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State of Florida
Department of Environmental Protection
David B. Struhs, *Secretary*

Division of Administrative and Technical Services

Florida Geological Survey
Walter Schmidt, *State Geologist and Chief*

Florida Geological Survey
Special Publication No. 43

Seasonal Variation in Sandy Beach Shoreline Position and Beach Width

by

James H. Balsillie

and

Open-Ocean Water Level Datum Planes: Use and Misuse in Coastal Applications

by

James H. Balsillie

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LETTER OF TRANSMITTAL

Florida Geological Survey
Tallahassee

Governor Jeb Bush
Florida Department of Environmental Protection
Tallahassee, Florida 32304-7700

Dear Governor Bush:

The Florida Geological Survey, Division of Administrative and Technical Services, Department of Environmental Protection is publishing two papers: "Seasonal variation in sandy beach shoreline position and beach width" and "Open-ocean water level datum planes: Use and misuse in coastal applications".

The first paper identifies a methodology for predicting seasonal shifts in Florida's shorelines. A number of practical uses emerge from the research, two of which are the analytical assessment of long-term shoreline erosion data, and determination of the seaward boundary of public versus private ownership.

The second paper is a companion paper to "Open-ocean water datum planes for monumented coasts of Florida" published by the Florida Geological Survey as a separate work. It identifies erroneous applications made when considering mean sea level (MSL), mean high water (MHW), mean low water (MLW), etc., tidal datum planes, illustrating why they are erroneous using practical examples, and details how proper applications should be determined.

Respectfully yours,
Walter Schmidt
Walter Schmidt, Ph.D., P.G.
State Geologist and Chief
Florida Geological Survey

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SPECIAL PUBLICATION NO. 43

SEASONAL VARIATION IN SANDY BEACH SHORELINE POSITION AND BEACH WIDTH

by

James H. Balsillie, P. G. No. 167

ABSTRACT

Annual cyclic fluctuations in beach width due to seasonal variability of forcing elements (*e.g.*, wave energy) have been a subject of concerted interest for decades. Seasonal variability can be used to 1) identify and evaluate the accuracy of historical, long-term shoreline data interpretations, 2) aid in the identification of the boundary of sovereign *versus* private land ownership, and 3) predict expected seasonal behavior of beach nourishment projects, which should be a stated up-front design anticipation.

In this paper, data representing monthly averages are used to compare "winter" and "summer" wave height and wave steepness as they relate to seasonal shoreline shifts. Coupled with astronomical tide conditions and beach sediment size, two quantifying relationships are proposed for predicting seasonal shift of shoreline position (*i.e.*, beach width).

INTRODUCTION

The configuration of the beach in profile view is primarily due to tidal fluctuations which cause periodic changes in sea level, and shore-breaking wave activity. Any change in wave characteristics and direction of approach will, depending on tidal stage, result in a change in the sandy beach configuration.

Systematic beach changes through a single astronomical tidal cycle are well noted (Strahler, 1964; Otvos, 1965; Sonu and Russell, 1966; Schwartz, 1967). Cyclic cut and fill associated with spring and neap tides (Shepard and LaFond, 1940; Inman and Filloux, 1960), and the effect of such phenomena as sea breeze (Inman and Filloux, 1960; Pritchett, 1976), can contribute additional modifying influences.

Beach changes are noted to occur at time intervals longer than a tidal cycle (*e.g.*, Dolan and others, 1974). Smaller beach cusps, for example, may range from 10 to 50 meters apart, while sinuous forms may span distances of from 450 to 700 meters, and such features often migrate alongshore at time scales on the order of days or weeks (Morisawa and King, 1974). As the bay between cusp horns passes a profile line, the beach becomes narrower, and as a horn passes, the beach widens. A prediction model for daily shoreline change has been suggested by Katoh and Yanagishima (1988).

Of the possible cyclic changes, perhaps the most pronounced is that occurring on the seasonal scale. During the "winter" season, when incident storm wave activity is most active, high, steep waves result in shoreline recession. Generally, the berm is heightened with a gentle foreshore slope, although erosion scarps may form. Sand removed from the beach is deposited offshore in one or more submerged longshore bars. During the "summer" season lower waves with smaller wave steepness values transport sand stored offshore back onshore, resulting in a wider beach. It should be noted that along some coasts such as the approximately east-west trending coastline of Long Island, New York (Bokuniewicz, 1981; Zimmerman and Bokuniewicz, 1987; Bokuniewicz and Schubel, 1987), no seasonal variability can be detected (H. J. Bokuniewicz, J. R. Allen, personal communications). Such lack of seasonal variability may be symptomatic of sub-seasonal storm wave groups combined with an almost imperceptible climatic change (J. R. Allen, personal communications), possibly exacerbated by changes in oceanic storm front azimuths relative to shoreline azimuths (Dolan and others, 1988). Similarly, the east-west trending shoreline of the northwestern panhandle coast of Florida, while having annual net longshore transport to the west, appears to be characterized by daily to weekly rather than seasonal reversals in longshore current direction (Balsillie, 1975). It appears, therefore, that east-west trending shorelines pose considerations deserving further attention. However, for much of the Earth's open, ocean-fronting shoreline seasonal changes are clear, which constitutes the subject of this paper.

SEASONAL VARIABILITY

Classically, seasonal variability is associated with California beaches where their geometric character changes noticeably from "summer" to "winter" (*e.g.*, Shepard and LaFond, 1940; Shepard, 1950; Bascom, 1951, 1980; Trask, 1956, 1959; Trask and Johnson, 1955; Trask and Snow, 1961; Johnson, 1971; Nordstrom and Inman, 1975; Aubrey, 1979; O'Brien, 1982; Thompson, 1987; Patterson, 1988; Collins and McGrath, 1989). A considerable number of such studies have also been conducted along the U. S. east coast (*e.g.*, Darling, 1964; Dolan, 1965; Urban and Galvin, 1969; DeWall and Richter, 1977; DeWall, 1977; Everts and others, 1980; Bokuniewicz, 1981; Miller, 1983; Zimmerman and Bokuniewicz, 1987).

Geometric characteristics of seasonal change have been described in terms of ***sand volume changes*** (Ziegler and Tuttle, 1961; Dolan 1965; Eliot and Clarke, 1982; Aubrey and others, 1976; Davis, 1976; DeWall and Richter, 1977; DeWall 1977; Thom and Bowman, 1980; Everts and others, 1980; Bokuniewicz, 1981; Miller, 1983; Zimmerman and Bokuniewicz, 1987; Samsuddin and Suchindan, 1987), by ***contour elevation changes*** (Shepard and LaFond, 1940; Ziegler and Tuttle, 1961; Gorsline, 1966; Urban and Galvin, 1969; Nordstrom and Inman, 1975; Aubrey, 1979; Felder and Fisher, 1980; Clarke and Eliot, 1983; Berrigan, 1985; Brampton and Beven, 1989), and in terms of ***horizontal shoreline shifts or beach width changes*** (Darling, 1964; Johnson, 1971; DeWall and Richter, 1977; DeWall, 1977; Aguilar-Tunan and Komar, 1978; Everts and others, 1980; Clarke and Eliot, 1983; Miller, 1983; Garrow, 1984; Berrigan and Johnson, 1985; Patterson, 1988; Kadib and Ryan, 1989).

Potential legal ramifications of seasonal shoreline changes as they relate to the jurisdictional shoreline boundary position have been addressed by Johnson (1971), Hull (1978), O'Brien (1982), and Collins and McGrath (1989). While there are other seasonal shoreline change applications (discussed in the section on Application of Results), the motivation for this work centers about derivation of a least equivocal methodology for identifying probable real shifts in historical long-term shoreline change.

In addition to wave height and wave steepness, wave direction and beach sediment characteristics can influence the degree of seasonal beach change. Wave direction is particularly influential for pocket beaches found along the U. S. west coast. Along some beaches (*e.g.*, Oceanside Beach just north of Cape Meares, Oregon) a sandy "summer" beach is removed during the "winter" season exposing a cobble beach. In such cases, "summer" to "winter" grain size differences are significant. In this study, however, we shall deal with relatively straight, ocean-fronting beaches composed entirely of sand-sized material.

DATA AND RESULTS

In an investigation of seasonal beach changes at Torrey Pines Beach, California, Aubrey and others (1976) state: "No field studies to date have been able to adequately quantify these wave-related sediment redistributions." In approaching a quantitative solution(s) to the problem, it becomes prudent to identify the force and response elements involved. Basic force elements are identified to be: 1) astronomical tides, 2) wave height, and 3) wave steepness. Response elements are: 1) volume change, 2) change in beach elevation, or 3) horizontal shoreline shift. While the beach sediment might be viewed as a response element, given the paucity of information about temporal/spatial sediment variation as it impacts this problem, it may be prudent to treat sediment characteristics (within the sand-sized range) as a property element (see section on Beach Sediments for further discussion).

The response element used here is the horizontal shoreline shift. Fortunately, we are dealing with a measure which, compared to the others, has the largest range in possible values. For example, vertical contour changes are less than 1-1/2 to 2 meters, and volumetric changes would be 3 to 4 times less than horizontal shift ("rule-of-thumb" guidance suggested by U. S. Army (1984) and Everts and others (1980)), while horizontal shift may range up to tens of meters.

Data

While the amount of data available to quantify seasonal variation in shoreline position is not large, 14 data sets for which sufficient information appears to exist were located to search for a solution (Table 1).

First, it might be reasonable to inspect the relationship between astronomical tidal conditions and horizontal seasonal shoreline shift, V_S, since the tidal condition essentially constitutes a signature characteristic for each site (*i.e.*, it can vary considerably depending on the coast under study). Horizontal seasonal shoreline shift is defined as $V_S = V_{max} - V_{min}$, where V_{max} is the largest measurement representing the widest seasonal beach, and V_{min} is smallest measurement representing the narrowest beach (in this paper V is the distance from an arbitrary permanent coastal monument to the shoreline at any one time). The mean range of tide, h_{mr}, (*i.e.*, the difference between mean low water and mean high water), is plotted against V_S in Figure 1. While there is scatter in the plot, a general trend is apparent.

In addition to astronomical tide conditions, we know that wave climate must be considered and that it, like tidal conditions, varies widely from coast to coast. Selection of values for variables given in Table 1 can be illustrated using time series plots of monthly averages for shoreline shift and wave data. An example for Torrey Pines Beach, California, is plotted in Figure 2, which represents two years of concurrently observed monthly averages for shoreline position, wave height, wave period, and sediment data (Nordstrom and Inman, 1975; Pawka and others, 1976). Further, the data have been smoothed by a three-point moving averaging sequence. Comparison of horizontal shoreline shifts and wave heights suggests that for the months from about December through April storm wave activity prevailed, resulting in a narrower beach, with lull conditions from about May through October coinciding with beach widening. Hence, the average storm wave height, H_S, is that occurring from December through April, and the average lull wave height, H_L, is that occurring from May

Table 1. Force, response, and property elements for seasonal shoreline shift analysis.

Site	V_s (m)	H_s (m)	H_L (m)	T_s (s)	T_L (s)	h_{mrt} m	D (mm)	Φ_L/Φ_s
Gleneden, OR	46.9	1.14	0.72	9.2	8.1	1.91	0.35	0.815
Stinson Beach, CA	42.7	1.28	0.99	16.1	12.1	1.21	0.30	1.370
Atlantic City, NJ	32.0	1.04	0.77	7.4	7.0	1.40	0.30	0.820
Torrey Pines, CA	29.0	1.34	0.99	11.8	11.4	1.28	0.28	0.794
Goleta Point, CA	22.9	1.07	0.73	12.5	14.0	1.28	0.21	0.547
Duck, NC (1982)	18.6	1.10	0.75	8.8	8.1	1.00	0.40	0.808
(1983)	20.4	1.26	0.73	9.2	8.1	0.98	0.40	0.749
(1984)	17.4	1.15	0.70	8.7	8.4	0.96	0.40	0.654
Surfside-Sunset, CA	20.1	1.10	0.73	10.2	13.2	1.07	0.26	0.398
Huntington Beach, CA	18.3	1.14	0.99	11.6	10.4	1.15	0.21	1.078
Holden Beach, NC	15.2	0.70	0.50	6.5	7.0	1.30	0.30	0.614
Jupiter Beach, FL	10.7	1.00	0.63	5.4	5.5	0.92	0.42	0.614
Boca Raton, FL	2.4	0.64	0.51	4.9	4.5	0.84	0.90	0.933
Hollywood, FL	2.1	0.49	0.47	4.7	4.5	0.79	0.60	1.037

V_S = Seasonal range in shoreline position or beach width; H_S = Storm season average wave height; H_L = Lull season average wave height; T_S = Storm season average wave period; T_L = Lull season average wave period; h_{mrt} = Mean range of tide; D = Swash zone mean grain size; Φ_L = Lull season wave steepness; Φ_S = Storm season wave steepness; CA = California, FL = Florida, NC = North Carolina, NJ = New Jersey, OR = Oregon. Sources of data are given by beach in the text.

through October. Note that wave period varies little throughout the year for this site.

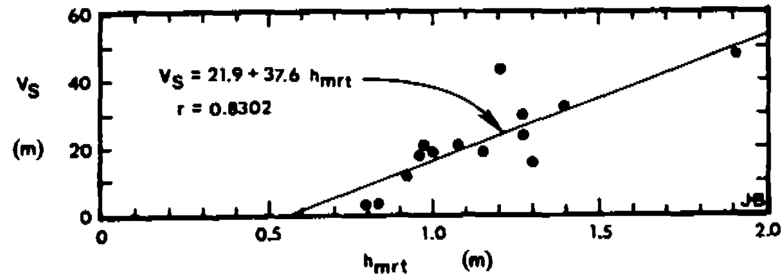

Figure 1. Relationship between seasonal shoreline variability, V_S, and mean range of tide, h_{mrt}.

The classic example of seasonal shoreline shift (Johnson, 1971; O'Brien, 1982) for Stinson Beach, California, represents a 22-year period (1948-1970), suggesting an average shoreline shift of about 43 meters annually. These data are plotted against six years of wave data for the period 1968 to 1973 (Schnieder and Weggel, 1982) in Figure 3. Sediment data are from a separate source (Szuwalski, 1970). Note that unlike the data plotted in Figure 2, wave period shows a concerted seasonal trend. The inference may be made, therefore, that special attention should be given to seasonal wave steepness values. More recent shoreline surveys published by Collins and McGrath (1989) for three years (1984-1986 inclusive) consistently result in the 43-meter seasonal shoreline shift reported by Johnson (1971) and O'Brien (1982).

Concurrently observed data for four years at Jupiter Beach, Florida (DeWall, 1977; DeWall and Richter, 1977) are plotted in Figure 4. It is apparent from Figure 4 that lull wave heights occur from about May through September resulting in a wider beach, with storm waves occurring from about October through at least January

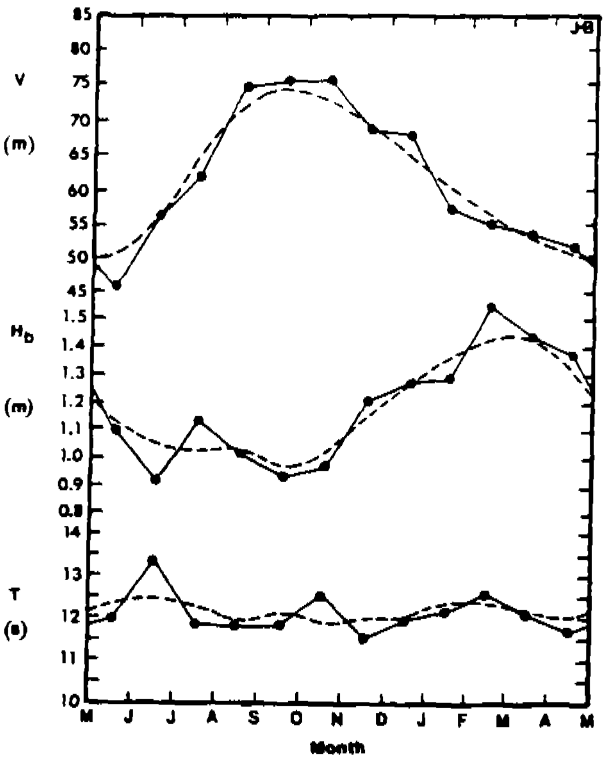

Figure 2. Monthly time series for Torrey Pines Beach, California, for shoreline variability, V; breaker height, H_b, and wave period, T.

producing a narrower beach. Monthly averages for wave heights and periods were concurrently measured, with a reported representative grain size.

