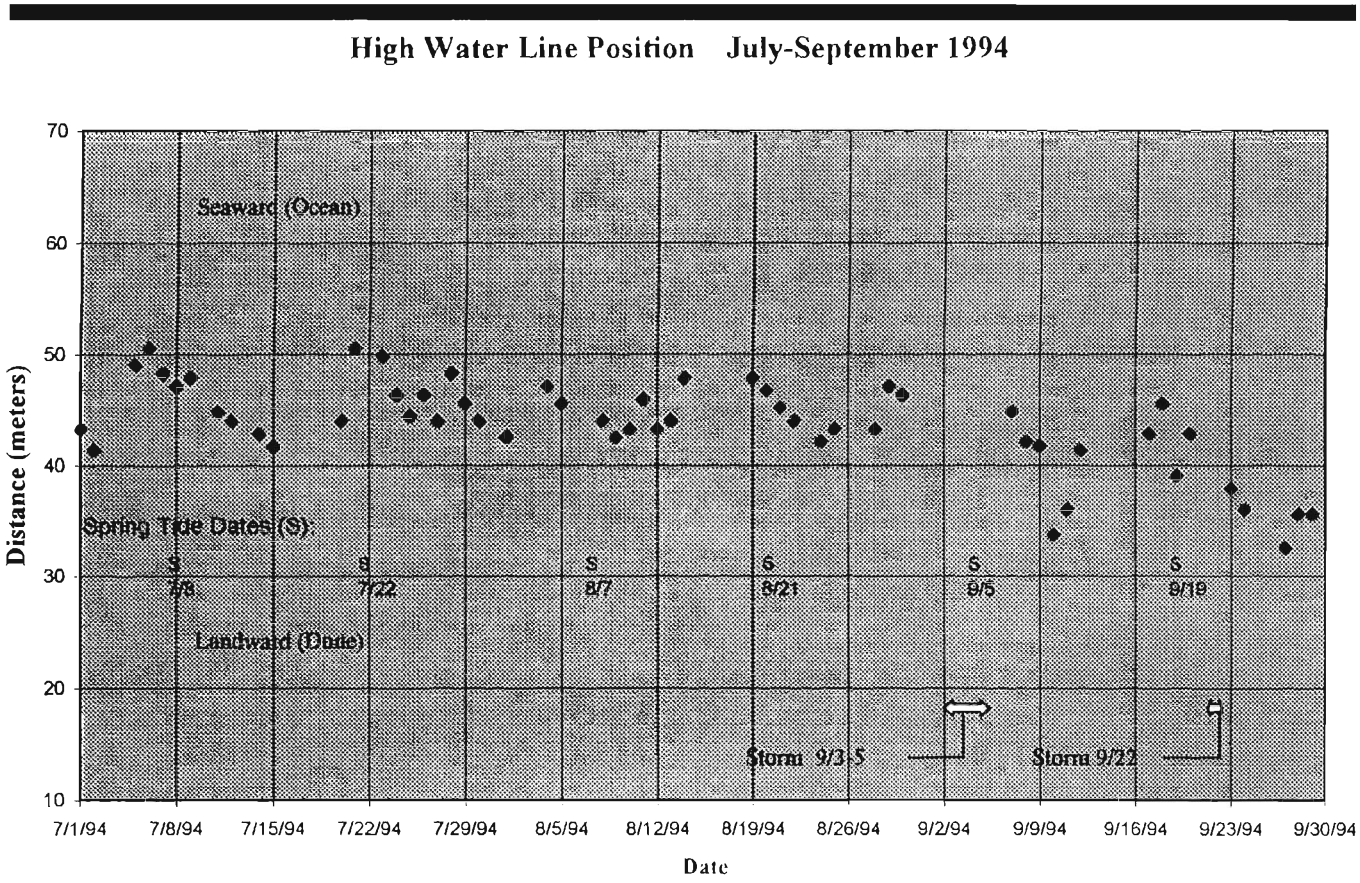

Figure 4. High water line position, Duck, N. C., July–September, 1994.

is contained within a 10 m band in July and August in 1994; it shifted landward about 5 m in 1994 because of offshore tropical storms.

