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Evaluation of Shorelines and Legal Boundaries Controlled by Water Levels on Sandy Beaches

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ABSTRACT

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Integration of beach profiles and water-level measurements at three sites on a microtidal, wave-dominated coast reveals that tide-gauge records systematically underestimate the actual elevations and horizontal positions that water reaches on the beach as a result of wave runup. On low-gradient sandy beaches, natural morphological beach features, such as the erosional scarp and vegetation line accurately reflect the positions of frequent maximum high water levels and the berm crest reflects the position of more frequent ordinary high water levels, whereas tide-gauge records consistently predict lower maximum and average levels of beach flooding.

The discrepancies between predicted and actual water positions on the beach have important scientific and legal implications. The scientific implications involve the need to map shoreline features that closely track the long-term trends in beach movement, but are insensitive to short-term fluctuations in water level. Neither the instantaneous high water line (wet beach-dry beach boundary) or the berm crest satisfy this requirement, and therefore, they are not recommended for monitoring shoreline position either in the field or interpreted from aerial photographs unless there is no reliable alternative. The legal implications pertain to land ownership and property boundaries in the United States that currently are surveyed from tide-gauge records but were originally defined by common law on the basis of high water levels that leave physical marks on the upland property. Because water levels are actually higher on the beach than predicted by tide gauges, land surveys based on a tidal datum allocate more littoral property to the upland owner than is justified by the physical facts or was intended by law. Consequently, the publicly-owned state submerged lands encompass less of the beach than that area which is regularly flooded by marine water.

ADDITIONAL INDEX WORDS: *Beach, tide gauge, water levels, legal boundary, shoreline changes, wave runup.*

INTRODUCTION

The use of oceanic shorelines to establish legal boundaries, construction setback lines, or flood hazard zones requires a high mapping standard that can only be achieved with highly accurate analyses of changes in shoreline position. The keys to improved accuracy and reliability of shoreline predictions are (1) understanding the factors that control beach morphology, (2) documenting short-term variability in shoreline position at representative sites, and (3) reducing the errors that are inherent in mapping and analyzing changes in shoreline positions (MORTON, 1991). This study addresses the issue of both long-term and short-term fluctuations in shoreline position and the large error factor (short-term variability in shoreline position) that currently is present in many of the data sets used to predict future shoreline positions.

For coastal scientists who are not land surveyors, the most common shoreline proxy derived from aerial photographs is the instantaneous high water line separating the wet beach from the dry beach. However, more than two decades of beach surveys and field observations have demonstrated clearly that the high water line mapped on aerial photographs is highly dynamic and therefore is a less reliable indicator of shoreline position than the base of the bluff, vegetation line, erosional scarp, or other beach feature that is either unaffected or only nominally altered by short-term changes in water levels. Furthermore, development of relatively rapid, low-cost, highly accurate beach surveys using Global Positioning System (GPS) now permit direct correlation between mapped shorelines and field observations of the mapped features, perhaps minimizing the need for shoreline interpretations from aerial photographs in many developed or accessible coastal areas (MORTON *et al.*, 1993).

Tide gauges are designed and constructed so that high frequency fluctuations in water level associated with wind-generated and/or short-period waves are physically dampened or eliminated. This process of mechanical filtering is accomplished by small openings that restrict the volume of water flowing into or draining out of the stilling well (EDWING, 1991). Because water level fluctuations associated with waves are deliberately eliminated from tide gauge measurements, the gauge records are biased toward lower water levels than are actually observed on adjacent beaches (POPE, 1958; KRAUS and HEILMAN, 1996).

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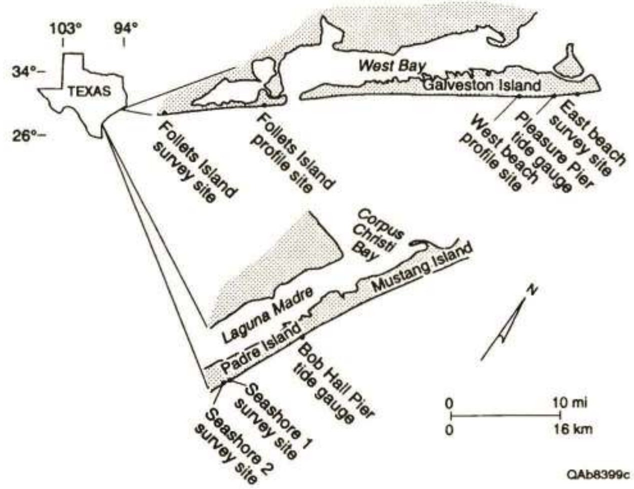

Figure 1. Locations of beach survey and profile sites on Galveston, Follets, and North Padre Islands, Texas and locations of nearest tide gauges used to establish water levels and tidal datums on the beach.

Objective

One primary objective of this study was to document the simultaneous horizontal positions and elevations of (1) morphological features on the beach, (2) the mean higher high water (MHHW) line, (3) the observed instantaneous high-water line (including wave runup), and (4) the predicted instantaneous high-water line as determined by water levels recorded at nearby tide gauges operated by the National Ocean Service (Figure 1). Another objective was to monitor the position of MHHW so that seasonal movement of a tidal boundary could be established and related to beach profiles routinely measured by coastal geologists and engineers. The purpose of this second task was to test the assertion by some water-level experts and court documents that the mean high water (MHW) line either does not move or moves imperceptibly during an 18.6 year tidal epoch (ROBERTS, 1960).

Numerous studies have monitored beach profiles for a year or more (for example SONU and VAN BEEK, 1971; WINANT *et al.,* 1975; SMITH and ZARILLO, 1990; and THOM and HALL, 1991). However, no prior study has simultaneously tracked and analyzed the movement of the vegetation line, berm crest, instantaneous high water line, and mean high water line, which are all used as the shoreline proxy or a legal littoral boundary.

The primary objectives of this study were accomplished by analyzing a data set of six beach profiles surveyed bi-weekly to monthly in 1995 and 1996 by the Texas General Land Office. The detailed surveys were conducted at two sites within Padre Island National Seashore, and were correlated to the tide gauge at Bob Hall Pier near Corpus Christi, Texas (Figure 1). This one-year time series was supplemented with two single-day surveys conducted on the Gulf beaches of Galveston Island and Follets Island that were correlated to the Pleasure Pier tide gauge at Galveston, Texas (Figure 1).