A single year of monthly wave data were collected (Aguilar-Tunan and Komar, 1978) at Gleneden Beach, Oregon, from which a seasonal shoreline shift of about 47 meters is evident. Because wave data reported by the authors are probably inappropriate (*i.e.*, they strongly appear to represent the initial offshore breaking wave height), the multi-year data reported by the U. S. Army (1984) are used. A single swash zone sediment size was reported by Aguilar-Tunan and Komar (1978). Shoreline shift and wave data are plotted in Figure 5.

These four examples illustrate how wave data values were determined to represent each season, where the lull season

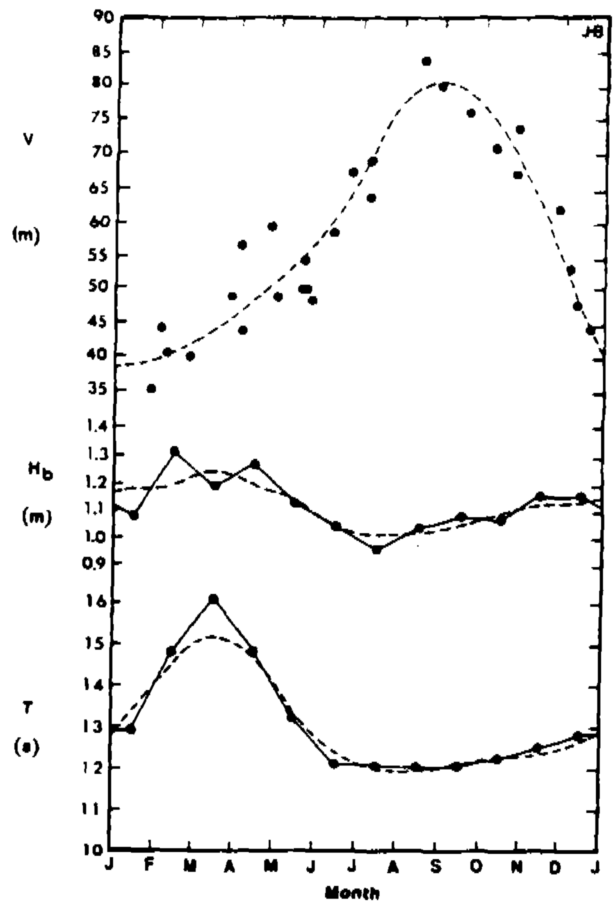

Figure 3. Monthly time series for Stinson Beach, California, for shoreline variability, V; breaker height, H_b; and wave period, T.

wave height and period are given by H_L, and T_L, respectively; similarly, storm season variables are given by H_S, and T_S. Wave heights and periods were selected to represent conditions for the lead flanks of seasonal accretion/recession trends, since it is under these force element conditions that responses are produced.

Similar analyses were conducted for Boca Raton and Hollywood Beaches in Florida (DeWall, 1977; DeWall and Richter, 1977) for four years of monthly data for V, wave height and period, with mean grain sizes for swash zone sediment.

Data published for Holden Beach, North Carolina (Miller, 1983) were plotted by the original author so that seasonal changes

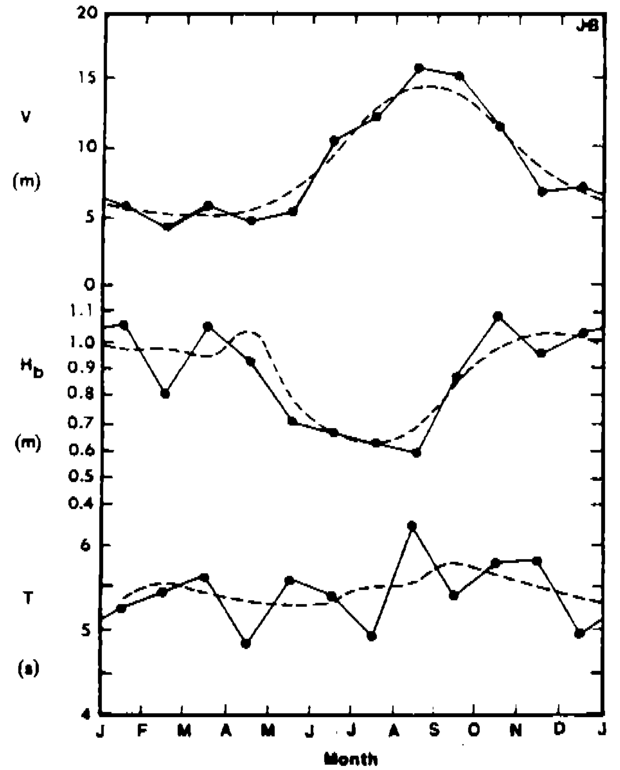

Figure 4. Monthly time series for Jupiter Beach, Florida, for shore variability, V; breaker height, H_b; and wave period, T.

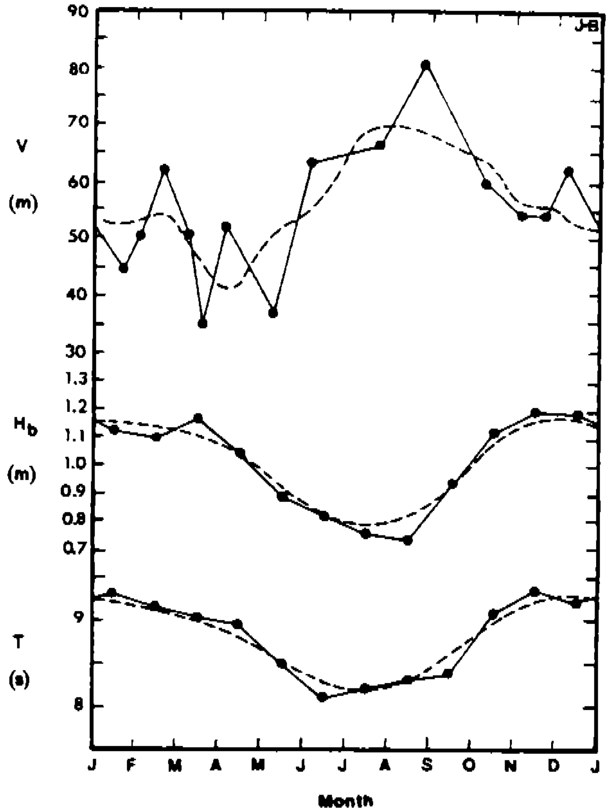

Figure 5. Monthly time series for Gleneden Beach, Oregon, for shoreline variability, V; breaker height, H_b; and wave period, T.

could be directly assessed by measuring peaks of change. The data represent four years of approximately monthly profiles for 16 alongshore profiles, with concurrently measured wave data. Sediment data are from the U. S. Army (1984).

Results for Goleta and Huntington Beaches, California (Ingle, 1966) include approximately monthly surveys for a one-year period, including beach profiles, wave, and sediment data. Unfortunately, wave information for these sites represents only those conditions for the day profiles were surveyed. While information for these sites generally was consistent, wave period data from Schneider and Weggel (1982) were used for Goleta Beach due to unresolvable dispersion in the few daily data.

Seasonal shoreline shift data for Atlantic City, New Jersey (Darling, 1964) were measured for a two-year period along with simultaneously measured seasonal wave data. Sediment data are from the U. S. Army (1984).

Perhaps the most complete data sets are for Duck, North Carolina, at the Coastal Engineering Research Center's Field Research Facility. All information necessary for this study was collected simultaneously to result in data for three years (Miller, 1984; Miller and others, 1986a, 1986b, 1986c).

For a 4-1/2 year period, Patterson (1988) reports a V_s of 20.1 meters for Surfside-Sunset Beach, Orange County, California, along with seasonal wave information. Sediment grain size information is from Szuwalski (1970).

Where the specific studies discussed above did not provide the necessary astronomical tide information, these data were obtained from other sources (Harris, 1981; U. S. Department of Commerce, 1987a, 1987b).

It is worthwhile to note that Berrigan and Johnson (1985) compared wave power computations to shoreline position for seven years of data at four localities along Ocean Beach, San Francisco, California. Deep water wave data were measured at sites ranging from 3.9 to 26.7 kilometers offshore (Berrigan, 1985). While some refraction effects may have occurred due to the San Francisco entrance bar, there appears to be a correlation between an increase in wave power and decrease in beach width.

Results

There is, from Figure 1, an indication that astronomical tides play a role in seasonal variability. The mean range of tide, h_{mrt}, and seasonal wave height difference, $\Delta H = H_S - H_L$, might be expressed as a sum, *i.e.*, $h_{mrt} + \Delta H$, or as a product, *i.e.*, $h_{mrt} (\Delta H)$. Since energy according to classical wave theory is proportional to the height squared, the product, *i.e.*, $h_{mrt} (\Delta H)$, might be more appropriate. On the other hand, the sum has merit because laboratory data, if available, could be used (i.e., since tides are almost never modelled in laboratory studies, a product would be meaningless because the result would always be zero). In either event, many combinations of parameters were investigated (Balsillie, 1987b; see also Table 2 for some of the equations), and it was found that the sum was not nearly as successful as the product; either scatter was excessive as indicated by a low correlation coefficient, r, and/or the fitted regression line did not pass through the origin of the plot.

Many researchers have emphasized the importance of wave steepness in influencing the shore-normal direction of sand transport (*e.g.*, Johnson, 1949; Ippen and Eagleson, 1955; Saville, 1957; Dean, 1973; Sunamura and Horikawa, 1974; Hattori and Kawamata, 1980; Sawaragi and Deguchi, 1980; Watanabe and others, 1980; Quick and Har, 1985; Kinose and others, 1988; Larson and Kraus, 1988; and Seymour and Castel, 1988). In this paper, the "summer" or lull season wave steepness is expressed as $\Phi_L = H_L/(g\ T_L^2)$, and the "winter" or storm season steepness as $\Phi_S = H_S/(g\ T_S^2)$. It became apparent that incorporation of the wave steepness ratio induced numerical consistency in quantitative prediction. Whether the ratio is evaluated as Φ_L/Φ_S or Φ_S/Φ_L becomes important. The form of the ratio for various arrangements of relating expressions for assessment purposes is given in Table 2. Hence, if $(\Phi_L/\Phi_S) < 1.0$ then wave height during the storm season must be more important; if $(\Phi_L/\Phi_S) > 1.0$ then wave steepness plays a stronger role. In fact, it would be expected that Φ_L/Φ_S results in better correlation, since beaches are eroded by steeper waves, with lower steepness waves resulting in accretion.

In addition, beach sediment characteristics have been touted to play a significant role. The general view is that, holding force elements constant, a beach composed of coarser sediment is more stable than a beach composed of finer material (*e.g.*, Krumbein and James, 1965; James, 1974, 1975; Hobson, 1977), *i.e.*, a beach comprised of coarser sediment should exhibit less seasonal variability than a beach composed of finer sediment (note that this explanation is not so straightforward, and will be addressed in greater detail in the following section). Since a number of investigators have published general quantifying relationships which in addition to wave height and steepness, incorporate sand size (*e.g.*, Dean, 1973; Hattori and Kawamata, 1980; Sawaragi and Deguchi, 1980; Watanabe and others, 1980), it would be prudent to consider granulometry in this study.

Again, it is to be noted that many forms of possible relating parameters were

Table 2. Assessment of the wave steepness ratio for a selection of expressions related to V_S.

Expressions Using Φ_L/Φ_S	r	Expressions Using Φ_S/Φ_L	r
$h_{mrt} + [(\Delta H)\ \Phi_L/\Phi_S]$	0.9339	$h_{mrt} + [(\Delta H)\ \Phi_S/\Phi_L]$	0.7445
$[h_{mrt} + (\Delta H)]\ \Phi_L/\Phi_S$	0.8843	$[h_{mrt} + (\Delta H)]\ \Phi_S/\Phi_L$	0.4071
$h_{mrt}\,(\Delta H)\ \Phi_L/\Phi_S$	0.9047	$h_{mrt}\,(\Delta H)\ \Phi_S/\Phi_L$	0.5498
$\frac{h_{mrt} + [(\Delta H)\ \Phi_L/\Phi_S]}{D}$	0.8567	$\frac{h_{mrt} + [(\Delta H)\ \Phi_S/\Phi_L]}{D}$	0.3837
$\frac{h_{mrt}\,(\Delta H)\ \Phi_L/\Phi_S}{D}$	0.9672	$\frac{h_{mrt}\,(\Delta H)\ \Phi_S/\Phi_L}{D}$	0.5478

r = Pearson product-moment correlation coefficient between each expression evaluated using measured force and property element data of Table 1, and measured V_S response data of Table 1.

considered in an earlier study, but that only the most successful are presented here. Incorporating the preceding considerations, two equations are presented, the first which includes force elements only, which posits:

$$V_s = 78.5\ h_{mrt}\,(\Delta H)\ \Phi_L/\Phi_S \qquad (1)$$

and is plotted in Figure 6. The cubic least squares regression coefficient (forced through the origin) of 78.5 is in units of m^{-1} where the mean range of tide, h_{mrt}, and seasonal wave height difference, ΔH, are in meters. The standard deviation of the data from the equation (1) regression line in the vertical direction (Ricker, 1973) is 11.4 m. The second equation includes the mean swash zone grain size, D, to yield :

$$V_s = 0.025\ \frac{h_{mrt}\,(\Delta H)\ \Phi_L/\Phi_S}{D} \qquad (2)$$

plotted in Figure 7, wherein all variables are expressed in consistent units. In terms of dimensions, one will note that when all dimensional cancellations are made in equations (1) and (2), length only remains. The coefficient of 0.025 was determined using the same fitting procedure as for equation (1). It is apparent from the figures that equation (2) reduces some of the scatter of equation (1). The standard error (Ricker, 1973) of equation (2) in the vertical direction is 6.8 m. It may also be of interest to note that the coefficient of equation (1) when expressed relative to the coefficient of equation (2) results in a mean grain size of 0.318 mm which, using the Wentworth classification scheme, is a medium-sized sand (Wentworth, 1922).

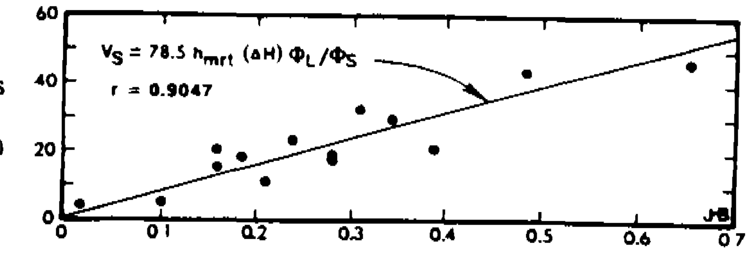

Figure 6. Illustration of mathematical fit for equation (1).