The ranges of high water line position for July through September of 1994 and 1996 are plotted for the USACE Field Research Facility Profile No. 135 (Figure 6). This profile is located about 100 m north of the pier, close to where the high water line position data were collected. The mean value for high water line position for July and August 1994 translates into a distance of 97 m on the profile. The mean value for high water line position for July and August 1996 translates into a distance of 87 m on the profile. These profiles show a significant change in the beach profile between 1994 and 1996. In addition to the loss of volume, the overall profile has flattened but the foreshore at the position of the high water line position has steepened. This steeper profile is evident in the increased consistency of the high water line position shown in the 1996 plot (Figure 5) compared to 1994 (Figure 4).

The profile plots also show both the vertical and horizontal difference in high water line position compared to the location of mean high water elevation. Horizontally, the high water line position is approximately 40 m landward of the mean high water elevation on the profile. The high water line position on the profile is approximately 2 m higher in elevation than the mean high water elevation due to the effects of wave runup (Figure 6).

DISCUSSION

The results of this study indicate that shoreline position on a sandy beach as determined by high water line position can be highly variable. Differences in water level at the time of high tide translate into many meters horizontally on a gently sloping sandy beach. Differences in wave height and period at the time of high tide can result in significant differences in high water line position due to wave runup. Therefore, day to day variations in high water line position can be significant on gently sloping beaches (MORTON and SPEED, 1998). The existence of a well-defined berm may considerably lessen the variability of the high water line position. Recognizing these factors and minimizing their impact on the high water line's variability make it possible to use the high water line as a shoreline indicator, and ensure that it is a representative indicator of shoreline position within certain limits.

High Water Line Formation

It may be difficult to accurately establish the mark left by the preceding high water with certainty on aerial photographs. At Assateague, often the mark left by the higher high