Geologic Setting

Beaches of the Texas Gulf Coast are in a microtidal storm-dominated region that is constantly changing as a result of active coastal processes directly linked to meteorological events. Wind-driven waves and currents are the most important geological agents controlling sediment transport onto and off of the Gulf beaches. Fair-weather Gulf waves in water depths of 3 to 5 m are normally 30 to 60 cm high and have periods of 2 to 6 sec (BRETSCHNEIDER, 1954; U.S. ARMY CORPS OF ENGINEERS, 1983). The broad shallow continental shelf bordering the Texas coast causes deep-water swell in the Gulf to decompose into these low, short-period waves. The largest deep-water waves in the Gulf are as much as 22 m high and have periods of about 16 sec. These hurricane-generated waves break far from the shoreline because of the shallow shelf. The waves reform and repeatedly break, creating a wide surf zone encompassing as many as nine bands of breakers that contribute to the landward transfer of water and eventual wave runup on the beach.

In the northern Gulf of Mexico, the direction and strength of predominant winds are seasonally distributed and the winds control the inundation of Gulf beaches several times each year. During the winter and early spring, dramatic changes in water level accompany the passage of cold fronts (DAVIS and FOX, 1975). As masses of Arctic air move southward toward the coast preceding a cold front, low barometric pressures and exceptionally strong onshore winds combine to flood the Gulf beaches to the vegetation line. After the front crosses the coast, wind directions reverse and strong winds blow offshore, abruptly lowering water levels and greatly reducing wave energy in the Gulf. During the winter, a cold front passes across the coast about every 10 to 12 days. Beaches are also flooded in the mid to late summer when tropical cyclones enter or are generated within the Gulf of Mexico. Highest sustained wind speeds and water levels accompany tropical storms and major hurricanes, which cross the coast about every 1.5 years (HAYES, 1967).

Astronomical tides in the Gulf of Mexico are diurnal or mixed and during a normal tidal cycle, water levels vary less than 66 cm between high and low tide (U.S. ARMY CORPS OF ENGINEERS, 1983). The wind-induced changes in water level are commonly larger than those caused by the astronomical tides. Wind stress coupled with changes in barometric pressure often cause water levels on Gulf beaches to be raised or lowered as much as one meter compared to the predicted astronomical tides.

All the beaches that were surveyed for this study are composed of well-sorted fine sand, and they all exhibit a well-developed berm crest during the constructional phases of seasonal beach fluctuations. The field surveys in 1995–1996 for this study were conducted on relatively stable beaches so the data of seasonal fluctuations would not include a systematic bias related to long-term retreat or advancement of the beach. East Beach of Galveston Island and the beaches of North Padre Island have undergone short-term cycles of advance and retreat, but their long-term position has remained relatively stable (PAINE and MORTON, 1989; MORTON, 1997). Water level positions are also included for the surveyed beach

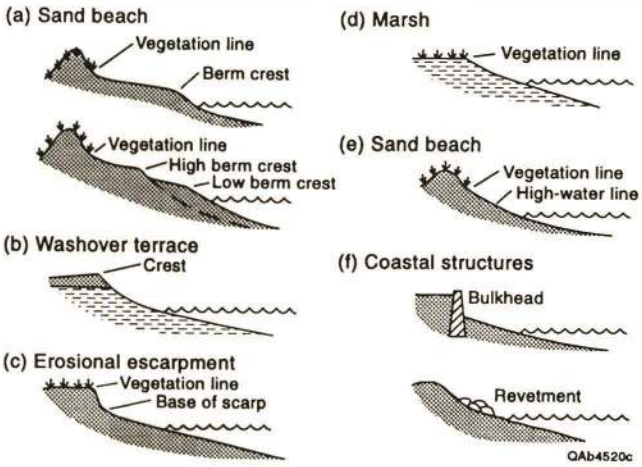

Figure 2. Generalized beach profiles illustrating typical beach morphologies and associated shoreline features observed in the study area. The profiles represent (a) sand beach with single and multiple berm crests, (b) sandy washover terrace overlying a mud beach, (c) erosional scarp, (d) marsh vegetation line, (e) concave erosional sand beach without berm crest, and (f) common small-scale coastal structures.

on Follets Island, which has undergone long-term retreat at average rates of about 1 m/yr (MORTON, 1997).

SHORELINE MONITORING FEATURES

Shoreline movement is documented by monitoring the positions of beach features that are leading indicators of beach movement. This means that the monitored feature should respond to changes in environmental conditions but should not be so sensitive to fluctuations in local conditions that it gives spurious results if monitored in the field or on aerial photographs. Typical morphological features on sandy and gravel beaches are the berm crest, erosional scarp, vegetation line, and crest of the washover terrace (Figure 2). In the absence of a more reliable morphological feature, the high water line or wet-beach/dry-beach line may be used as the shoreline proxy. Shoreline positions may also be defined by hard structures or other artificial features that largely constrain the inland extent of high water.

Berm Crest

The berm crest (Figure 2*a*) is the morphological feature that separates the steeper forebeach from the gentler sloping backbeach. It is a depositional feature when constructed by runup of normal waves (generally summer conditions) and a destructional feature when eroded by waves at abnormally high water levels (generally winter conditions). The berm crest may be entirely eroded by high storm waves, transforming the beach into a broad, featureless surface that slopes seaward uniformly.

Some beaches have two berm crests: a high crest and a low crest (Figure 2*a*). Multiple berm crests are constructed by erosion of the backbeach and subsequent deposition on the forebeach by onshore migration of a sand bar and runup by low waves. Eventually the low berm will increase its height and merge with the high berm or the cycles of erosion and partial recovery will be repeated. Where there are multiple berm crests, the highest, most landward crest may be used as the shoreline monitoring feature because it is more stable and responds to events of lower frequency than the lower berm crest. Laterally along the beach, the berm crest may become steeper and change to a mid-beach erosional scarp (Figure 2*c*) or it may flatten, become indistinct, and grade into a concave beach profile without a berm crest (Figure 2*e*).

Erosional Scarps and Bluffs

Erosional scarps and bluffs are destructional features that are located in the mid-beach or form an abrupt break in slope at the landward limit of the backbeach (Figure 2*c*). Bluffs and backbeach scarps normally represent the long-term beach morphology and they typically coincide with the vegetation line. In contrast, mid-beach scarps are ephemeral features that are excavated during a rapid rise in water level when waves approach the shore at a high angle and generate strong alongshore currents, or a mid-beach scarp may be constructed when the forebeach gradient is extremely steep such as after a beach nourishment project. Backbeach scarps typically grade into low dunes or washover terraces (Figure 2*b*), whereas mid-beach scarps generally pass laterally into high berm crests (Figure 2*a*).

Vegetation Line

On beaches and in wetlands, the vegetation line (Figure 2*a*, 2*c*, 2*d*, 2*e*) is a biological indicator of the limits of regular flooding by high water and therefore it represents a nearly ideal indicator of shoreline movement. Plants that colonize the dunes and backbeaches can tolerate salt spray but they cannot survive if their roots are submerged in saltwater for prolonged periods. The vegetation line can be a more reliable indicator of long-term shoreline movement than the high water line because it is not affected by short-term variations in water level.