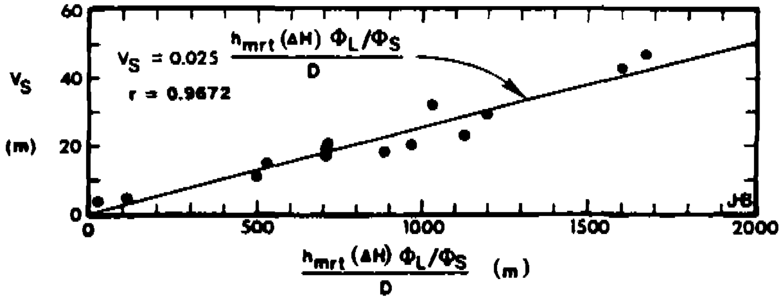

Figure 7. Illustration of mathematical fit for equation (2).

DISCUSSION

A favorable result from many of the prediction equations tested during the course of this investigation is that most showed a trend between V_S and the relating parameters (*e.g.*, column 1 of Table 2). Ostensibly, such consistency should not be surprising since the major factors known to cause seasonal variability were considered, and the remainder of the work involved rearranging the variables to reduce scatter. Further, the goal to delineate seasonality was a simplified approach (compared to relating the entire time series of monthly values which becomes increasingly complex).

Equations (1) and (2) engender some heterogeneity that needs discussion. Both ΔH and ϕ_L/ϕ_S are seasonal parameters. Granulometry as it appears in equation (2) is a property element application, although a seasonal response element application is possible and is discussed in a later section. The quantity, h_{mrt}, however, is not a seasonal measure. It is, rather, an average approximate hourly measure where one tide (diurnal) or two tides (semi-diurnal) occur in one tidal day of 24 5/6 hours. Hence, h_{mrt} is also a property element that is a signature value for each site, noting that it can vary significantly depending upon the locale. Seasonal mean sea level change for which there are no site-specific data for Table 1 localities, is discussed in a following section.

The results of this work might be best viewed as a first appraisal until more data become available to further test and/or enhance the prediction relationships. Nevertheless, the results presented here are statistically valid; one should not be timid in applying resulting computational values pending future refinement in prediction methodology. One purpose of this paper is to act as a plea for more data. Following are discussions of a few concerns related to seasonal shoreline variation predictions.

The Single Extreme Event and the Combined Storm Season

The sandy littoral zone is comprised, from offshore-to-onshore, of the nearshore, the beach, and the coast. Each of these three subzones is created and maintained by sets of force elements normally different from each other within the long-term temporal framework. When a storm or hurricane impacts the littoral zone, the following scenarios are possible: 1) the extreme event produces a combined total storm tide which rises above the beach-coast interface elevation to affect all three subzones, 2) the combined total storm tide does not rise above the beach-coast interface elevation but does persist long enough for the beach to be eroded and the coast is attacked by storm waves, 3) the combined storm tide does not rise above the beach-coast interface elevation and is short enough in duration so that only the nearshore and beach are affected, and 4) the extreme event remains out at sea so that impact is indirect (*i.e.*, a combined total storm tide does not or only fractionally reaches the shore) and storm waves primarily affect the nearshore and beach. The combined total storm tide used here is defined by Dean and others (1989) as the storm surge due to astronomical tide, wind stress, barometric pressure, and breaker zone dynamic setup, which defines the active phenomena for scenarios 1, 2, and 3 (*i.e.*, the ***storm tide event***). Scenario 4 includes only the effects of breaking wave activity, including dynamic wave setup, and is termed the ***storm wave event***. Scenarios 1 and 2 are those which, depending on storm strength, duration, continental slope, and approach angle, usually produce the design erosion event (Balsillie, 1984, 1985a, 1985b, 1986). Probabilistically, the frequency of occurrence increases from scenario 1 to 4.

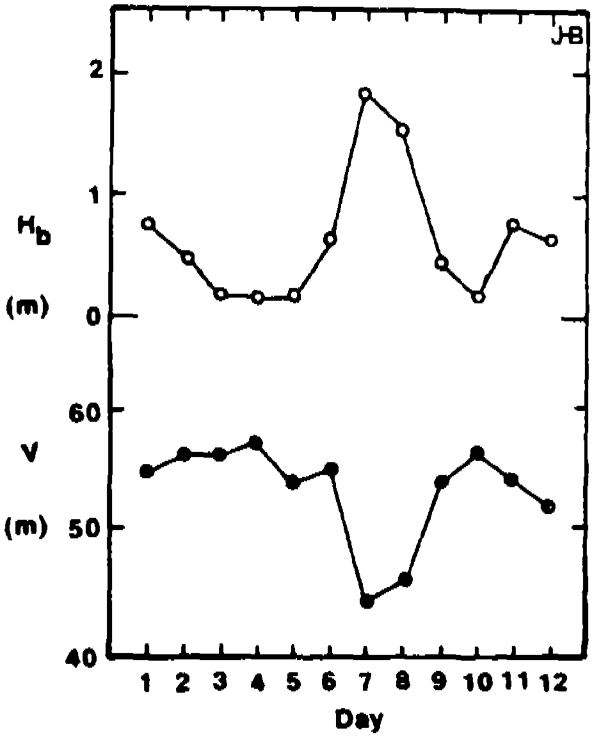

Figure 8. Example of the quick response and recovery of the beach to storm wave activity, Pensacola Beach, Florida, December 1974; the storm peak occurred on December 7 (data courtesy of James P. Morgan, personal communications).

Under certain circumstances of event longevity, astronomical tides, and nearshore slopes, exceptions can occur. One such exception occurred when Hurricane Gilbert struck Cancun, Mexico in 1988. Because there is essentially no continental shelf and nearshore slopes are steep, all eroded sand from Cancun's beaches was removed and natural beach recovery was not possible. Potentially, other exceptions can occur where, for instance, submarine canyons might act as a sediment transport conduit and sand is irremeably lost from the littoral system. For most shores, however, continental shelves are wide and nearshore slopes gentle enough that beach recovery to pre-storm dimensions following single storm impact occurs in a period of one to several days (Birkemeier, 1979; Bodge and Kriebel, 1986; Savage and Birkemeier, 1987), for events described by scenarios 1, 2 and 3 above. Beach recovery following the effects of a storm wave event (*i.e.*, scenario 4) was recorded by James P. Morgan at his Pensacola Beach, Florida, home (Figure 8); within a day following storm wave abatement, the beach had recovered to its pre-storm width.

The magnitude of seasonal shoreline change may vary from year-to-year, since for any site some years may have more frequent and intense storm tide and wave activity than other years. Horizontal shoreline shifts due to direct storm and hurricane impacts are now usually recorded. However, for storms that do not directly impact the shore (*i.e.*, are far out at sea, for example Tropical Storm Juan (Clark, 1986) which affected Florida) but generate storm waves that do cause shoreline erosion, such erosion is usually not measured.

Dolan and others (1988) conducted an extensive study on extratropical storm activity, assessed also in terms of storm wave hours, for 41 years of data (1942 to 1984) along the Outer Banks of North Carolina. These data (Figure 9) show a concerted seasonal trend. In addition, the author extracted from Neumann and others (1981) tropical storms and hurricanes whose tracks came within about 250 miles of the Outer Banks for the period 1940 to 1980. These latter data, also plotted in Figure 9, are added to the extratropical data (plotted as a bold, solid line). Hence, the total storm record is nearly represented and, except for only a few direct impacts, represent storm wave events (*i.e.*, scenario 4 above). For the mid-Atlantic, about 35 storms occur per year on the average (about 26 winter events and 9 summer events), 93% of which are extratropical events. In terms of storm wave duration, Dolan and others (1988), determined using hindcast techniques that on the average, storm waves occur for about 571 hours per year (*i.e.*, 24 days per year) for extratropical storms off of the Outer Banks; winter storm waves persist for an average of 433 hours (*i.e.*, 18 days), and summer storm waves about 156 hours (*i.e.*, 6.5 days). These data strongly correlate with the expectation of wider mid-Atlantic east coast summer beaches and narrower winter beaches, and illustrate the important fact that ***a large number ... not a few ... winter storm events are required to maintain a narrower winter beach relative to a wider summer beach.***

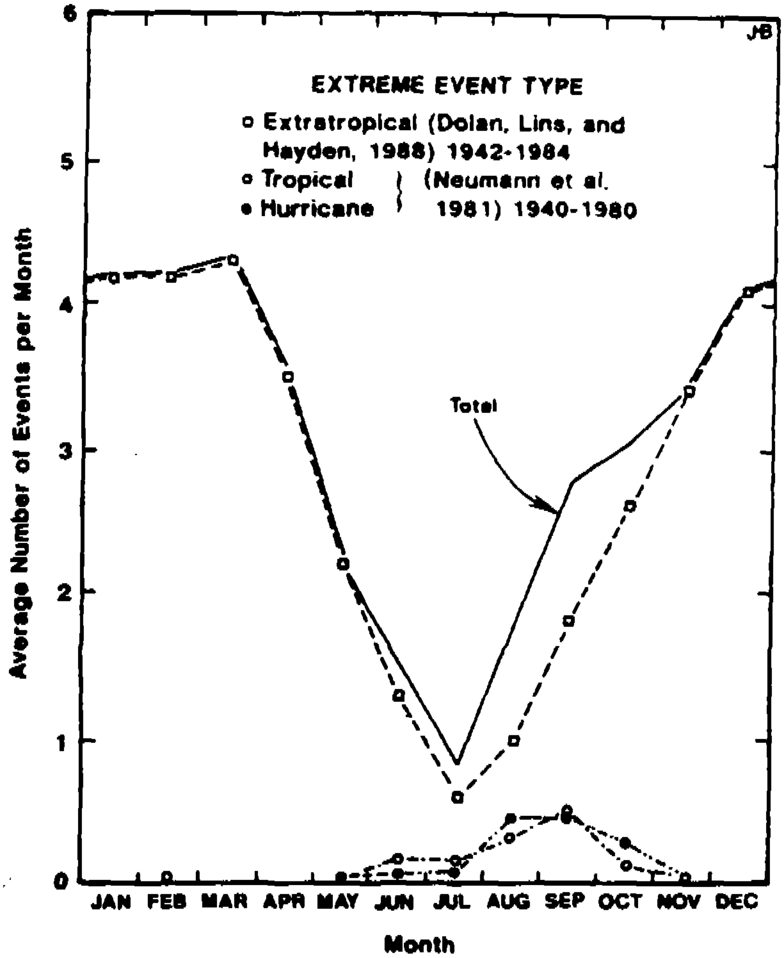

Figure 9. Monthly average occurrences of extreme event wave events for the Outer Banks of North Carolina.

Beach Sediments

Beach sediments engender some interesting concerns. How we consider sediments depends upon whether granulometry is applied as a property element or a response element, which in turn has an effect on the dimensional configuration of a numerical representation. As an example, equation (1) requires an additional parameter with units of L^{-1} for the equation to be unit consistent. Equation (2) was rendered unit consistent by dividing by a granulometric parameter with a length dimension. If this is to be the applied case, it is useful to note that when sedimentologic grain size is specified in S. I. units, the mean grain size and standard deviation moment measures have units of mm, while skewness and kurtosis are dimensionless. Otherwise, the granulometric moment measures can be specified all in dimensionless phi units.

Beach sands characteristically have a range in size from 0.1 mm to 1.0 mm (U. S. Army, 1984) which occupies about 46% of the sand-sized range of Wentworth (1922; *i.e.*, 0.0625 to 2.0 mm). From Table 3, it is apparent that the range in mean grain sizes occurring over an annual period is less than 1/3 of the commonly found range in beach sand size (*i.e.*, 0.9 mm). Therefore, the typical annual mean grain size, D, for any beach might be an appropriate measure to consider as a ***property element*** provided that sufficient samples are available annually to obtain a reliable measure (*e.g.*, a suite of monthly samples). This implies that there needs to be a real difference in mean grain sizes from site-to-site for the application to have meaning. Even so, the use of mean grain size alone without consideration of standard deviation, skewness and kurtosis remains somewhat of a curiosity other than: 1. its use results in a good fit for equation (2), 2. is properly applied in equation (2) (*i.e.*, the larger the value of D, the smaller becomes V_S), 3. produces the proper unit dimensions for the equation, and 4. has been a considered variable in other research results.

Table 3. Mean annual beach grain size (foreshore slope samples) from monthly data, and range in size.

Site	Annual D (mm)	Range of D (mm)	Source
FLORIDA			
St. Andrews St. Pk.	0.29	0.04	Balsillie, 1975
Grayton Beach	0.37	0.13	" "
Crystal Beach	0.37	0.15	" "
J. C. Beasley St. Pk.	0.40	0.11	" "
Navarre Beach	0.41	0.14	" "
Fort Pickens Beach	0.43	0.27	" "
NORTH CAROLINA			
Duck	0.40	0.19	Miller, 1984
CALIFORNIA			
Goleta Pt. Beach	0.21	0.16	Ingle, 1966
Trancas Beach	0.22	0.18	" "
Santa Monica Beach	0.26	0.29	" "
Huntington Beach	0.21	0.14	" "
La Jolla Beach	0.17	0.04	" "

Table 4. Two cases of sedimentologic response of moment measures to wave energy levels.

CASE 1 Energy Levels Are Excessive to Sedimentologic Response	**CASE 2** Energy Levels Are Not Excessive to Sedimentologic Response
MEAN GRAIN SIZE	
$D_S \hat{=} D_L$	$D_S > D_L$
SKEWNESS	
$Sk_S \hat{=} Sk_L$	$Sk_S < Sk_L$
KURTOSIS	
$K_S < K_L$	$K_S < K_L$
NOTES: Subscripts S and L refer to the storm season and lull season, respectively. The corresponds to symbol, $\hat{=}$, is meant to signify that the measure did not change due any recognizable response to energy level force element changes.	

It is generally the case (CASE 1 of Table 4) that the coarsest beach sand is found in the swash zone, and which is the only type of sample considered here since it directly represents energy expenditures of the littoral hydraulic environment. One might suspect that swash samples are coarser during the storm than the lull season. However, the range in sediment size within the sand-sized range is limited for any beach to the coarsest available material commensurate with bulk properties meeting conservation of mass and energetics constraints (Passega, 1957, 1964). In fact, the negligible effect of sand-sized material on runup for larger waves has been noted by Savage (1958). His results strongly imply that relative to sand size, as the wave height increases there is reached a point beyond which sediment size within the sand-sized range no longer discriminately responds. That is, the level of wave energy is overpowering even to the coarsest fraction of sediment available within the sand-size range.

Hence, unless the wave climate is closely in equilibrium with sediment comprising the beach, one would not necessarily expect to find significantly correlative seasonal changes in mean grain size (or for that matter skewness, although it might be somewhat less sensitive to energy) within the sand-size range. The author located data where at least monthly sand samples were collected with concurrent wave data for sites along the U. S. west, east, and Gulf coasts. There was no discernible seasonal correlation between waves and mean sediment grain size. Several typical examples are illustrated in Figure 10.