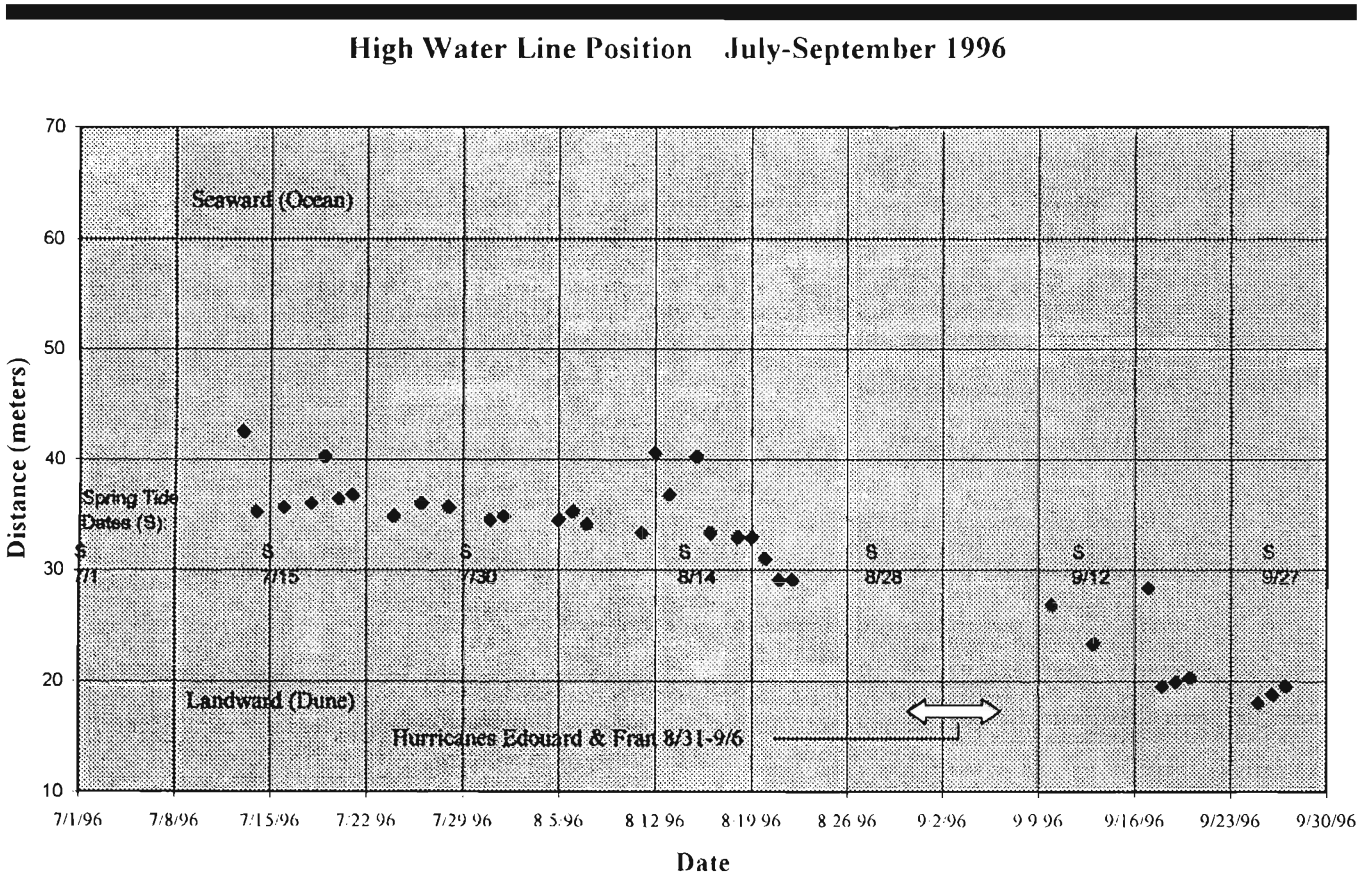

Figure 5. High water line position, Duck, N. C., July–September, 1996.

tide of the previous day remained visible throughout the next 24-hour tidal cycle. The previous high water lines that remained visible were not as distinct as the most recent high water line as observed in the field (but perhaps not obvious on aerial photographs). On a tidal cycle with levels falling from spring to neap, a mark left from a higher high tide from preceding days may remain visible on the beach and cause misinterpretation of the high water line for the day of the observation. Therefore, GPS field measurements should be taken close to the occurrence of high tide to avoid any possible misinterpretation.

Field Location vs. Photo Interpretation of the High Water Line

The high water line signature may be subtle, and other features (*e.g.*, multiple debris lines, heavy mineral lag deposits, scarps, *etc.*) may exist on a beach that could be interpreted as the high water position. Previous high water lines may remain on a beach for several tidal cycles. Because of the potential for misinterpretation, the high water line position identified by investigators may differ when comparing *field identification* and *photographic interpretation*. Aerial photographs, when used, should be of the highest possible quality and resolution. Lesser quality photographs, or even the use of different types of film, such as infrared, may result in photographs that do not pick up subtle differences between features. It is important for investigators to be familiar with the area being studied and to know the specific characteristics of the beach being measured. Variability in the identification of high water line position can be minimized when making a measurement in the field by scheduling the data collection soon after the occurrence of the high tide and during moderate wave conditions.

Monitoring of the High Water Line

Changes in the high water line position relate to both water level and beach profile changes. While significant variability exists in the data set collected, much of this variability is due to the occurrence of storm events. If these events are eliminated from the data set, the high water line position range is on the order of 10 m, which is influenced by the variability in wave runup and water level variations due to the spring/neap tidal cycle. Aside from high variability caused by significant wind and wave events, the extreme ranges of high water line position at some locations may be explained by the occasional overtopping of the berm during spring high tides. Often a slight depression (swale) exists on the beach landward of the berm, and once overtopping occurs, the high water line position can be significantly shifted landward due to ponding in this low area. While such an occur-