Two factors prevent the vegetation line from being an ideal mapping boundary. First, the vegetation line is a biological feature that responds to terrestrial environmental conditions in addition to those oceanic conditions that control beach morphology and shoreline position. For long periods (decades) the vegetation line will naturally reflect beach movement, but the vegetation line on sandy beaches can move independently of and in directions opposite to those of the beach for short periods (MORTON, 1974). Second, the vegetation line is not always a distinct, easily identifiable feature and it exhibits alongshore irregularities in planform. On many stable or advancing sand beaches, there are two vegetation boundaries that can be mapped; a line of older dense vegetation that spreads continuously inland, and a line of younger sparse vegetation adjacent to the bare backbeach (MORTON, 1974). The line of dense vegetation marks the most stable position beyond which the beach is typically unaffected by most storm surges. The zone of sparse vegetation consists of low sand mounds or dunes that have accumulated since the last major storm but have not coalesced to form a more continuous ridge of vegetated dunes, or there may be a natural zonation in plant assemblages such as sparse, relatively young vines and grasses versus more mature woody vegetation.

The vegetation line is also subject to either deliberate or unintentional manipulation and artificial stabilization. On some developed beaches, position of the vegetation line is at least partly controlled by property owners or beach scraping activities. Property owners erect sand fences, plant dune grasses, and engage in other activities that tend to encourage the accumulation of sand and seaward advancement of the vegetation line.

Artificial dunes have also been created in conjunction with beach raking and scraping. Beach cleaning inadvertently mixes some sand with the beach debris. To keep the sand on the beach, piles of sand and trash commonly are pushed into the backbeach where they become vegetated and act as low dunes. Along some beach segments, the piles of sand and debris form a zone as much as 40 m wide, which represents an artificial advancement of the vegetation line.

In wetlands, such as salt-water marshes, the vegetation line is typically lower in elevation and seaward of the high water line because the wetland plants require frequent flooding to survive. Despite this discrepancy between the shoreline and the high water line, the marsh vegetation line is a good indicator of shoreline movement.

Crest of Washover Terrace

Washover terraces (Figure 2*b*) are deposited where beaches are highly erosional and adjacent ground elevations are lower than the highest storm surges. The terraces are composed of sand with or without high concentrations of shell and rock fragments. Where they are present, the crest of the washover terrace forms the highest beach elevation and is the best indicator of shoreline movement for these types of beaches. Terrace crests can pass laterally into backbeach erosional scarps (higher elevations) or marshes (lower elevations). During storm washover, beach sand and shell are transferred onshore burying adjacent marsh or upland vegetation and concealing the vegetation line until either the vegetation grows through the washover deposit or new vegetation colonizes the washover surface.

High Water Line

Some rapidly retreating beaches exhibit a concave upward profile that lacks a distinct berm crest (Figure 2*e*). The instantaneous high water line is commonly mapped on aerial photographs as the shoreline proxy because it is easily identified (STAFFORD, 1971; DOLAN and HAYDEN, 1983; LEATHERMAN, 1983: MORTON, 1991) and because there is an implied or assumed correlation between the instantaneous high water line and the mean high water line. However, field surveys clearly show that the position of the high water line is a function of beach morphology, water level, and wave characteristics immediately preceding the field observation or photographic mission.

Table 1. *Instantaneous maximum and average high water elevations and distances compared to elevations and distances of beach features on East Beach, Galveston Island January 27, 1995. Distances are measured from the vegetation line.*

Tidal Datum or Beach Feature	Elevation (m)	Distance (m)
Vegetation line	1.50	0
Berm crest	1.20	36
Average of highest monthly water levels (1958–1986)	1.02*	39
Mean higher high water line (MHHW)	0.36*	61

* Galveston tide gauge measurement

Coastal Structures

On some developed beaches, the most prominent shoreline features are coastal structures erected parallel to the shore (Figure 2*f*). Such structures include bulkheads, seawalls, and revetments that are designed to protect the adjacent upland property from flooding by high water and erosion by storm waves. Coastal structures have variable lengths parallel to the beach. Some structures are more than 15 km long whereas others may extend only the width of a single lot (25 m). Because coastal structures are products of human intervention, they have discrete lateral limits and can be adjacent to any other type of shoreline or shoreline feature.

Coastal structures such as seawalls and bulkheads do not always indicate that the beach is eroding and they are commonly constructed on stable or advancing beaches to prevent storms from damaging upland property. In these situations, the coastal structure is landward of the shoreline feature that should be used for monitoring beach movement. On retreating beaches, coastal structures form the shore and coincide with the landward limit of annual flooding by high water. Where beaches are highly erosional, coastal structures may fail physically and the shore will continue to retreat, thus establishing a new shoreline feature or another coastal structure position for monitoring.

RECORDED VERSUS ACTUAL WATER LEVELS

The instantaneous high water line observed in the field and on aerial photographs has been described as closely approximating the position of mean high water (MCBETH, 1956; SHALOWITZ, 1964; STAFFORD, 1971). This assertion, which has been perpetuated by coastal engineers and land surveyors, was tested by simultaneously comparing water levels recorded at tide gauges and water levels observed on nearby beaches at three beach locations in Texas (Figure 1, Tables 1–4). For this study, beach elevations and water levels surveyed by licensed land surveyors were available for only one time at Follets Island and Galveston Island (Table 2), whereas six beach profile sites on North Padre Island were surveyed 18 times in a year to examine the temporal and spatial variability in beach features. The six North Padre Island profile sites are within the Padre Island National Seashore. They consist of two locations (SS1 and SS2), about 1.6 km apart, with three profiles 15 m apart at each location. The position of the vegetation line at SS1 is influenced by vehicular traffic and beach cleaning activities, whereas the beach

Table 2. *Comparison of elevations and horizontal distances between actual (HWa) and gauged (HWg) high water levels, and distances between the vegetation line (VL) and mean higher high water line (MHHW) on three Texas beaches.*

Location	Date	Δ Elevation HWa-HWg (m)	Δ Distance HWa-HWg (m)	Δ Distance MHHW-VL (m)	Source
Follets Is.	05-14-56	0.73	45.1	53.7	Pope (1958)
Galveston Is.	01-27-95	0.59	18.0	61.0	D. Shine*
N. Padre Is.	08-16-95†	0.36	8.2	37.9	Texas General Land Office*
N. Padre Is.	09-14-95†	0.19	8.1	36.0	Texas General Land Office*
N. Padre Is.	09-28-95†	0.19	11.6	34.1	Texas General Land Office*
N. Padre Is.	10-06-95†	0.30	6.0	38.5	Texas General Land Office*

† Average of six sites, from Table 4

* Personal communication

at SS2 is in a natural area of the park where vehicular traffic and beach scraping are not allowed.