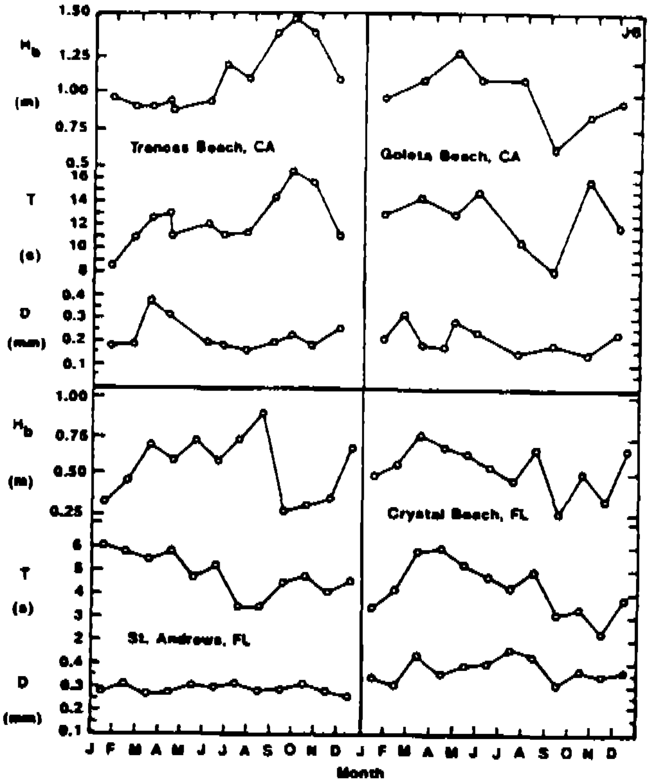

Figure 10. Typical examples of time series relation of monthly data for breaker height, wave period, and foreshore slope grain size for California (data from Ingle, 1966) and northwestern Florida panhandle (data from Balsillie, 1975) sites.

Samsuddin (1989), however, reports to have found correlation between seasonal changes in wave conditions, foreshore slope, and sand-sized textural changes along the southwest Kerala coast of India, wherein mean grain size increased and kurtosis decreased during higher seasonal wave energy conditions (CASE 2, example 1). Samsuddin's one-year investigation, in which beach foreshore sand was seasonally sampled, may have been a fortuitous year in which equilibrium conditions were more nearly manifest. Kerala sand samples are also characterized by a consistently large standard deviation which allows for greater leeway in sorting potential (0.6 to 0.7 phi compared to 0.2 to 0.55 phi commonly found for U. S. beach sands). Unfortunately, Samsuddin did not describe the mineralogy or shape characteristics of the samples which may or may not differ from the characteristically rounded, quartzose-feldspathic U. S. beach sands considered in this work.

There also occurs the case (CASE 2, example 2) where a beach is comprised of sediments exceeding the sand-sized range. An example is Oceanside Beach, Oregon, mentioned earlier, in which all the sand-sized summer beach material is removed to expose a winter cobble beach. Under such conditions, one would expect that sediment coarsening, as reflected by the mean grain size and skewness, would result from higher wave energy levels because of the excessive size of coarser sediments.

When singularly considered, the 1st moment measure (mean grain size) tells us nothing about the nature of the distribution.

The 2nd moment measure (standard deviation) tells us about the dispersion about the 1st moment measure, but leaves no insight as to how the distribution departs either symmetrically or asymmetrical from the normal bell-shaped frequency curve (or from the straight line for the cumulative curve plotted on standard probablity paper). Such departure is a characteristic of the tails of the distribution about which knowledge is progressively imparted to us by considering the 3rd moment measure (skewness), 4th moment measure, (kurtosis), and higher moment measures (Tanner, personal communication; Balsillie, 1995). It is, in fact, the tails of the distribution which can provide a great deal of environmental information. It has been demonstrated, for instance, that there is an inverse relationship between the kurtosis and the level of surf wave energy expenditure (Silberman, 1979; Rizk, 1985; Rizk and Demirpolat, 1986; Tanner, 1991, 1992). Tanner (1992) has reported a correlation between sea level rise and kurtosis, because the rise component is attended by an increase in surf wave energy expenditure.

From the preceding discussion, it is apparent that two general cases can be identified where wave energy levels either exceed stability constraints of the coarsest fraction of the sedimentologic distribution, or they do not. For three moment measures considered to best represent sedimentologic response to the wave energy force element, storm and lull season responses are listed in Table 4. For the two cases (Table 4) only the kurtosis persists in providing a response, because the 4th moment measure is not rendered ineffective to register a change by excessive wave energy levels. Therefore, a parameter for consideration that more nearly quantifies sedimentologic response might be given by:

$$\theta = \frac{(20 + Sk)\,K}{D} \qquad (3)$$

where the moment measures are defined in Table 4. The 3rd moment measure (skewness) of equation (3) has a value of 20 added to it in order to assure that positive values will result. The parameter θ when evaluated using S. I. units has units of L^{-1} (dimensionless units result when granulometric measures are evaluated in phi units). By using seasonal values of θ, that is, θ_S for the storm season and θ_L for the lull season, it may be possible to compile a sedimentologic ***response element*** parameter that can be incorporated into equation (1). The proper form of the parameter, including equation (3), however, requires additional data, research, and testing.

Astronomical Tides

That mean astronomical tide elevations exhibit cyclic seasonal variability has long been established (Marmer, 1951; Swanson, 1974; Harris, 1981) and is included in tide predictions. The U. S. Department of Commerce (1987a, 1987b) states, however, that at "... ocean stations the seasonal variation is usually less than half a foot." Marmer (1951) notes that seasonal variation in terms of monthly mean sea level for the U. S. can be as much as 0.305 m (1 foot; Table 5); some examples for the U. S. east, Gulf, and west coasts are illustrated in Figure 11. Based on the many years of monthly data, researchers (Marmer, 1951; Harris, 1981) note slight variations in the seasonal cycle from year-to-year, but also recognize the periodicity in peaks and troughs over the years. For much of our coast, lower mean sea levels occur during the winter months and higher mean sea levels during the fall. Harris (1981) inspected the record to determine if storm and hurricane occurrence was in any way responsible for the seasonal change, but found "... no systematic variability". Galvin (1988) reports that seasonal mean sea level changes are not completely understood, but suggests that there appears to be two primary causes for lower winter mean tide levels for the U. S. east coast: 1. strong northwest winter winds blow the water away from shore, and 2. water contracts as it cools. He notes that winds are more important in shallow water where tide gauges are located, but that contraction becomes important in deeper waters. Swanson (1974) also notes "... seasonal changes resulting from changes in direct barometric pressure, steric levels, river discharge, and wind affect the monthly variability."

Seasonal variation in tides is usually attributed to two harmonic constitutents: one with a period of one year termed the solar annual tidal constituent, and the other with a period of six months termed the solar semiannual constituent (Cole, 1997). Some consider these to be meteoroligical in nature, rather than astronomic. However, because the root cause of cyclic seasonal weather is the changing declination of the sun, they should more nearly be astronomical in origin. Harmonic analysis of the annual tidal record can easily determine the amplitude and phase of each of these constituents, thereby providing a mathematical definition of the seasonal variation. (George M. Cole, personal communications.)

Comparing the closest appropriate curve from Figure 11 to Figures 2 through 5, it is apparent that the lowest seasonal stand of mean sea level and, therefore, average astronomical tide effects occurs when the beach is narrowest for Stinson Beach and Torrey Pines Beach, California, and Jupiter Beach, Florida. For Gleneden Beach, Oregon, narrow beach widths and monthly average tidal highs seem to be more nearly in phase. Therefore, it is not clear that seasonal changes in astronomical tides significantly affect seasonal shoreline variability, at least not in terms of average monthly measures. Quite clearly, however, such data needs to be procured for each site to confirm a correlation or lack thereof. Should the proper correlation consistently occur (*e.g.*, low monthly average mean sea level - wider beaches, and high monthly average mean sea level - narrower beaches) then a relating parameter needs to be incorporated in the quantifying predictive relationship(s). It is of consequence to note, for the data of Tables 1 and 4, that the seasonal range of monthly average mean sea level is from 9 to 33% of the mean range of tide (h_{mrt}).

Table 5. Seasonal range in monthly average water levels.

Site	No Years	h (m)	Low	High
U. S. East Coast				
New York	19	0.177	Feb	Sep
Atlantic City	19	0.165	Feb	Sep
Baltimore	19	0.238	Feb	Sep
Norfolk	19	0.177	Feb	Sep
Charleston	19	0.253	Mar	Oct
Mayport	19	0.314	Mar	Oct
Miami Beach	17	0.259	Mar	Oct
U. S. Gulf Coast				
Key West	19	0.216	Mar	Oct
Cedar Key	10	0.244	Feb	Sep
Pensacola	19	0.232	Feb	Sep
Galveston	19	0.247	Jan	Sep
Port Isabel	4	0.262	Feb	Oct
U. S. West Coast				
Seattle	19	0.159	Aug	Dec
Astoria	19	0.219	Aug	Dec
Cresent City	14	0.180	Apr	Dec
San Francisco	19	0.104	Apr	Sep
Los Angeles	19	0.152	Apr	Sep
La Jolla	19	0.143	Apr	Sep
San Diego	19	0.152	Apr	Sep

Notes: 1. h = seasonal range based on average of n years of monthly means where monthly means are average of hourly heights; 2. San Diego gauge is located in San Diego Bay; 3. Astoria gauge is located 15 miles upstream from the mouth of the Columbia River.

APPLICATION OF RESULTS

While horizontal shoreline shift (or beach width change) addresses only one

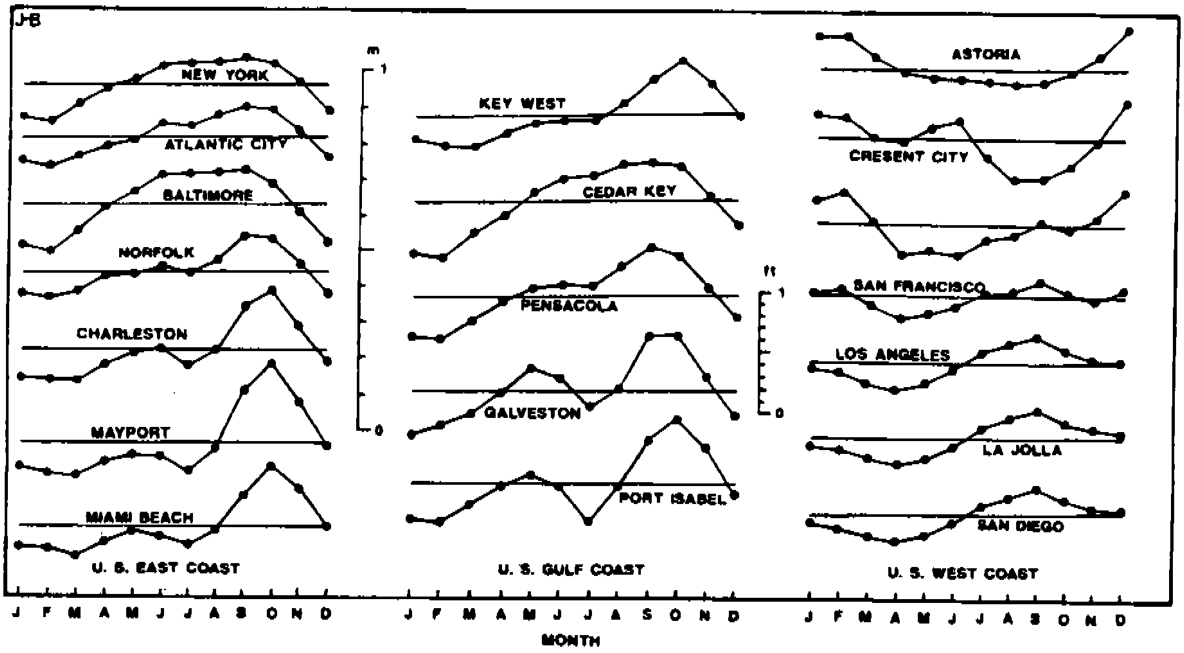

Figure 11. Monthly variation in sea level for the contiguous United States (after Marmer, 1951).

dimension of a measure of beach change, it does serve to straightforwardly punctuate the nature of the phenomenon. The manner of approaching quantification of the phenomenon here, allows for a simply applied methodology that is useful for educational, technical, and planning purposes.

General Knowledge

Seasonal beach shifts are not generally known by the layman. In Florida, with 35,000 new residents arriving monthly (Shoemyen and others, 1988), new coastal property owners have been alarmed after purchasing ocean-fronting property during the "summer" when their beach is wide, to find or return to find a narrow "winter" beach, believing that they have unwittingly purchased eroding property. Ostensibly, this might result in an application for a permit to construct a coastal hardening structure such as a bulkhead or seawall without investigating seasonal beach width variation on the part of the applicant, the applicant's design professional, or the permitting agency. The results of this paper provide a quantitative basis upon which to inform the public, and a method to assess a permit application.

Seaward Boundary of Public versus Private Ownership

The boundary between private (*i.e.*, upland) and public (*i.e.*, seaward) beach ownership is fixed by some commonly applied tidal datum. For most of the U. S. this is the plane of mean high water (MHW) which, when it intersects the beach or coast forms, the mean high water line. However, unlike other riparian ownership determinations (*i.e.*, fluvial, lacustrine and estuarine), littoral properties must, in addition, contend with significant wave activity that seasonally varies. Hence, ocean-fronting beaches all-too-often experience cyclic seasonal width changes of a magnitude long recognized as problematic in affixing an equitable boundary (Nunez, 1966; Johnson, 1971; Hull, 1978; O'Brien, 1982; Graber and Thompson, 1985; Collins and McGrath, 1989).

Many investigators have suggested that the legal boundary for ocean-fronting beaches should not be continuously moving with the seasonal changes, but should be the most landward or "winter" line of mean high water (Nunez, 1966). Selection of the "winter" MHW line would be the most practical to locate and would be the most protective of public interest by maintaining maximum public access to the shoreline (Collins and McGrath, 1989).

In Florida, the ocean-fronting legal boundary - seasonal fluctuation issue was deliberated upon in State of Florida, Department of Natural Resources *vs* Ocean Hotels, Inc. (State of Florida, 1974) as it related to locating the MHW line from which a 50-foot setback was to be determined. Judge J. R. Knott, upon consideration of all the options, rendered the following decision:

> ***This court therefore concludes that the winter and most landward mean high water line must be selected as the boundary between the state and the upland owner. In so doing the court has had to balance the public policy favoring private littoral ownership against the public policy of holding the tideland in trust for the people, where the preservation of a vital public right is secured with but minimal effect upon the interests of the upland owner.***

A 1966 California Court of Appeal decision rejected the application of a continuously moving boundary in People *vs* Kent Estate (State of California, 1966). However, no decision has been rendered as to what line to use (Collins and McGrath, 1989). More recently, however, Collins and McGrath (1989) report:

> ***The Attorney General's Office in California has offered its informal opinion that, if squarely faced with the issue, California courts would follow the reasoning in the Florida case and adopt the "winter and most landward line of mean high tide" as the legal boundary between public tidelands and private uplands ... (it should be understood that such a boundary, while relatively stable, would not be permanently fixed but would be ambulatory to the extent there occurs long-term accretion or erosion).***

Collins and McGrath also discuss special issues such as shore and coastal hardening structures, artificially induced accretion of sand, *etc.*, and their work is highly recommended for further reading.

However, no formal legal adoption of the littoral MHW boundary has found nation-wide acceptance. This is symptomatic of mankind's tendency to give credence to codes of anthropic conduct through the ***Laws of Man*** (published in local codes, state statutes, and federal regulations, etc.) but to essentially ignore the environment and how it works through the ***Laws of Nature*** (published in scientific papers and journals). Until a balance is more nearly achieved, we shall continue to exacerbate the environmental crisis that has befallen us all. The results of this paper provide for one small aspect of the behavior of nature an opportunity to achieve a balance between the two sets of laws.