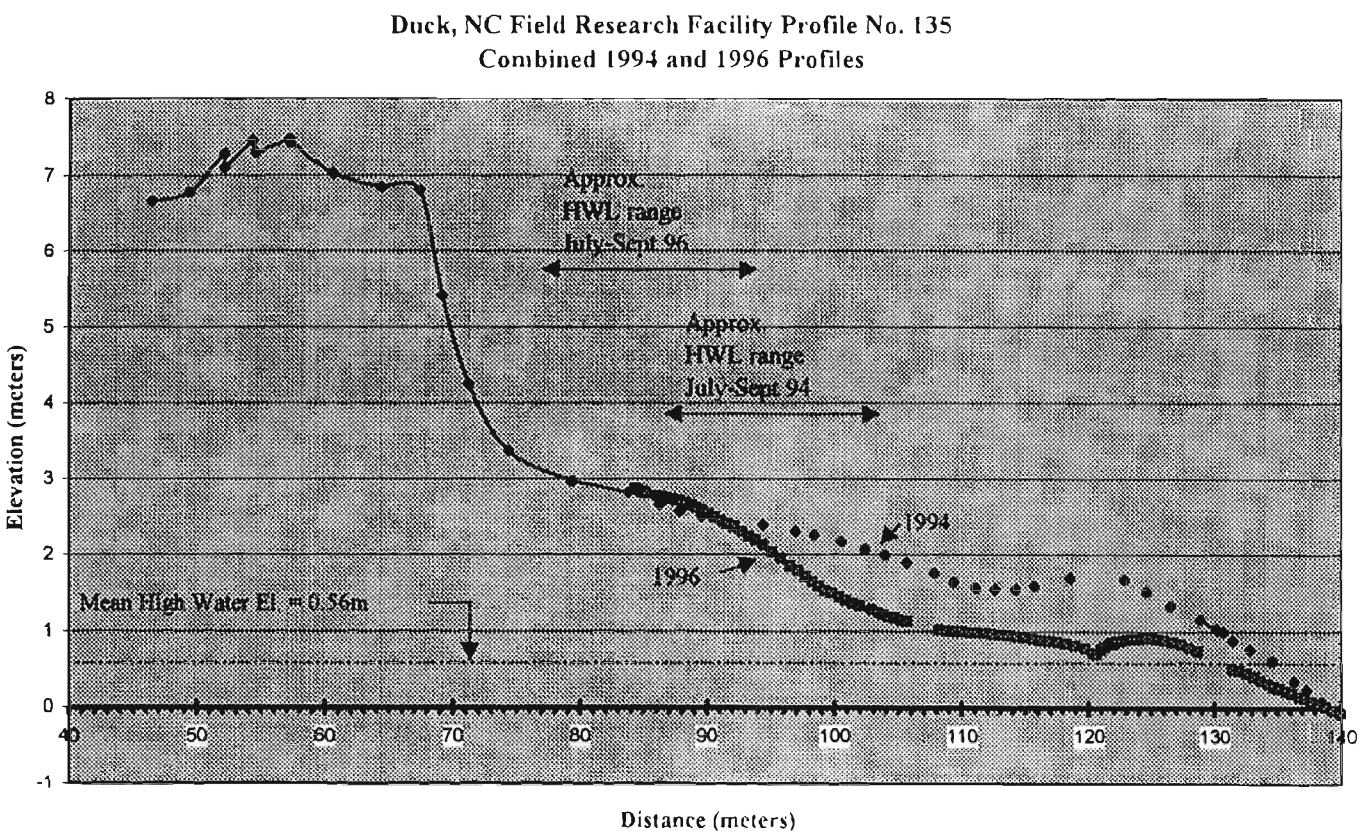

Figure 6. Comparison of averaged summer beach profiles during 1994 and 1996 at Duck, N. C.

rence may prove problematic in airphoto interpretation of the high water line, this situation could be noted and accounted for in GPS field surveys.

CONCLUSIONS

The beach is the most stable during the summer, barring any tropical storm activity. Therefore, this time period provides the best window of opportunity for data collection along the U. S. East Coast. Post-storm data should not be used to populate the data set of historical shoreline positions, especially in the calculation of long-term erosion rates. Storm events add another dimension of variability that is not representative of a typical shoreline position, and can greatly bias the data set toward higher long-term erosion rates.

Field identification of the high water line has many advantages over photographic interpretation of this non-morphologic feature. Subtle features present on a beach, such as multiple drift lines, heavy mineral lag deposits, scarps, etc., may lead to misinterpretation of photographic data for identifying the high water line position. Therefore, kinematic GPS surveys are recommended for collecting new shoreline position data. Because of its practicality, repeatability and reliability (when only summer time, non-storm data are utilized), the high water line will probably continue to be used as the shoreline indicator. Technology is rapidly advancing (e.g., airborne lasers) so that it may be just as easy to identify the position of an elevation contour along a sandy shoreline as it is to identify the wet/dry sand boundary that identifies the landward limit of the previous high tide. The position of any shoreline indicator used on a sandy shoreline is by definition variable because of the very nature of beaches, and it is important to be aware of this variability. These results may only be valid for beach environments similar to the U. S. East Coast

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