The land survey conducted on Follets Island in 1956 used the MHW line as the legal boundary separating public lands from private property, whereas the MHHW line was used in the most recent surveys of Galveston and North Padre Island (Tables 1–4). The tide range is so low in the western Gulf of Mexico that the elevation difference between the MHW line and the MHHW line is minor (~0.07 m). Consequently, any observations made regarding the MHW and MHHW lines are essentially the same.

Galveston Island

Comparisons of physical features surveyed on East Beach of Galveston Island in 1995 and water levels recorded at the nearby tide gauge at Galveston demonstrate that there are significant differences in elevation between the vegetation line, highest observed water on the beach, highest water recorded at the tide gauge, the berm crest, and the MHHW line (Table 1, Figure 3). The berm crest is the physical manifestation of ordinary high water positions associated with wave runup, and yet the mean elevation of the highest monthly tides recorded at the Galveston gauge for 29 years (1958–1986) plots 0.2 m lower and 3 m seaward of the berm crest, and the MHHW line plots 0.84 m lower and 25 m seaward of the berm crest (Table 1, Figure 3). The MHHW legal boundary also plots 1.14 m below and 61 m seaward of the vegetation line, which is the physical/biological marker of regular beach inundation by marine water. Instantaneous high water levels observed on East Beach and projections of water levels recorded at the same time at the tide gauge have a difference of 0.59 m elevation and a horizontal separation of 18 m (Table 2). These instantaneous differences in water elevation and position are similar to the differences in elevation and distance between the berm crest and MHHW line.

Table 3. *Differences in vertical elevations between the mean higher high water line (MHHW) and the vegetation line on three Texas beaches.*

Location	Veg. Line Elev. (m)	MHHW Elev. (m)	Δ Elev. (m)	Source
Follets Island*	2.50	1.40	1.10	Pope (1958)
Galveston Island	1.50	0.36	1.14	D. Shine
North Padre Island	1.57	0.45	1.12	Texas General Land Office

* Elevations appear to be about 1 m high

Each year on Galveston Island, saltwater from the Gulf of Mexico regularly floods the backbeach and dunes to the vegetation line. However, a 29 year plot of the maximum water level recorded each month between 1958 and 1986 at the Galveston tide gauge implies that the water only reached the elevation of the vegetation line briefly in 1961, 1971, and 1983 (Figure 4). These three super-elevated water events were associated with storm surge flooding during Hurricanes Carla, Fern, and Alicia. The differences in elevation between the vegetation line and the maximum measured monthly water levels also indicate that the tide gauge underestimates actual beach water levels by at least 0.5 to 0.75 m.

Follets Island

More than forty years ago, Pope (1958) presented tide gauge records and field data from Follets Island (Figure 1) that showed significant differences between the actual elevations and positions of water on the beach and those predicted by tide gauge measurements (Tables 2 and 3). A ten-year record (1946–1956) of weekly high-water levels from the Galveston tide gauge suggested that the water never reached the elevation of the vegetation line. These predictions made by a Federally maintained tide gauge were clearly in error despite the fact that surveyors and local residents observed that the beach was entirely inundated to the vegetation line several times each year.

The beach survey on Follets Island showed that the vertical and horizontal difference between the actual high water position observed on the beach and the high-water position predicted from the tide gauge was 0.73 m and 45 m, respectively (Pope, 1958; Table 2). At the same location and at the same time, the difference in elevation between the MHHW line and the vegetation line was 1.1 m, and the horizontal displacement between the MHHW line and the vegetation line was 53.7 m (Tables 2 and 3).

North Padre Island

On North Padre Island (Figure 1), the variability of wave runup alongshore at the same time and at different times of the year are captured in beach surveys at six different sites and at four different times (Figure 5, Table 4). The differences in observed and recorded instantaneous high water el-

Table 4. *Difference in horizontal distance and elevation between instantaneous high water levels observed (HWa) on North Padre Island beaches and the positions predicted at the same time from the Bob Hall Pier tide gauge (HWg). Units of measurement are meters. Average Δ distance is 8.5 m and average Δ elevation is 0.26 m.*

			Δ Distance	HWa-HWg		
Date	SS1 Base	SS1 North	SS1 South	SS2 Base	SS2 North	SS2 South
8-16-95	9.06	8.27	9.82	7.78	5.70	8.69
9-14-95	8.91	14.46	4.42	10.52	8.05	2.47
9-28-95	13.57	7.53	9.58	14.21	13.02	11.74
10-06-95	7.93	5.49	7.14	5.61	4.88	4.73
			Δ Elevation	HWa-HWg		
8-16-95	0.33	0.33	0.45	0.34	0.40	0.32
9-14-95	0.22	0.13	0.14	0.18	0.19	0.26
9-28-95	0.18	0.17	0.23	0.16	0.21	0.17
10-06-95	0.27	0.35	0.32	0.29	0.28	0.29

evations range from 0.13 to 0.45 m and average 0.26 m. For these fine-grained sandy beaches the horizontal displacement of the observed and predicted position of high water ranges from 2.5 to 14.5 m and averages 8.5 m (Table 4). There is considerable scatter in the data and generally they are distributed throughout the range from 5 to 14 m (Figure 6).

SHORT-TERM AND LONG-TERM FLUCTUATIONS IN BOUNDARY POSITION

In order to delineate the extent of marine and upland property, land owners and the courts have sought a seashore property boundary that is simple to identify, that is stable in position through time, and that is repeatable by different surveyors (LIPSCOMB, 1957). Coastal scientists understand that the sea and adjacent sandy shores are not stable features, and the position of any tidal datum (legal boundary) or geomorphic feature changes position frequently as the beach responds to changing environmental conditions. Unfortunately some legal opinions are still made assuming that property boundaries surveyed from tidal datums are stable and predictable. Also, some recent reports pertaining to accurate shoreline mapping still assert that the instantaneous high water line (wet beach-dry beach boundary) is a reasonable proxy for shoreline position and imply that it is suitable for long-term trend analysis of shoreline movement (DOLAN *et al.*, 1991; MORTON, 1991; CROWELL *et al.*, 1993; THIELER and DANFORTH, 1994; MCBRIDE and BYRNES, 1995).

To test the ideas of stable and representative beach boundaries, bi-weekly to monthly surveys at six sites on North Padre Island were surveyed for a year to evaluate the temporal and spatial variability in positions of the MHHW line, the instantaneous high water line, the berm crest, and the vegetation line. Results of the North Padre Island field surveys (Figure 7) show two different trends in beach variability, one of cyclical fluctuations (fall of 1995 through spring 1996) and the other related to a systematic increase in subaerial sediment volume and associated advancement of the beach (summer 1996).