Long-Term Shoreline Changes

The initial motivation to investigate this subject was the development of a methodology to analyze and assess long-term shoreline changes. Quantitative behavior of long-term shoreline change to assess coastal stability is best accomplished using actual historical surveys. In Florida, as many surveys as possible are located for the period from about 1850 to present (aerial photography is used where an historical hiatus occurs), usually resulting in from 8 to 14 points to represent the historical shoreline position (Balsillie, 1985a, 1985b; Balsillie and Moore, 1985; Balsillie and others, 1986). These data are assessed alongshore at a spacing of approximately 300 m. Hence, historical change rate analysis requires both a ***temporal*** analytical component and a ***spatial*** analytical component.

Of the numerical methods available to analyze such data, many can actually magnify the uncertainty and/or error associated with the final results of an involved computational approach. Caution with respect to this aspect of analysis cannot be over emphasized. In fact, the topic is so important that a series of standard equations for assessing the propagation of error in computing have been provided in the Appendix.

The nature of historical shoreline location data is such that there is associated error and variability. Surveying error includes inherent closure errors, error due to older technologies, and non-adjustment error for more recent vertical and horizontal epoch readjustments. Survey nets established for county surveys may not precisely relate to adjacent county nets as they would in a state-wide net. Long-term sea level changes, though slight, affect long-term shoreline changes. These sources of error may be called map-source errors after Demirpolat and others (1989), for which a magnitude of ± 9 to 15 m may be appropriate (Demirpolat and others, 1989). Interpretive plotting of errors of shoreline location (depending on data concentration) on original survey maps must be assumed, especially for older maps. Present digitizing technology results in an error of ± 3 to 4 m (Demirpolat and others, 1989).

Except for recent technologies, magnitudes of errors for examples suggested above are not known with certainty in the majority of cases. Even so, it can be envisioned that they are of sufficiently large magnitude that we must keep the number of computational steps to a minimum in order to minimize the propagation of error in computing (bear in mind that in addition to the ***temporal*** analytical component a ***spatial*** component remains, which further increases analytical computation).

The "bottom line" is that we need to use the most appropriate and computationally simple analytical methodology available. The most appropriate statistical analytical tool is undoubtedly ***trend analysis*** which already includes measures of determining the associated error or variability. In addition, what we might learn and quantify about nature's own systematic variability can be used to our advantage both in terms of assessing the acceptability of data, and as an analytical tool. Such is the usefulness of horizontal seasonal shoreline change.

An example of temporal analysis is illustrated in Figure 12 for a locality about 2.7 kilometers south of a major inlet on the east coast of Florida. Equation (1) was evaluated using the appropriate wave data of

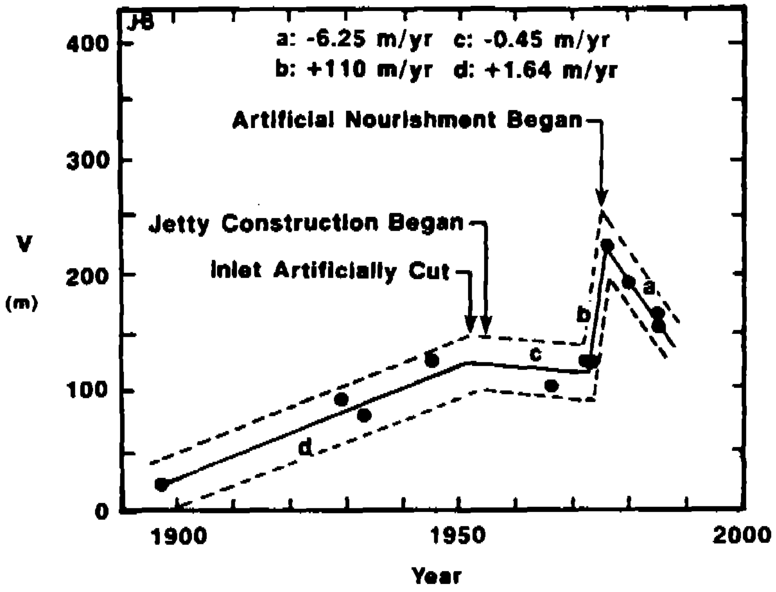

Figure 12. Example of long-term shoreline change rate (solid lines) temporal analysis using seasonal shoreline shift data (dashed lines); see text for explanation.

Thompson (1977) and tidal data from Balsillie (1987a). To the result, one standard deviation was added to yield a predicted seasonal variability measure of 50.5 m. Starting with the most recent data and moving back in time, regression techniques are used to determine a trend line (solid line in Figure 12) about which plus and minus one-half the seasonal variability measure is affixed in the vertical direction (dashed lines in Figure 12). The slope of the trend line of the time series is the rate of erosion or accretion (a zero slope or horizontal line represents stability). Now the seasonal variability measure becomes a valuable asset towards identifying spurious data or long-term change segments in shoreline behavior. For instance, if a point lies outside the seasonal variability envelop in the middle of segment d, one would conclude that either seasonal variability was extreme for that year (for which there are undoubtedly no records) or the survey was made immediately following extreme event impact (either storm tide or wave event for which there are probably no records). In either case, we have reason to not include the data point in our analysis, since there are sufficient data points for the segment to suggest a strong trend. Interactively, trends in segment d at localities up- and down-coast can be used to verify such a trend in the spatial component of the change rate analysis.

We also can use historical information about the area to assist in analysis. For instance, we know that the inlet was artificially constructed in 1951, and jetty construction began in 1953. Furthermore, artificial nourishment south of the inlet began in 1974. Each of these events is coincident with a new episode in shoreline behavior, and may be verified with similar analyses at nearby up- and down-coast sites. Note that there are too few data points to quantify the shoreline change trend for segment c; either additional data points are required or verification/readjustment from analyses at nearby adjacent sites are required to assure quantification of representative shoreline change.

Project Design and Performance Assessment

Both ***long-term changes*** and ***extreme event impacts*** have long been considered in assessing coastal development design activities (until recently the former has by-and-large been qualitative). In proper order, long-term changes should first be determined, followed by the design extreme event impact. The first determination allows for prudent siting of the development activity, and the second for responsible structural design solutions to withstand storm tide, wave, and erosion event impacts. However, without knowledge of ***seasonal shoreline shifts*** for a particular locality, uncertainty will be introduced into such assessment. Following long-term determination of where the shore will be (*e.g.*, say, a standard 30-year mortgage period) it would, for instance, be prudent to adjust the beach width of a given topographic survey to its narrowest expected seasonal dimension, then to apply extreme event analyses. Considering the significant outlay of resources for beach nourishment projects, it would seem appropriate to consider seasonal shoreline variability both in project design and in assessing performance.

The controversial issue of whether coastal hardening structures (*e.g.*, seawalls, bulkheads, revetments) promote the erosion of beaches fronting them, is one of complex proportions. Without being long-winded, the issue might finally be resolved by inspecting long-term shoreline location data. Again, however, seasonal shoreline shifts would require quantification and application in the analysis. At the very least, methodology developed here would allow one to determine if seasonal shoreline change was of significant proportions that it should be considered in design applications. Using known wave, tidal, and sedimentological data it would be a straightforward task to compile such results, particularly in Florida where the coast has been monumented.

CONCLUDING REMARKS

For much of our shoreline, seasonal shifts in shoreline position occur. While the phenomenon has been the subject of considerable concern, no specific quantification has, until now, surfaced.

It has been noted earlier that some shorelines (*e.g.*, east-west trending shores) apparently do not exhibit seasonal shifts. This may be due to storm wave impacts occurring in groups for periods of less than monthly and/or due to climatic change affecting storm front azimuths relative to shoreline azimuths. Correlation might be attained by selecting most and least active monthly averages, or by applying moment statistics.

An historical study of Gulf of Mexico storm wave and direct coastal impacts, as Dolan and others (1988) conducted for the Atlantic Ocean off North Carolina, is needed. Results of such a study would shed light on the regional behavior of east-west trending shores of the central Gulf, and would also be applicable to the more nearly north-south trending shores of the lower Gulf coasts of Florida and Texas.

While the methodology for assessing average seasonal shoreline and beach width variability can be used for a variety of important applications, the developments presented here are a first appraisal. The intent of this work is to invoke interest in the subject and to act as a plea for additional data on which to test existing predictive methodology and/or develop more exacting technology. For instance, while this work treats straight ocean-fronting beaches composed of sand, seasonal changes of pocket beaches might be treated by including seasonal wave approach angle changes, and data for beaches composed of sand and pebbles (i.e., a very large standard deviation) would help in understanding the role of the sedimentologic property element.

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APPENDIX: PROPAGATION OF ERRORS IN COMPUTING

(compiled from formulations in Barry, 1978)

Where R is the result of some numerical operation (*e.g.*, addition, subtraction, multiplication, division, power function, average, etc.) for measured quantities N_1, N_2, $N_3,\dots,N_n$, each with associated measurement errors E_1, E_2, $E_3,\dots,E_n$, respectively, then the total error E_{tot} is applied as:

$$R \pm E_{tot}$$

where E_{tot} is determined according to:

ADDITION OR SUBTRACTION

$$E_{tot} = \sqrt{E_1^2 + E_2^2 + E_3^2 + \dots + E_n^2}$$

PRODUCT OR QUOTIENT

$$E_{tot} = R\sqrt{\left(\frac{E_1}{N_1}\right)^2 + \left(\frac{E_2}{N_2}\right)^2 + \left(\frac{E_3}{N_3}\right)^2 + \dots + \left(\frac{E_n}{N_n}\right)^2}$$

AVERAGE

$$E_{tot} = \frac{\sqrt{E_1^2 + E_2^2 + E_3^2 + \dots + E_n^2}}{n}$$

CONSTANT ERROR

where $E = E_1 = E_2 = E_3 = \dots = E_n$

$$E_{tot} = E\sqrt{n}$$

POWER

where $(R + E_1)^m = (N_1 + E_1)^m$

$$E_{tot} = E_1 N_1^{m-1}$$

ROOT

where $(R + E_1)^{1/m} = (N_1 + E_1)^{1/m}$

$$E_{tot} = m^{-1} E_1 N_1^{(1/m)-1}$$

OPEN-OCEAN WATER LEVEL DATUM PLANES: USE AND MISUSE IN COASTAL APPLICATIONS

by

James H. Balsillie, P. G. No. 167

ABSTRACT

Swanson (1974) notes that tidal datum planes "... are planes of reference derived from the rise and fall of the oceanic tide". There are numerous tidal datum planes. Commonly used datums in the United States include the planes of ***mean higher high water*** (MHHW), ***mean high water*** (MHW), ***mean tide level*** (MTL), ***mean sea level*** (MSL), ***mean low water*** (MLW), and ***mean lower low water*** (MLLW). Each datum is defined for a specific purpose or to help describe some tidal phenomenon. For instance, MHW high water datums have been specified by cartographers in some states (*e.g.*, Florida) as a boundary of property ownership. Low water datum planes have been used as a chart datum because it is a conservative measure of water depth and, hence, provides a factor of safety in navigation. High water tidal stages have historically been of importance because they identified when sailors should report for duty when "flood tide" conditions were favorable for ocean-going craft to leave port, safely navigate treacherous ebb tidal shoals, and put to sea. Not only do tidal datum specifications vary geographically based on local to regional conditions for purposes of boundary delineation, cartographic planes, design of coastal structures, and land use designations, etc., but they have changed historically as well. Moreover, given ongoing technological advancements (*e.g.*, computer-related capabilities including the advent of the personal computer), how we approach these data numerically is highly important from a data management viewpoint.

INTRODUCTION

Tide gauges are usually located in water bodies connected to the oceans, such as estuaries and rivers, and may even be used to record seiches such as those occurring in the Great Lakes. Here, however, the concern is with ***open ocean tides***. Open ocean tide gauges are defined "... as those gauges sited directly upon the open ocean nearshore waters and subject to the influence of ocean processes, excluding those under the influence of inlet hydrodynamics ..." (Balsillie and others, 1987a, 1987b, 1987c). The latter constraint in the definition is included even though it is difficult to determine the extent of influence from inlet to inlet.

Open ocean tidal datum applications in Florida are problematic because there are a limited number of gauging stations to represent astronomical tidal phenomena. While it has been standard practice to linearly interpolate open ocean tidal datums between gauges, such an approach is not recommended should the gauges be spaced further apart than about 6.2 miles (Balsillie and others, 1987a). Of the 33 currently available open ocean gauges in Florida (Table 1), only three pairs of stations meet this constraint. In fact, the average distance between Florida open ocean tide gauges is 27.4 miles. Ostensibly, the 6.2-mile constraint is recommended since concurrently similar tidal stage datum elevations can vary significantly over segments of the coastline when this distance

Table 1. Tidal Datums and Ranges for Open Coast Gauges of Coastal Florida (Updated in 1992 after Balsillie, Carlen and Watters, 1987a, 1987b, 1987c).

Station Name	Open Coast Gauge I. D.	State Plane Coordinates		MHHW	MHW	MTL	MLW	MLLW	MTR (Feet)	X (Miles)
		Easting (Feet)	Northing (Feet)	(Ft. NGVD)						
FLORIDA EAST COAST										
Fernandina Beach	0061	362649.81	2287406.62	3.52	3.11	0.25	-2.61	---	5.72	5.831
Little Talbot Island	0194	372355.76	2216450.20	3.60	3.30	0.55	-2.19	-2.35	5.49	19.753
Jacksonville Beach	0291	377952.02	2163090.54	3.25	2.94	0.39	-2.17	-2.33	5.11	30.150
St. Augustine Beach	0587	417053.67	2008422.56	2.73	2.48	0.15	-2.17	-2.33	4.62	60.491
Daytona Beach	1020	498405.18	1779242.33	2.52	2.27	0.19	-1.88	-2.06	4.15	106.820
Daytona Beach Shores	1120	511704.59	1749549.40	2.44	2.06	0.07	-1.89	-2.06	3.98	112.990
Patrick Air Force Base	1727	628785.91	1421930.52	2.27	2.09	0.32	-1.45	-1.61	3.54	185.030
Eau Gallie Beach	1804	619782.34	1383121.82	2.25	2.07	0.33	-1.33	-1.49	3.40	191.810
Vero Beach	2105	707153.65	1213218.30	2.01	1.89	0.19	-1.51	-1.67	3.40	227.560
Lake Worth Pier	2670	815854.41	829171.49	1.93	1.87	0.47	-0.93	-1.10	2.80	304.910
Hillsboro Inlet	2862	800981.65	700015.89	1.79	1.73	0.43	-0.87	-1.03	2.60	329.700
Lauderdale-by-the-Sea	2899	797331.41	675151.18	1.99	1.93	0.63	-0.67	-0.83	2.60	334.580
North Miami Beach	3050	789219.52	581194.67	1.77	1.71	0.46	-0.79	-0.96	2.50	352.520
Miami Beach (City Pier)	3170	785773.29	522409.95	1.76	1.67	0.42	-0.84	-1.00	2.51	363.780
NOTE: X is the shoreline distance in miles south of the center line of St. Mary's Entrance Channel (origin: northing = 2317969.50 feet; easting = 366516.31 feet).										
FLORIDA LOWER GULF COAST										
Bay Port	7151	291286.83	1527111.33	2.31	1.88	0.70	-0.48	-0.97	2.36	4.472
Howard Park	6904	241667.70	1389244.60	1.87	1.50	0.43	-0.64	-1.19	2.14	33.555
Clearwater	6724	231561.35	1325079.09	1.62	1.29	0.33	-0.64	-1.17	1.88	46.634
Indian Rocks Beach Pier	6623	224898.87	1295432.55	1.50	1.13	0.25	-0.63	-1.15	1.76	52.650
St. Petersburg Beach	6430	261046.14	1218243.36	1.52	1.16	0.42	-0.32	-0.83	1.48	69.560
Anna Maria	6243	268746.05	1150335.15	1.52	1.20	0.45	-0.29	-0.76	1.49	83.284
Venice Airport	5858	352475.83	995445.81	1.35	1.07	0.36	-0.35	-0.84	1.42	117.918
Captiva Island, South	5383	351707.10	779777.00	1.52	1.27	0.42	-0.42	-0.94	1.69	163.464
Naples	5110	563431.54	652958.84	1.81	1.55	0.50	-0.54	-1.17	2.09	205.226
Marco Island	4967	589299.92	572441.43	1.96	1.71	0.56	-0.59	-1.20	2.30	222.015
NOTES: 1. X is the shoreline distance in miles south of an arbitrary location in Hernando County, FL. (origin: northing = 1551271.53 feet; easting = 287952.53 feet). 2. State Plane Coordinates and distances are based on Zone 3 transformations where necessary.										
FLORIDA NORTHWEST PANHANDLE COAST										
Dauphin Island	5180	472269.39	871380.81	0.87	0.82	0.26	-0.29	-0.34	1.11	-33.347
Gulf Shores	1269	467866.88	999712.52	1.20	1.13	0.50	-0.12	-0.18	1.25	-9.228
Navarre Beach	9678	508373.97	1254261.65	1.20	1.13	0.50	-0.14	-0.21	1.27	39.737
Panama City Beach	9189	434604.55	1579274.67	1.25	1.18	0.54	-0.09	-0.14	1.27	104.489
St. Andrews Park	9141	414248.96	1610651.22	1.16	1.06	0.47	-0.12	-0.23	1.18	111.489
Mexico Beach	8995	346061.53	1706517.15	1.06	1.00	0.41	-0.17	-0.22	1.17	134.479
Cape San Blas	8942	244076.07	1726862.58	1.01	0.99	0.30	-0.38	-0.38	1.37	162.615
Alligator Point	8261	325491.24	2035385.12	1.73	1.49	0.53	-0.44	-1.02	1.93	232.302
Bald Point	8237	344903.70	2050145.99	2.09	1.76	0.62	-0.52	-0.98	2.28	238.633
NOTE: X is the shoreline distance in miles east of the Alabama/Florida border (origin: northing = 478050.00 feet; easting = 1047360.00 feet).										