Of the beach features surveyed, the vegetation line is the most stable observable boundary that is controlled by regular flooding associated with high water levels. The minor landward shift of the vegetation line in the fall of 1995 (Figure 7) was caused by a weak seasonal storm that locally increased water levels and wave heights. The storm flooded the backbeach and deposited about 30 cm of sand at and slightly landward of the vegetation line. The vegetation line quickly re-

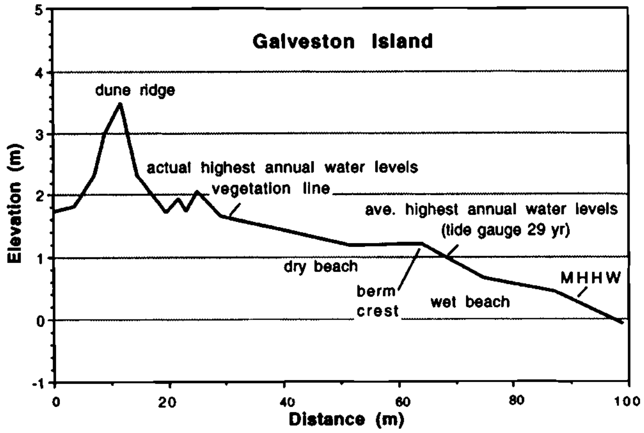

Figure 3. Beach profile at Galveston Island showing differences in water levels observed on the beach compared to the levels recorded at the Galveston Pleasure Pier tide gauge. Locations shown in Figure 1.

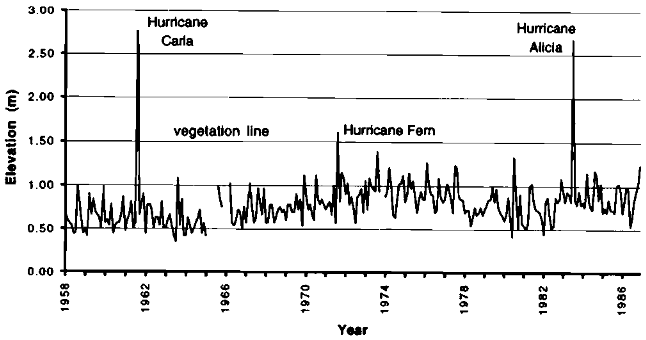

Figure 4. Maximum monthly water levels recorded at the Galveston Pleasure Pier tide gauge from 1958 to 1986. Water actually reaches the vegetation line (1.5 m elevation) several times each year.

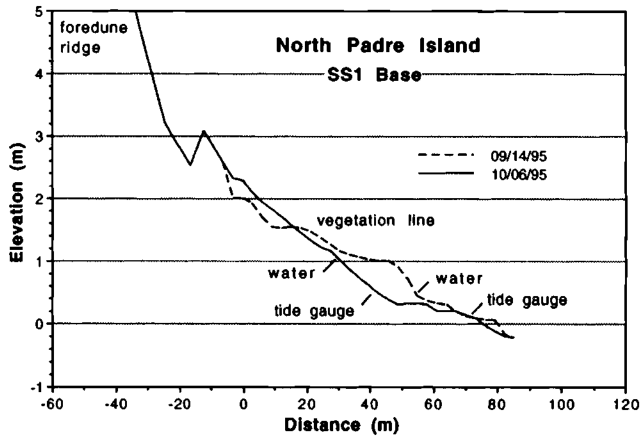

Figure 5. Beach profiles at North Padre Island Seashore 1 Baseline showing for two different times the instantaneous differences in water levels observed on the beach compared to the levels recorded at the Bob Hall Pier tide gauge.

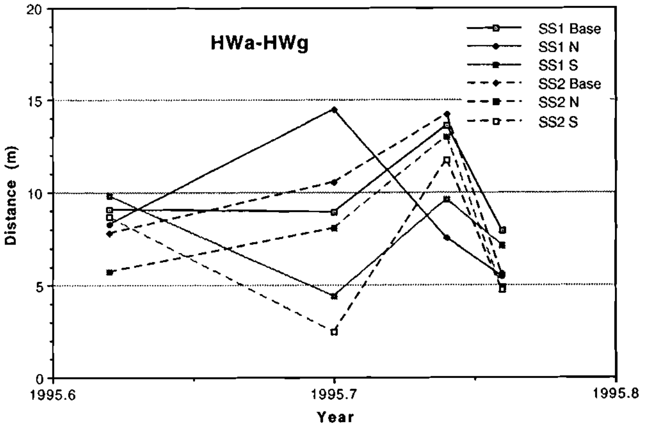

Figure 6. Plots of the horizontal distance between the actual position of instantaneous high water on the beach at North Padre Island and the position simultaneously predicted by the water level recorded at the Bob Hall Pier tide gauge.

covered to its pre-storm position as the buried vegetation grew through the washover deposit. The vegetation line remained in approximately the same position throughout most of the year except for the minor retreat after the storm and minor advance at the end of the second summer when the entire beach at SS2 advanced (Figure 7).

The instantaneous high water line and the berm crest are the least stable beach features surveyed. Within a year at the North Padre Island sites they migrated 40 and 50 m respectively. Movement of the instantaneous high water line and the berm crest are closely correlated to cycles of beach aggradation and degradation (Figure 7). The berm crest is destroyed and the high water line penetrates farther inland after high energy events and the berm crest rebuilds and forces the high water line seaward during periods of beach aggradation and onshore bar migration. The instantaneous high water line seldom coincides with the berm crest or with the MHHW line. It usually is seaward of the berm crest but it can also be landward of the berm crest when slowly rising water floods the backbeach (spring tides) without completely eroding the berm.

The MHHW line is slightly more stable than the berm crest or the instantaneous high water line, but is substantially less stable than the vegetation line in both the magnitude and frequency of its fluctuations (Figure 7). Positions of the MHHW line form an envelope about 20 m wide, and no two consecutive surveys of the MHHW line were in the same position. Furthermore, the MHHW line was not in the same position at the beginning and at the end of the one-year monitoring period. The vegetation line, on the other hand, was consistently in the same or similar position.

Some tidal boundary surveyors, lawyers, and water level experts also assert that the long-term average positions of tidal boundaries are stable and that they remain in essentially the same position for several years or a 19 year period (LIPSCOMB, 1957; ROBERTS, 1960; WINTERS, 1960; C. THURLOW, personal communication, 1995). This assertion can be traced back to the seminal court case of *Borax Consolidated Ltd. vs. City of Los Angeles* tried in 1935 (MALONEY and AUSNESS, 1975; COLE, 1997). This lawsuit established the use of average water level recorded at a tide gauge for an 18.6 year epoch as the accepted scientific method of determining a legal littoral boundary in the United States. Those individuals who claim that a surveyed shoreline is stable are confusing the vertical tidal datum, which changes little during a tidal epoch, with the horizontal intercept of the vertical datum on the beach, which is completely free to advance or retreat depending on sediment supply and oceanic conditions.

Although these same experts recognize that the boundary can change horizontal position due to accretion or erosion over a period of years, they fail to recognize that these same processes operate at much higher frequencies producing rap-

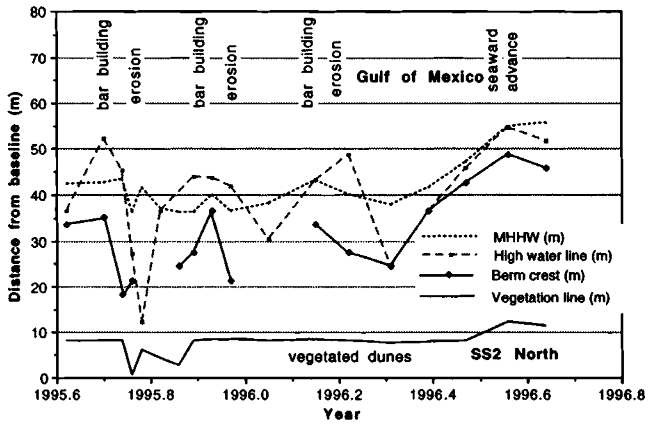

Figure 7. One year summary of fluctuations in the vegetation line, berm crest, instantaneous high water line, and mean higher high water line at Seashore 2 survey site on North Padre Island. Rapid and erratic movement of the mean higher high water line is shown.

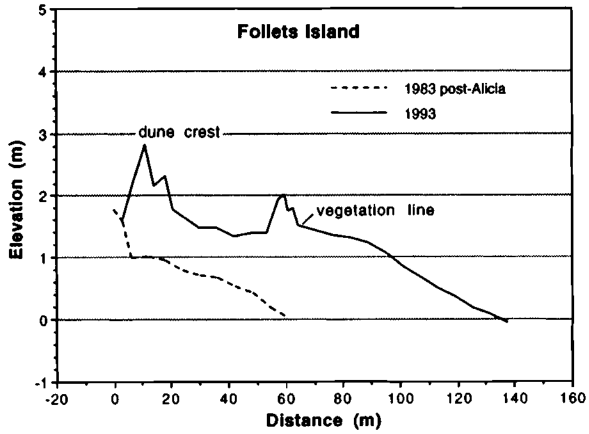

Figure 8. Ten-year evolution of an advancing beach on Follets Island. Beach profile location shown on Figure 1.

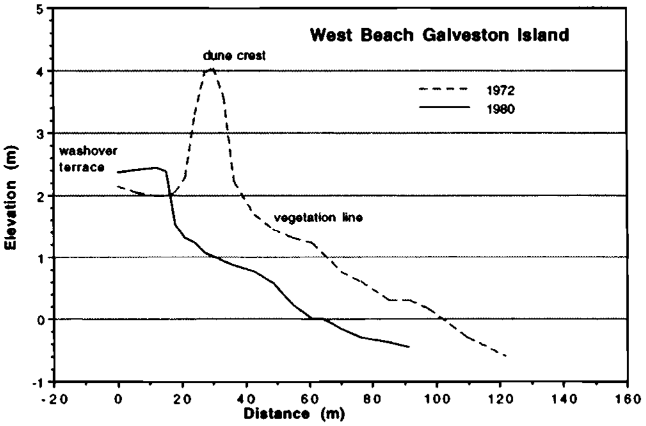

Figure 9. Eight-year evolution of a retreating beach on West Beach, Galveston Island. Beach profile location shown on Figure 1.

id and perceptible changes in the seashore boundary (Figure 7).

Topographic profiles from Follets Island and Galveston Island that span nearly a decade, illustrate that any legal boundary projected on the beach surface is directly linked to the long-term systematic movement of the beach (Figures 8 and 9). Beaches composed of mobile sediment, even those few that occupy the same average position over long periods of time, vary in horizontal position as a result of changing oceanic conditions (wave energy and angle of approach, water level fluctuations, changes in sediment supply).

DISCUSSION

Field surveys of the instantaneous high water position and water levels simultaneously recorded at the nearest tide gauge show that the recorded water levels are consistently lower than the actual elevations of high water on the beach. The horizontal offset between water levels recorded at a tide gauge and those measured on nearby beaches is directly related to wave runup, which is controlled by the shape and steepness of the beach as well as its composition and the degree of water saturation (NIELSEN and HANSLOW, 1991). Wave conditions and tidal stage can also influence the magnitude of wave runup.

Horizontal runup of waves was greatest at the Follets Island beach site and least at the North Padre Island beach sites (Table 2) because elevations are generally lower and the berm crest is less well developed on Follets Island compared to North Padre Island.

The instantaneous positions of the berm crest, high water line, and the MHHW line are controlled by beach morphology, water level, and wave characteristics immediately preceding the field surveys. In contrast, the vegetation line is much less sensitive to high frequency (daily, weekly, monthly) fluctuations in beach shape, and it responds to lower frequency changes in beach sediment volume. The elevation and horizontal position of the vegetation line are not constant, but the variability of its position is minor during annual changes in beach morphology. The MHHW elevation is constant, but the fluctuations in horizontal position of the MHHW are much greater than those of the vegetation line and they are not as predictable as those of the vegetation line.

The vegetation line occupies one of two positions; its normal spring and summer advanced position and a post-storm recessed position that is established after a high water event floods the backbeach and either deposits sand on the existing vegetation or erodes to a sufficient depth that the vegetation, including the roots, is entirely removed. Recovery of the vegetation line to the advanced position is more rapid after burial but slow after the root system has been destroyed by erosion (MORTON and PAINE, 1985).

The detailed time series data from North Padre Island show that the MHHW line is not a stable property boundary and it can move 10 to 15 meters in a few weeks (Figure 7). The data also show that the trends of the seasonal fluctuations are similar at all profiles, but there is intersite variability in the magnitudes of the changes due to beach dynamics and minor variations in beach shape, such as the positions of beach cusps at the time of the survey.

SCIENTIFIC AND LEGAL IMPLICATIONS

Shoreline Mapping

Since the concept of monitoring shorelines from aerial photographs was first proposed, there has been an ongoing debate regarding the most appropriate proxy for shoreline position along coasts where beach morphologies are diverse. The wet beach/dry beach boundary, also referred to as the instantaneous high water line, has been widely accepted as the reference feature for mapping shorelines (STAFFORD, 1971; DOLAN and HAYDEN, 1983; LEATHERMAN, 1983; SMITH and ZARILLO, 1990; BYRNES *et al.*, 1991; DOLAN *et al.*, 1991; MORTON, 1991; CROWELL *et al.*., 1993, THIELER and DANFORTH, 1994; MCBRIDE and BYRNES, 1995). The wet-beach/dry beach boundary was adequate for a first approximation of shoreline movement and before our present understanding that the instantaneous high water line is an unstable feature that moves frequently throughout the year (Figure 7). However, the lack of agreement between the instantaneous high water line, berm crest, or MHHW, and the large variability associated with the instantaneous high water line make it unsuitable for future monitoring of beach movement.