GENERAL NOTES:

1. Tidal datums are referenced to NGVD of 1929.
2. Source of information - Bureau of Survey and Mapping, Division of State Lands, Florida Department of Environmental Protection, for the National Tidal Datum Epoch of 1960-1978.
3. MLLW = mean lower low water; MLW = mean low water; MTL = mean tide level, which along the open coast = MSL = mean sea level; MHW = mean high water; MHHW = mean higher high water; MTR = mean range of tide (*i.e.*, MTR = MHW - MLW).

is exceeded. In addition, it was found that linear interpolation led to results that simply do not reflect the natural behavior of coastal processes. Hence, in 1987, a non-linear nth-order polynomial numerical methodology was introduced and utilized to determine quantitatively open ocean tidal datums for a significant portion of Florida's ocean-fronting coasts (Balsillie and others, 1987a, 1987b, 1987c). Updated results (Balsillie and others, 1998) are plotted in Figures 1, 2, and 3.

This work is a companion paper to tidal datums listings for Florida originally published by Balsillie and others (1987a, 1987b, and 1987c) and updated by Balsillie and others (1998). It was determined necessary to undertake the present compilation because of an increasing number of misapplications of tidal datums appearing in the coastal engineering literature. For example, Foster (1989, 1991), Foster and Savage (1989a, 1989b), and Schmidt and others (1993) consistently used MHW as their vertical reference from which volumetric beach changes were measured. Komar (1998) used NGVD (it is assumed that this is NGVD of 1929, although such is not stated) but stated that for his site NGVD "... is approximately equal to mean sea level ...". Lee and others (1998) used NGVD at a North Carolina coastal location; they did not state, however, how NGVD departs from MSL at their site. These exemplify instances in which tidal datums referencing can introduce significantly compounded error. One illustrates other cases where no explanation detailing how tidal datums are applied is given, and one cannot be sure if he or she can have confidence in final results.

To one extent or another, misapplication of tidal datums may be due to a lack of understanding as to how they have been

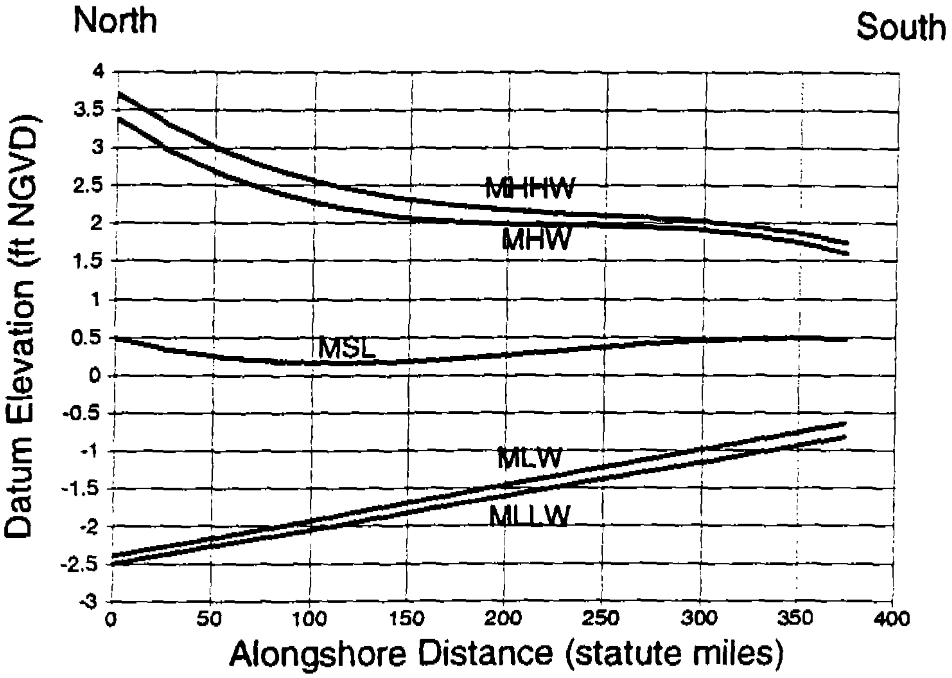

Figure 1. Relationship between open coast dial datums and National Geodetic Vertical Datum of 1929 for the Florida East Coast. Alongshore distance is measured from the center line of St. Mary's Entrance Channel proceeding south to Cape Florida. (Updated in 1992 after Balsillie and others, 1987a).

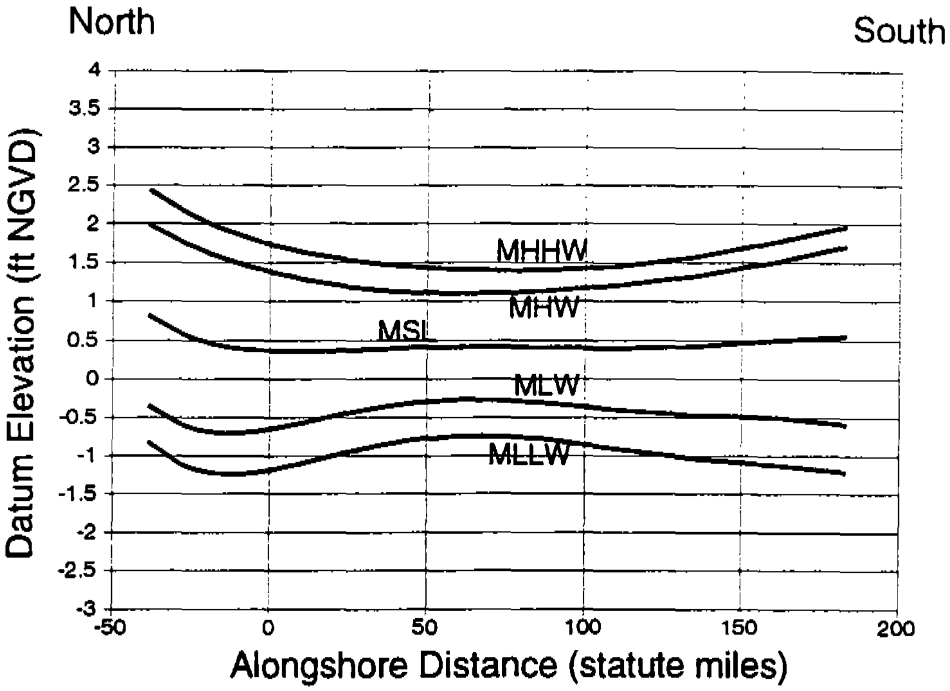

Figure 2. Relationship between open coast tidal datums and National Geodetic Vertical Datum of 1929 for the Florida Lower Gulf Coast. Alongshore distance is measured from north to south with the origin located at the north end of Pinellas County (i.e., north end of Honeymoon Island) and terminating to the south at Caxambas Pass. (Updated in 1992 after Balsillie and others, 1987b).

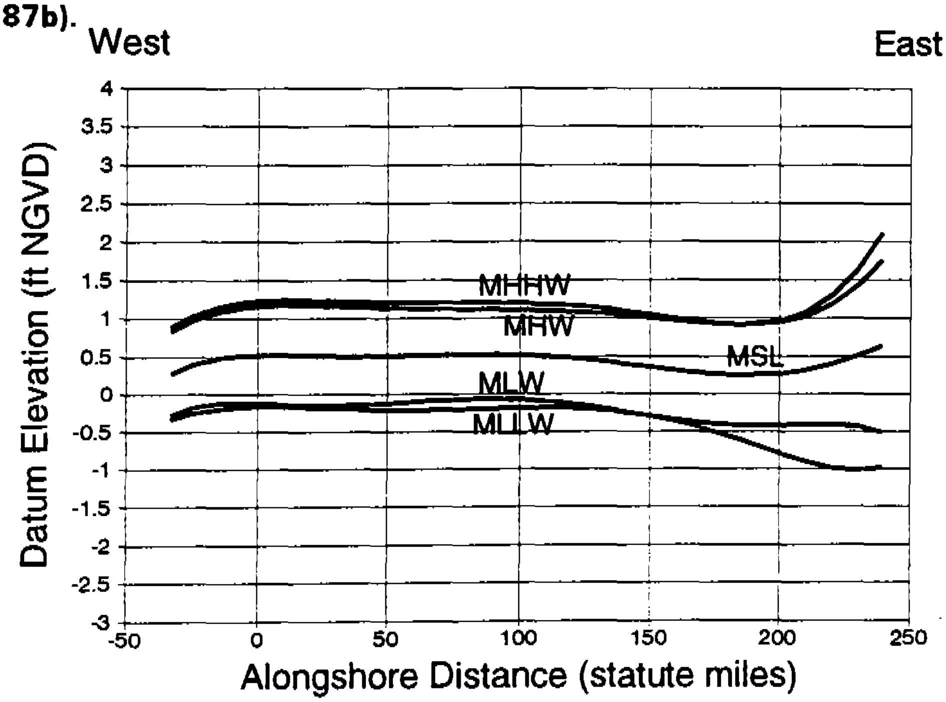

Figure 3. Relationship between open coast tidal datums and National Geodetic Vertical Datum of 1929 for the Northwest Panhandle Gulf Coast of Florida. Alongshore distance is measured from the Florida-Alabama border east to Ochlockonee River Entrance. (Updated after Balsillie and others, 1987c).

established, and what they represent. The first part of this work, therefore, discusses the history of tidal datums determination and definition in U. S. coastal waters.

Guidance illustrating proper tidal datums applications for coastal scientists and engineers is available for important basic tidal datums applications (*e.g.*, Cole, 1983, 1991, 1997; Pugh, 1987; Lyles and others, 1988; Brown and others, 1995; Gorman and others, 1998; Stumpf and Haines, 1998). For other specific cases it is absent. Verbal communications by a few professionals reach only a small audience. Even then, the latter often results in a blank stare, leaving the instructor with the message that the explanation was not comprehended by the informant, that he or she has predetermined that it is not important, or that the informant has already predetermined just what is proper. The author has, therefore, in the latter portion of this work presented a series of selected examples and discussion about tidal datums applications. At the outset, one needs to understand that the surveying profession, in large part, is concerned with the management of error and variability associated with horizontal and vertical control. It is often the case that one is not convinced by simple directive that there is a proper methodology, so evidenced by recent improper uses of datum applications in coastal engineering works cited above. This occurs because there isnothing to convince one that the methodology is better or best at reducing error or variability. Therefore, the author has opted to present a series of common improper tidal datums applications and to demonstrate, relative to the proper application, just why, numerically, they are inappropriate.

INLETS/OUTLETS AND THE ASTRONOMICAL TIDE

The preceding definition of open ocean tides excludes the influence of inlets (perhaps more appropriately termed outlets after Carter, 1988, p. 470). Hence, exclusion of inlets might be an oversight, particularly in view of the current inlet management effort undertaken by the State. At a most basic level, the classification of inlets is well known depending upon the effect of astronomical tides relative to volume of fluvial discharge (*e.g.*, van de Kreeke, 1992). In fact, for many inlets, selection of the proper datum plane assists in providing a least equivocal representative design water reference level. Hence, a section on inlets as they relate to astronomical tides in Florida is herein developed.

WATER LEVEL DATUM PLANES

In endeavors concerning hydraulic phenomena with a free fluid surface, many practitioners have lost perspective in selection of the reference fluid plane across which force elements propagate, in both the prototypical setting and the natural environment. Given this assertion, perhaps it would be appropriate to review the basics of historical development of tidal datum plane quantification that has withstood the practicable tests of time.

The first recorded effort of geodetic leveling in the United States began in 1856-57. During ensuing years surveying control become better. As chronicled by Schomaker (1981), by the first quarter of this century:

> ***After the previous period of comparatively short intervals between adjustments, 17 years elapsed before the network was adjusted again. In the meantime, it had become more extensive and complex, and included many more sea-level connections. The General Adjustment of 1929 incorporated 75,159 km of leveling in the United States and, for the first time, 31,565 km of leveling in Canada. The U.S. and Canadian networks were connected by 24 ties between Calais, Me./Brunswick, New Brunswick; and Blaine Wash./ Colebrook, British Columbia. A fixed elevation of zero***

> ***was assigned to the points on mean sea level determined at the following 26 tide stations.***
>
> *Father Point, Quebec*
> *Halifax, Nova Scotia*
> *Yarmouth, Nova Scotia*
> *Portland, Me.*
> *Boston, Mass.*
> *Perth Amboy, N.J.*[1]
> *Atlantic City, N.J.*
> *Baltimore, Md.*
> *Annapolis, Md.*
> *Old Point Comfort, Va.*
> *Norfolk, Va.*
> *Brunswick, Ga.*
> *Fernandina, Fla.*
> *St. Augustine, Fla.*
> *Cedar Keys, Fla.*
> *Pensacola, Fla.*
> *Biloxi, Miss.*
> *Galveston, Tex.*
> *San Diego, Calif.*
> *San Pedro, Calif.*
> *San Francisco, Calif.*
> *Fort Stevens, Ore.*
> *Seattle, Wash.*
> *Anacortes, Wash.*
> *Vancouver, British Columbia*
> *Prince Rupert, British Columbia*
>
> ---
>
> ***[1] There was no tide station at Perth Amboy, but the elevation of a bench mark at Perth Amboy was established by leveling from the tide station at Sandy Hook.***
>
> ***The 1929 adjustment provided the basis for the definition of elevations throughout the national network as it existed in 1929, and the resulting datum is still used today.***

The elevation adjustment of 1929 was referred to as the "Sea Level Datum of 1929", although it commonly became known as the "Mean Sea Level". In coastal work, however, there are two standard Design Water Levels (DWLs) that are applied. These and their definitions (Galvin, 1969) are:

Mean Water Level (MWL) - the time-averaged water level in the presence of waves, and

Still Water Level (SWL) - the time-averaged water level that would exist if the waves are stopped but the astronomical tide and storm surge are maintained.