For shores composed of erodable material, the stability of shoreline features increases landward and the frequency of movement of a shoreline feature increases seaward. Consequently, the vegetation line, crest of washover terrace, erosional scarp, or bluff toe are more stable than the berm crest or the instantaneous high water line. However, redefining the shoreline as the erosional scarp, vegetation line, or crest of the washover terrace instead of the instantaneous high water line or berm crest may result in a landward shift of the mapped shoreline feature and an apparent change in the rate of movement for the period that includes the redefined shoreline. The magnitude of the discrepancy and apparent shift in shoreline position attributed to redefinition is the ground distance between the newly defined and previously defined features.

In some coastal regions, aerial photographic missions are commonly flown in the winter after a cold front passes the coast because then the atmosphere is clear and there are no clouds to block the view of the camera. Preceding passage of a cold front is also the time when low barometric pressure and strong onshore winds typically cause abnormally high water and flooding of the backbeach. Under these conditions the high water line depicted on aerial photographs corresponds to the vegetation line, erosional scarp, or other backbeach feature regardless of whether the forebeach morphology is characterized by a convex profile with a berm crest or a concave profile without a berm crest. Beach observations during the past 25 years clearly demonstrate that (1) the instantaneous high water line responds to high frequency events and therefore does not have any particular physical significance regarding long-term shoreline movement, and (2) the lateral mobility of the high water line results in noisy data sets and may be responsible for apparent cycles of shoreline advance and retreat that are only a function of sequential differences in water levels and not actual changes in beach sediment volume (MORTON, 1991).

It has been suggested that the effects of water level variability on regional mapping of coastal boundaries can be minimized by coordinating aerial photographic missions with water levels recorded at the nearest tide gauge. Proponents of this technique assert that the shoreline is marked by the water at a particular tidal datum, such as mean high water, but they acknowledge that wave runup will cause water levels to be higher than predicted by the gauge (L. LAPINE, National Geodetic Service, personal communication, 1997).

Accurate prediction of future shoreline positions depends primarily on reducing the extraneous variability that currently is in many of the older long-term data sets of shoreline positions. A key to improving predictions is understanding the variability, eliminating it if possible, or reducing its influence, especially in future measurements. Several studies have examined the physical sources of intrinsic shoreline variability present in most measurements of shoreline position. SMITH and ZARILLO (1990) and DOLAN *et al.* (1991), among others, have identified several sources of short-term temporal variability in shoreline positions derived from beach surveys and aerial photographs. Short-term variability in shoreline position is attributed to frequent fluctuations in water levels such as wave swash, seasonal fluctuations in beach morphology, annual tidal harmonics, and storm elevated water.

There are at least three primary sources of variability in shoreline position that currently are not differentiated in most data sets used to calculate rates of change and to predict future shoreline positions. Large scale, high-frequency fluctuations of the instantaneous high water line or berm crest (Figure 7) probably represent the largest source of variability in most data sets, especially those derived from aerial photographs. These random fluctuations in shoreline position can be eliminated by monitoring a more stable beach feature such as the vegetation line, base of dunes, base of bluff, or erosional scarp. In data sets that incorporate immediate post-storm shoreline positions, a source of large-scale, low frequency variability is the rapid recession of the shore caused by the storm, and slow advancement of the shoreline either by natural processes or as a result of artificial activities (bulldozing, beach replenishment, sand fences). Although the maximum observed magnitude of shoreline retreat associated with a storm is important information for hazards management, it should not be included in the data sets that are used to predict long-term trends and rates of shoreline movement because the bias is so great it may mask the true trend of shoreline movement. A third source of shoreline variability is the cyclical change in shoreline position associated with fluctuations in sediment supply. This variability represents real advances and retreats of the shoreline that are common near tidal inlets, shoals, and other geologic features where impoundment and release of sediments is episodic but the trends are not predictable in terms of volume or duration.

Boundary Determination

Location of the shoreline, or boundary between state-owned submerged land and upland property, has been complicated in recent decades by various rulings of the courts and the introduction of tide gauge measurements as a basis for determining the average and highest water levels reached on the beach. Prior to the widespread use of tide gauges for oceanic boundary determinations, land surveyors routinely used morphological features and field evidence (drift lines, changes in surface gradient, vegetation) to establish the position where a shore was regularly inundated, which by common law is the boundary separating public and private property. In a landmark decision in the United States (*Borax Consolidated Ltd. vs. City of Los Angeles*), tide gauge records were established as a simple, mathematically precise, and reliable source of data that could be used by land surveyors to predict where water would regularly inundate the beach, and thus to determine the position of the land boundary and associated property rights.

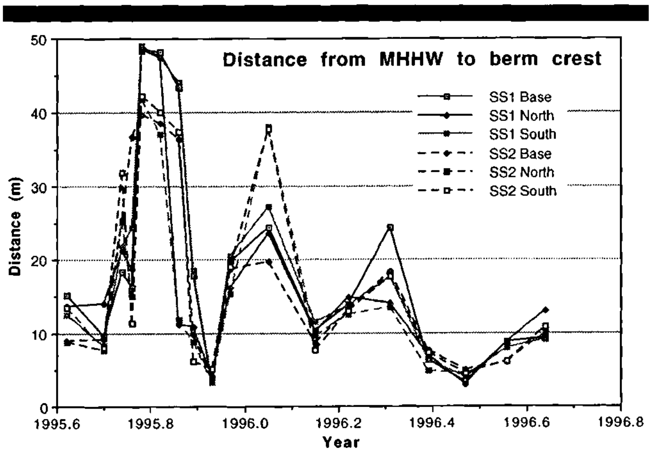

Figure 10. Simultaneous distances between the mean higher high water line and the berm crest at each of the six beach profile sites on North Padre Island. The one-year plot represents the differences between average ordinary high water levels marked by a physical feature on the beach (berm crest) and the statistical mean of the higher high water levels recorded at the nearest tide gauge.