These water levels (*i.e.*, MWL and SWL) apply for any length of time over which a field study or experiment is conducted, while Mean Sea Level and other tidal datums are determined as an average of measurements made over the 19-year National Tidal Datum Epoch (*i.e.*, the Metonic cycle; shorter series are appropriately named, e.g., Monthly Mean Sea Level, etc.). It was not until 1973 that the confusion over the Sea Level Datum or "Mean Sea Level" as it popularly came to be known and Mean Water Level was resolved by assigning the more appropriate name of "National Geodetic Vertical Datum of 1929" (NGVD) to replace "Sea Level Datum of 1929". NGVD of 1929 is additionally defined (Harris, 1981) as a fixed reference adopted as a standard geodetic datum for elevations determined by leveling. It does not take into account the changing stands of sea level. Because there are many variables affecting sea level, and because the geodetic datum represents a best fit over a broad area, the relationship between the geodetic datum and local mean sea level is not consistent from one location to another in either time or space. For this reason NGVD should not be confused with mean sea level, even though it has always been defined by a mean sea level (Schomaker, 1981).

The various North American tidal datum planes are defined (*e.g.*, Marmer, 1951; Swanson, 1974; U. S. Department of Commerce, 1976; Anonymous, 1978; Harris, 1981; Hicks, 1984) as follows:

National Tidal Datum Epoch - the specific 19-year period adopted by the National Ocean Service as the official time segment over which tide observations are taken and reduced to obtain mean values for tidal datums. It is necessary for standardization because of periodic and apparent secular trends in sea level. It is reviewed annually for possible revision and must be actively considered for revision every 25 years.

Mean Higher High Water (MHHW) - the average of the higher high water heights of each tidal day observed over the National Tidal Datum Epoch.

Mean High Water (MHW) - the average of all the high water heights observed over the

National Tidal Datum Epoch.

Mean Sea Level (MSL) - the arithmetic mean of hourly heights observed over the National Tidal Datum Epoch. Shorter series are specified in the name; *e.g.*, monthly mean sea level and yearly mean sea level.

Mean Tide Level (MTL) - a plane midway between Mean High Water and Mean Low Water that may also be calculated as the arithmetic mean of Mean High Water and Mean Low Water. MTL and MSL planes approximate each other along the open coast (Swanson, 1974, p. 4).

Mean Low Water (MWL) - the average of all the low water heights observed over the National Tidal Datum Epoch.

Mean Lower Low Water (MLLW) - the average of the lower low water heights of each tidal day observed over the National Tidal Datum Epoch.

Mean astronomical tide elevations exhibit cyclic seasonal variability (Marmer, 1951; Swanson, 1974; Harris, 1981) and are included in tide predictions. Marmer (1951) notes that seasonal variation in terms of monthly mean sea level for the U. S. can be as much as one foot. Based on the many years of monthly data, researchers (Marmer, 1951; Harris, 1981) note slight variations in the seasonal cycle from year-to-year, but also recognize the periodicity in peaks and troughs over the years. For much of our coast, lower mean sea levels occur during the winter months and higher mean sea levels during the fall. Harris (1981) inspected the record to determine if storm and hurricane occurrence was in any way responsible for the seasonal change, but found "... no systematic variability". Galvin (1988) reports that seasonal mean sea level changes are not completely understood, but suggests that there appears to be two primary causes for lower winter mean tide levels for the U. S. east coast: 1) strong northwest winter winds blow the water away from shore, and 2) water contracts as it cools. He notes that winds are more important in shallow water where tide gauges are located, but that contraction becomes important in deeper waters. Swanson (1974) also notes "... seasonal changes resulting from changes in direct barometric pressure, steric levels, river discharge, and wind affect the monthly variability." Cole (1997) notes that seasonal variation in tides is usually attributed to two harmonic constitutents: one with a period of one year termed the solar annual tidal constituent, and the other with a period of six months termed the solar semiannual constituent. Some consider these to be meteoroligical in nature, rather than astronomic. However, because the root cause of cyclic seasonal weather is the changing declination of the sun, they should more nearly be astronomical in origin. Harmonic analysis of the annual tidal record can easily determine the amplitude and phase of each of these constituents, thereby providing a mathematical definition of the seasonal variation. (George M. Cole, personal communications.) Shorter-term changes occur bi-weekly and monthly; longer-term changes occur in the relative levels of land and sea that are of eustatic or isostatic origins (*e.g.*, Embleton, 1982). It is apparent, therefore, that there is natural variability associated with any average representation of tidal datums. Given these natural insensitivities associated with averages, it is important that we do not exacerbate them through improper manifestations of our own making when applying tidal datums as references.

At this point it is necessary to define certain terms. If one is interested in merely referencing a vertical distance without a requirement of spatial comparability, the result is termed a ***monergistic application***. That is, the result of the application is good only for that particular location. If, however, in addition to a vertical datum, one has a need that the resulting application will have spatial comparability (*i.e.*, it can be compared to the same application at <u>any other</u> site), the result is a ***synergistic application***. We shall discuss this latter class of application first.

SYNERGISTIC TIDAL DATUM PLANE APPLICATIONS

It has been widely recognized, as demonstrated in the introduction to this paper, that selection of the proper tidal datum depends upon the purpose to which it is to be applied. The main purpose of this work is to determine the proper tidal datum for use in coastal science and engineering for referencing littoral force and response elements. ***Force elements*** include astronomical tides, storm tides, nearshore currents, waves, etc. ***Response elements*** include extreme event beach and coast erosion, foreshore slope changes, long-term shoreline changes, seasonal shoreline changes, etc. It became apparent during the course of preparation of this paper that determination of the proper datum plane is probably best accomplished by discussing application/use examples.

EXTREME EVENT IMPACT

From the preceding description of tidal datum planes we must, from the scientific perspective, be quite careful in selecting a reference water level from which we define such response elements as beach and coast erosion due to extreme event impact, and such force elements as the peak combined storm tide accompanying extreme events that, in part, induces such erosion. As noted previously, water level datum planes include certain insensitivities regardless of the rigorous nature of statistical methods applied. It is necessary that we do not further exacerbate these insensitivities, creating additional variability and error through selection of improper reference datums.

As an example, suppose that we are analyzing and interpreting profile data to determine volumetric erosion of sandy beaches and coasts due to extreme event impact. Further, let us select as our reference water level datum Mean High Water, MHW. That is, we shall assess erosion volumes above MHW to an upland point that must be carefully deliberated depending upon whether the coast was non-flooded (interpretations are normally straightforward) or flooded and/or breached (interpretations can be problematic) as discussed by Balsillie (1985b, 1986). It must be recognized that MHW can be assigned the status of a signature value for a particular locality, representing its National Tidal Datum Epoch. This assessment can be levied because MHW can change significantly from locality-to-locality. For instance, in Florida MHW varies from +3.12 feet MSL (or +3.36 feet NGVD; Balsillie and others, 1987a) along the northern portion of Nassau County on the Atlantic east coast, to +0.66 feet MSL (or +0.90 feet NGVD; Balsillie and others, 1987c) along the western portion of Franklin County on the northwestern panhandle Gulf of Mexico coast of Florida. This embodies a potential maximum difference of almost 2.5 feet in MHW elevation about the State of Florida. Suppose that for the above two areas, profile conditions are comparable. Furthermore, suppose that extreme events embodying precisely the same magnitudes and characteristics producing identical force elements impacted the two areas, resulting in identical response elements, that is, the same erosion volumes (*i.e.*, the area above the dashed lines and below the solid lines of Figure 4). If, however, we reference the erosion volumes to MHW (shaded areas) as illustrated in Figure 4, 8.12 cubic yards of sand per foot are eroded above MHW along the northern portion of Amelia Island, 33 per cent less than the 12.05 cubic yards of sand per foot eroded above MHW along western St. George Island. It becomes quite clear, therefore, that erosion volumes around the state cannot be compared using MHW, since the MHW base elevation is not only

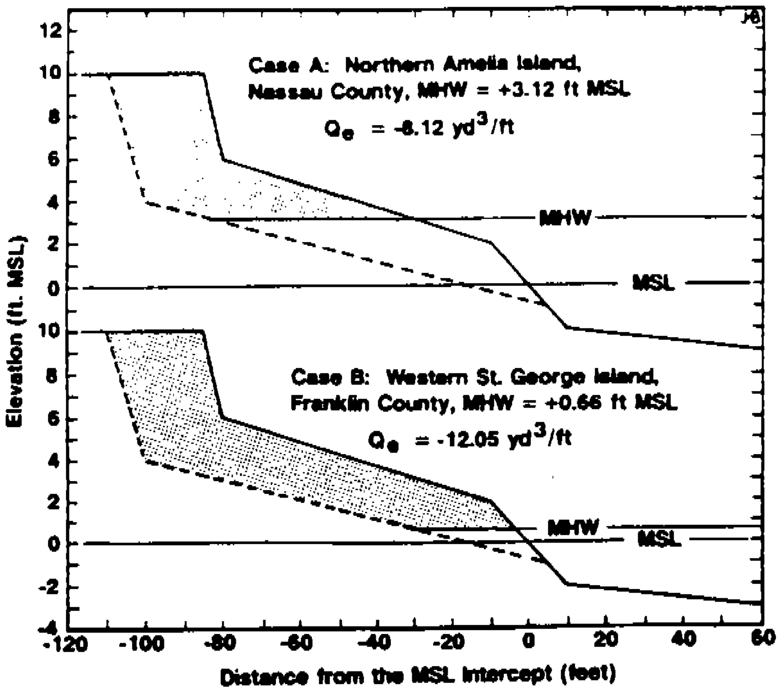

Figure 4. Erosion volumes, Q_e, above MHW for identical profiles impacted by identical storm events, but with different local MHW planes.

geographically variable, but significantly so. One will note further that, for other North American MHW datums (see Table 2), the problem can become even further exaggerated. In fact, it has been demonstrated that MSL is the best datum from which to reference erosion volumes; "... at the seaward extremity of the post-storm profile, some material of the seaward sink (also including some degree of post-storm beach recovery) may reside above MSL (determined to be about 6% of the seaward sink volume from 245 analyzed profile pairs), the analytical method is fairly unbiased since it is applied equally to all profiles investigated" (Balsillie, 1986). Seaward datums or depth of profile closure are not suitable references, if only because survey response is slow compared to the response of subaqueous sand-sized sediments in the energetic force element surf environment (*e.g.*, Pugh, 1987; Lyles and others, 1988).

It becomes apparent, therefore, that MHW is not the proper reference water level datum to apply for erosion volumes. It also becomes apparent that it is not proper to use the datum for reference for such a force element as the peak combined storm tide. Similar logic results in the conclusion that use of the MHHW, MLW, and MLLW datum planes would also be improper. It should, in fact, be clear that MSL (or MTL) is the <u>only</u> tidal datum that is to be used for reference.

LONGER-TERM BEACH RESPONSES

It is clear why the MSL datum is the desired convention to apply for extreme event impacts to which force and response elements are to be referenced. MSL datum should also be applied to longer-term force and beach responses. Notwithstanding the need for a standardized convention already required for extreme event impact, there is sound reasoning that it applies to longer-term scenarios, although, such application is more subtle than for the extreme event impact case. The preceding extreme event impact scenario has dealt with physical beach and coast conditions of a sort which transcend certain physiographic limitations. That is, the energetics associated with storms and hurricanes so exceed physical stability constraints that individual gradients comprising the beach and coast (*e.g.*, shoreface, foreshore slope, berm(s), dune or bluff stoss slope; see Figure 5) do not, in themselves, impose limiting conditions. Under normal littoral force conditions, however, physiographic slope characteristics become more nearly a limiting condition. Perhaps the most important of these gradients is the foreshore slope, a subject that needs some discussion prior to addressing two additional synergistic application/use examples, namely, seasonal beach changes and long-

Table 2. Selected North American Datums and Ranges Referenced to MSL (after Harris, 1981).

Station	MHHW	MHW	NGVD	MTL	MLW	MLLW	MTR
Eastport, ME	9.32	8.88	-0.20	-0.10	-9.01	-9.41	18.20
Portland, ME	4.87	4.45	-0.22	0.00	-4.46	-4.80	8.91
Boston, MA	5.16	4.72	-0.31	-0.15	-4.86	-5.19	9.58
Newport, RI	2.18	1.93	-0.23	+0.15	-1.69	-1.75	3.62
New London, CN	1.48	1.22	-0.43	-0.10	-1.34	-1.45	2.60
Bridgeport, CN	3.61	3.31	-0.54	-0.05	-3.36	-3.52	6.70
Willets Point, NY	3.85	3.59	-0.58	-0.05	-3.58	-3.78	7.10
New York, NY	2.51	2.19	-0.49	+0.05	-2.29	-2.42	4.50
Sandy Hook, NJ	2.66	2.33	-0.51	0.00	-2.34	-2.47	4.60
Breakwater Harbor, DE	2.46	2.04	-0.41	-0.05	-2.08	-2.15	4.10
Reedy Point, DE	3.07	2.73	-0.35	-0.10	-2.77	-2.85	5.51
Baltimore, MD	0.74	0.51	-0.43	-0.03	-0.52	-0.64	1.03
Washington, DC	1.54	1.39	-0.54	0.00	-1.37	-1.42	2.76
Hampton Roads, VA	1.41	1.22	-0.02	+0.03	-1.22	-1.26	2.44
Wilmington, NC	2.26	2.02	-0.38	+0.02	-2.24	-2.33	4.26
Charleston, SC	1.88	2.87	-0.05	+0.21	-2.67	-2.81	5.17
Savannah River Entr.	3.77	3.38	-0.28	-0.15	-3.56	-3.70	6.94
FLORIDA	**Listed in Table 1.**						
Mobile, AL	0.73	0.65	-0.05	-0.05	-0.62	-0.70	1.27
Galveston, TX	0.57	0.47	-0.10	-0.05	-0.44	-0.85	0.91
San Diego, CA	2.90	2.11	-0.21	-0.05	-2.09	-3.06	4.10
Los Angeles, CA	2.63	1.91	-0.08	0.00	-1.87	-2.82	3.80
San Francisco, CA	2.59	2.04	+0.06	+0.30	-1.93	-3.14	4.00
Cresent City, CA	3.22	2.56	-0.12	0.00	-2.49	-3.75	5.10
South Beach, OR	3.22	2.56	-0.49	+0.02	-3.09	-4.48	6.30
Seatle, WA	4.83	3.94	-0.35	0.00	-3.75	-6.48	7.60

NOTES:
MTR = Mean range of tide; average value of MTL is -0.01 feet MSL; average value of NGVD (1929) is -0.29 feet MSL; these stations do not necessarily represent open coast gauging sites.

term beach changes.

The foreshore slope or beach face slope (Figure 5) is defined by the ***Shore Protection Manual*** (U. S. Army, 1984) as "... that part of the shore lying between the crest of the seaward berm (or upper limit of wave wash at high tide) and ordinary low water mark, that is ordinarily traversed by the uprush and backwash of waves as tides rise and fall." Komar (1976) elaborates further, stating that the foreshore slope "... is often nearly synonymous with beach face but is commonly more inclusive, containing also some of the beach profile below the berm which is normally exposed to the action of the wave swash." The berm or beach berm is the "... nearly horizontal part of the beach or backshore formed by the deposit of material by wave action ... some beaches have no berms, others have one or several" (U. S. Army, 1984). The berm and foreshore (or beach face) are separated at the berm crest or berm edge.