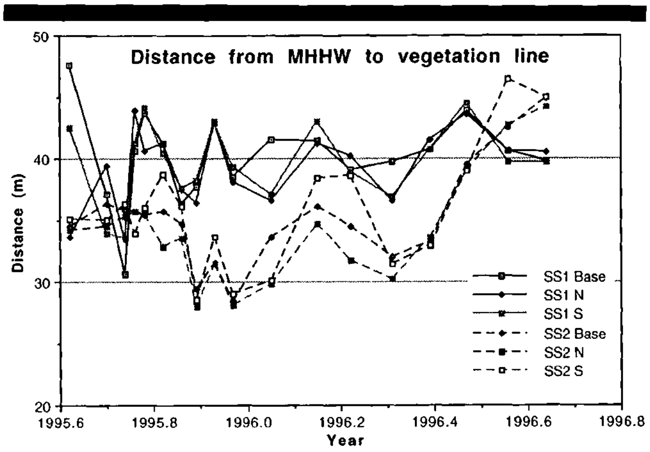

Figure 11. Simultaneous distances between the mean higher high water line and the vegetation line at each of the six beach profile sites on North Padre Island. The one-year plot represents the differences between the limit of regular beach flooding by the highest water levels marked by a physical feature on the beach (vegetation line) and the statistical mean of the higher high water levels recorded at the nearest tide gauge.

Beach profiles and water level data from the Texas coast provide three independent estimates of the difference between water levels observed on the beach and those predicted from tide gauges. One estimate is provided by the distance of instantaneous wave runup, which ranges from 2.5 to 45 m (Tables 2 and 4). These values, like many other instantaneous measurements in a times series, exhibit high variability that is difficult to evaluate. In physical terms the variability is associated with wave climate, tidal phase and stage, and beach morphology.

Another method of estimating the horizontal difference between predicted and actual high water levels is to compare the distance between the MHHW line and the berm crest. This method correlates the mathematical long-term average of highest daily water levels on the beach (tide gauge records) with a physical beach feature that also is a product of daily high water levels. Horizontal distances between the MHHW line and the berm crest on North Padre Island range from 3 to 49 m (Figure 10), which is similar to the range for instantaneous wave runup. Horizontal distances between the MHHW line and the berm crest are controlled by beach morphology. The greatest separation occurs when the berm crest is recessed or eliminated (broad flat beach) after a high wave energy event erodes the beach and the berm crest is an erosional feature located in what is normally the backbeach. Predicted and actual ordinary high water levels agree closely only when the beach is gaining sand volume, the berm crest is well defined, and the forebeach is relatively steep. Those periods of optimum agreement (least difference in horizontal offset) occur during periods of bar building and beach recovery as the beach advances seaward and the berm elevation is lowered, or when the beach width is fully developed, such as during summer conditions (compare Figures 7 and 10).

The effects tide gauge records have on water level boundaries can also be evaluated by examining the differences in elevation and distance between maximum annual beach flooding, defined by the vegetation line, and the MHHW line. The differences in elevation between MHHW and the vegetation line at all three beach survey sites in Texas are nearly identical (Table 3). This means that backbeach flooding to a height of about 1 meter above MHHW is common on these low gradient sand beaches. Most of the beach profile data for one year from North Padre Island show that the MHHW line is between 30 and 45 m seaward of the vegetation line (Figure 11, Table 2), whereas the instantaneous measurements between the vegetation line and the MHHW line at Follets and Galveston Islands are somewhat greater, 54 and 61 m respectively (Table 2). Perhaps a better comparison for the beach at Galveston Island is the 39 m horizontal separation between the vegetation line and the position of the 29 year average position of highest monthly water levels (Table 1).

Establishment by the courts of tidal datums as the legal method for determining property lines in the littoral zone introduced an arbitrary boundary in the middle of the oceanfront beach that does not coincide with any diagnostic physical feature and therefore can only be determined by a land surveyor. More important to land ownership is the fact that water actually floods farther inland than predicted by the tide gauge as a result of the combined tidal, wave, and meteorological forces. Systematic underestimation of water levels on beaches by tide gauges leads to a property boundary position that incorrectly increases the area of beach claimed by the upland owners while proportionally reducing the area of adjacent submerged land owned by the state. If the average difference between predicted and actual maximum beach flooding each year is about 40 m (Figure 11, Tables 1 and 2), then this is equivalent to a loss of state-owned property of approximately 4 hectares per kilometer of beach. Even if a more conservative estimate of 10 m between actual and predicted water levels is used, this still translates to 1 hectare per kilometer of beach or approximately 590 hectares for the entire Texas Gulf shoreline.

Systematic seasonal fluctuations of sandy beach profiles are predictable if sufficient data are available for morphological or statistical analysis (SONU and VAN BEEK, 1970; WINANT *et al.*, 1975 among others). Knowledge of seasonal changes in beach morphology can be used to minimize or maximize the area of a tract of land delineated by a littoral boundary. In Florida, a court ruling recognized that seasonal beach changes are predictable and consequently a surveyed property boundary is controlled by the width of the beach. The court determined that the most landward (winter) position of the mean high water line was consistent with the public trust doctrine of land ownership (COLE, 1997). The ambulatory nature of a littoral property boundary can be minimized by establishing the seasonal range of beach widths and elevations and determining when the property surveys should be conducted within the cycle of morphological changes.

CONCLUSIONS

(1) Tide gauges systematically underestimate the position of high water on sandy beaches because the tide gauges are designed to eliminate high-frequency fluctuations in water level and they do not account for the horizontal runup of breaking waves.

(2) The horizontal offset between water levels recorded at a tide gauge and those measured on nearby beaches is directly related to the wave characteristics, the shape and steepness of the beach as well as its composition and the degree of water saturation.

(3) The discrepancies between measured and actual water levels is greatest on low gradient sandy beaches along a microtidal-wave dominated coast such as the Gulf of Mexico. In these microtidal settings, the MHHW line consistently plots in the middle of the wet beach and far seaward of the berm crest.

(4) The wet beach-dry beach boundary commonly mapped on aerial photographs as the shoreline is an ephemeral non-morphological feature that undergoes large-scale high-frequency fluctuations. Consequently it should not be used to delineate the shoreline or to predict future shoreline stability. Despite widespread use of the wet beach-dry beach boundary in the past, accuracy of data sets and future predictions can be improved by monitoring morphological features that are linked to the long-term movement of the beach, but are relatively insensitive to high frequency fluctuations in water level.

(5) In the examples from Texas, the strip of beach above the level of MHHW that is regularly inundated by marine water (state-owned submerged land by definition), but is surveyed as private property, ranges from 1 to 4 hectares per kilometer of coast, depending on whether the strip is measured from the MHHW line to the berm crest or to the vegetation line.

(6) The seasonal cyclity of beach changes could result in a systematic bias in the position of the legal boundary depending on whether surveys were conducted during the winter or summer. Surveys conducted in the late summer would tend to minimize the ambulatory nature of the MHHW boundary, but they would favor the upland property owner in terms of land area.

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