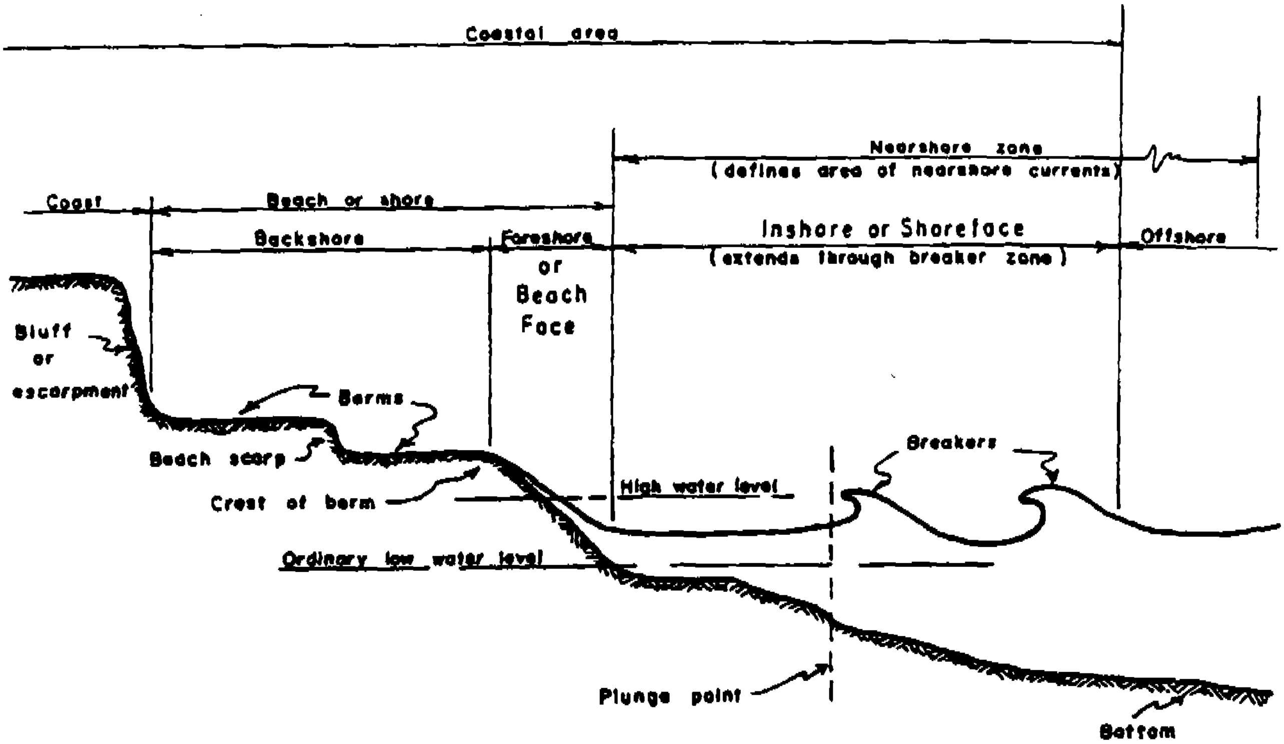

Figure 5. Beach profile-related terms (from U. S. Army, 1984).

In Florida, the foreshore slope is defined (Chapter 16B-33, Florida Administrative Code, State of Florida) as:

> ***... that portion of the beach or coast that is, on a daily basis, subject to the combined influence of high and low tides, and wave activity including wave uprush or backwash. For purposes of this Chapter, it includes that part of the beach between mean higher high water (MHHW) and mean lower low water (MLLW).***

The slope of the foreshore, the steepest portion of the beach profile, is a useful design parameter since along with the berm elevation it determines beach width (U. S. Army, 1984, p. 4-86). As a response, element the foreshore is a function of force elements such as astronomical tides, waves, currents, and property elements such as grain size, sediment porosity, and sediment mass density.

The slope of the foreshore tends to increase with an increase in the grain size of the sediment (U. S. Army, 1933; Bascom, 1951; King, 1972). Dubois (1972) found an inverse relationship between grain size and foreshore slope where the foreshore sediments contain appreciable quantities of heavy minerals. Sediment porosity and permeability effects on the foreshore are discussed by Savage (1958).

Generally, foreshore slope increases with an increase in nearshore wave energy (all other factors held constant), and an inverse relationship is found when wave steepness is applied (*e.g.*, Bascom, 1951; Rector, 1954; King, 1972). For instance, steeper eroding waves such as winter waves will result in flatter foreshore slopes, while longer (less steep) accretionary waves such as post-storm or summer waves produce steeper slopes. Average foreshore slope statistics for Florida are listed in Table 3. While this treatment of foreshore slopes is general, it

Table 3. Florida Foreshore Slope Statistics by County and Survey.

County	Survey Type	Survey Date	n	Average Slope	Standard Deviation
FLORIDA EAST COAST					
Nassau	Control Line	Feb 1974	81	0.0359	0.0235
Nassau	Control Line	Sep-Oct 1981	85	0.0474	0.0344
Duval	Control Line	Mar 1974	68	0.0199	0.0178
St. Johns	Control Line	Aug-Sep 1972	203	0.0523	0.0322
St. Johns	Control Line	Feb-May 1984	210	0.0339	0.0384
Flagler	Control Line	Jul-Aug 1972	99	0.1077	0.0273
Volusia	Control Line	Apr-Jun 1972	227	0.0348	0.0306
Brevard	Control Line	Sep-Nov 1972	217	0.0798	0.0413
Brevard	Control Line	Aug 1985-Mar 1986	219	0.0719	0.0347
Indian River	Control Line	Nov 1972	116	0.1163	0.0335
Indian River	Control Line	1986	119	0.1201	0.0793
St. Lucie	Control Line	Jun 1972	115	0.1012	0.0358
St. Lucie	Condition	Jan-Feb 1983	36	0.0919	0.0248
Martin	Control Line	Oct-Nov 1971	115	0.0939	0.0378
Martin	Control Line	Jan-Feb 1976	96	0.0867	0.0287
Martin	Control Line	Feb-Apr 1982	104	0.0845	0.0301
Palm Beach	Control Line	Nov 1974-Jan 1975	226	0.1011	0.0347
Palm Beach	Condition	Aug 1978	24	0.1113	0.0334
Broward	Control Line	1976-1976	127	0.1099	0.0423
Dade	Condition	Nov 1985-Feb 1986	28	0.1243	0.0328
Total n and Weighted Averages			2,515	0.0760	0.0359
FLORIDA LOWER GULF COAST					
Pinellas	Control Line	Sep-Oct 1974	185	0.0747	0.0447
Manatee	Control Line	Aug 1974	67	0.1009	0.0419
Manatee	Control Line	Aug 1986	67	0.0942	0.0377
Sarasota	Control Line	Jun-Aug 1974	181	0.0983	0.0375
Sarasota	Condition	Apr 1985	62	0.1051	0.0469
Charlotte	Control Line	May 1974	67	0.0757	0.0343
Charlotte	Control Line	Dec 1982	68	0.1127	0.0363
Lee	Control Line	Feb 1974	238	0.0843	0.0415
Lee	Control Line	May-Sep 1982	236	0.0980	0.0419
Collier	Control Line	Mar-Apr 1973	144	0.0796	0.0265
Collier	Condition	Sep 1984	40	0.0927	0.0277
Total n and Weighted Averages			1,355	0.0903	0.0389
FLORIDA NORTHWEST PANHANDLE COAST					
Franklin	Control Line	May-Jul 1973	147	0.0933	0.0349
Franklin	Control Line	Jun-Sep 1981	244	0.1155	0.0472
Franklin	Condition	Oct 1982	31	0.0769	0.0322
Gulf	Control Line	Jul-Sep 1973	161	0.1032	0.0540
Gulf	Condition	Jan 1983	45	0.0785	0.0327
Bay	Control Line	Feb 1971-Feb 1973	141	0.0707	0.0255
Walton	Control Line	Oct 1973	130	0.0991	0.0699
Walton	Control Line	May 1981	130	0.1060	0.0578
Okaloosa	Control Line	Nov-Dec 1973	49	0.0650	0.0406
Escambia	Control Line	Jan-Feb 1974	213	0.0988	0.0429
Total n and Weighted Averages			1,219	0.0970	0.0458
Grand Total n and Weighted Average			5,089	0.0848	0.0391

NOTE: n = number of profiles per survey.

will suffice for the following use/application examples.

Seasonal Beach Changes

Beach changes due to extreme impacts from storms and hurricanes are considered to more nearly represent isolated events. There are, however, beach changes that are more nearly episodic or cyclic. For instance, systematic beach changes through an astronomical tidal cycle (*e.g.*, Strahler, 1964; Sonu and Russell, 1966; Schwartz, 1967), cut and fill associated with spring and neap tides (*e.g.*, Shepard and LaFond, 1940; Inman and Filloux, 1960), and effects of sea breeze (*e.g.*, Inman and Filloux, 1960; Pritchett, 1976), are well known. Of the possible cyclic occurrences, however, perhaps the most pronounced is that occurring on the seasonal scale. Using the above prescribed rules, the following scenarios can be suggested. During the winter season, when incident storm wave activity is most active, high, steep waves result in shoreline recession. Normally, the berm is eroded and a gentle foreshore slope is produced. Sand removed from the beach is stored offshore in one or more longshore bars. During the summer season smaller waves with smaller wave steepness values transport the sand stored in longshore bars back onshore, resulting in a wider beach berm and steeper foreshore.

Seasonal beach changes have been described in terms of sand volume changes, contour elevation changes, and horizontal shoreline shift or beach width changes (see Balsillie, 1998). Here, however, beach width is used since, compared to the others, it offers the largest range in magnitudes.

Let us investigate such seasonal changes for two localities with identical profile conditions and average seasonal MSL shoreline variations, but different MHW datums. First, however, we need some representative foreshore slope data. From Table 3, let us select the average foreshore slope of tan α_{fs} = 0.085 to represent a winter foreshore slope and a maximum of tan α_{fs} = 0.2 (*i.e.*, 0.085 + 3 standard deviations) to represent a summer foreshore slope. The two cases, each with a summer and winter profile are illustrated in Figure 6.

Like Figure 4, Figure 6 is a simplification,

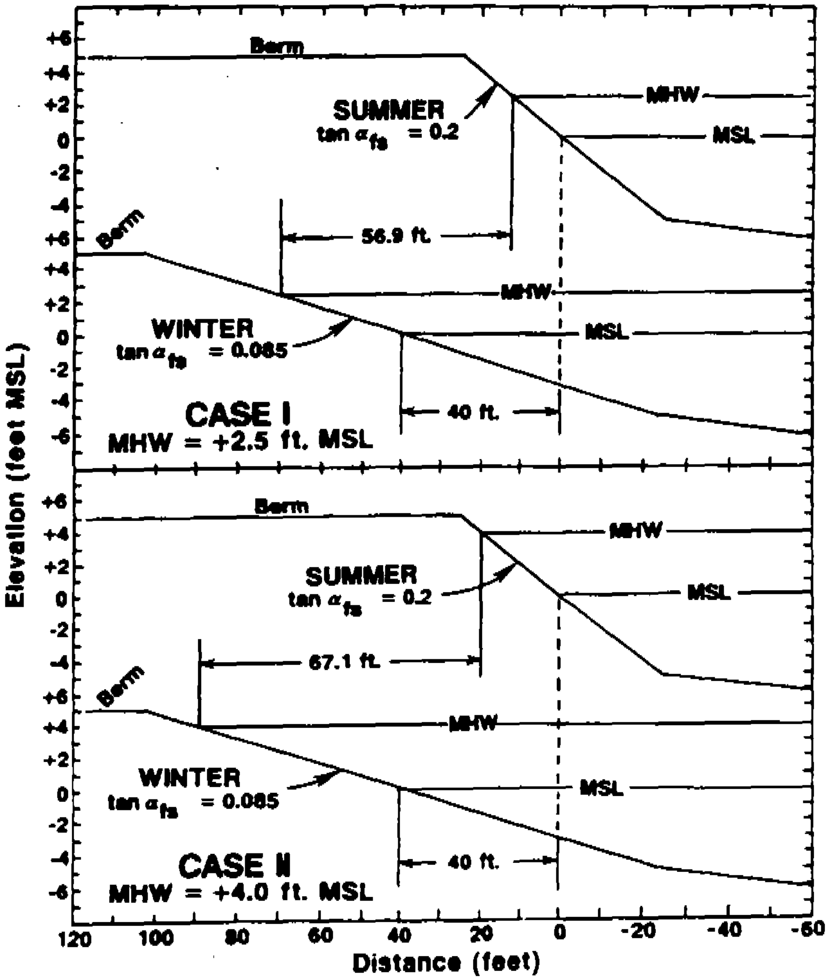

Figure 6. Seasonal horizontal shoreline shift analysis.

albeit representative since the slopes and distances presented are precise. First, let us focus our attention on the CASE I locality where MHW = +2.5 feet MSL. One will see that if we utilize MSL as the reference datum, the seasonal variability in beach width shifts by 40 feet. If, however, one uses MHW as the reference datum, the shift is 56.9 feet. The two values depart from each other by 30 per cent. If, on one hand, the CASE I locality were to be singularly assessed using the MHW reference plane shoreline, consistent results would emerge. If, on the other hand, one would wish to relate force elements (e.g., wave and tide characteristics) to the shoreline response, the use of MHW would pose problems (more about this later).

Similar assessment for the CASE II locality (MHW = +4.0 feet MSL) results in a departure of the MHW - MSL shoreline change of 40 per cent. As for CASE I, application results similarly apply.

Now let us compare the results of shoreline shift at the two localities. MSL shoreline shifts would remain comparable from locale to locale, since they directly represent both the tide base and surf base. MHW shoreline shifts, however, depart from each other by 15 per cent. Again, as with extreme event impact, MHW shoreline shifts can not be compared from locality to locality (the same would hold true for other datums such as MHHW, MLW, MLLW, etc.). In fact, if we evaluated seasonal beach changes volumetrically, MHW or any of the other site-specific variable datums would result in precisely the same non-comparability problems of the extreme event example previously given.

Long-Term Beach Changes

Long-term beach changes pose some highly important concerns. Profile type surveys provide a source of detailed coast, beach, and nearshore conditions. Such data offer the opportunity for calculation of volumetric changes which, if sufficient alongshore profiles are surveyed, allows for sediment budget determinations.

Profile surveying for temporal beach changes, however, requires a monument system maintained over many years. For instance, Florida's coastal monument system has been in place for some 26 years. Other such efforts occur on a site-specific basis. For most of our coasts there is insufficient monumentation, or it has not been in place for enough time to assure long-term records. Even the 26 years for the Florida program is not lengthy. Moreover, early surveys measured shoreline positions. In order to obtain volumetrics from shoreline position data, horizontal shoreline change (ΔX) and volumetric change (ΔV) have been related in the ***Shore Protection Manual*** (U. S. Army, 1984) according to:

$$\Delta X = c \, \Delta V$$

where c is a relating coefficient. If not very carefully applied, such an approach can produce highly misleading results (Balsillie, 1993a).

Long-term shoreline change rate data for Florida (Balsillie and Moore, 1985; Balsillie, 1985f, 1985g; Balsillie, and others, 1986) are determined from shoreline position data for the period from about 1850 to present. Commonly up to about a dozen data points are available from which to conduct temporal analyses.

By way of example, let us inspect the application of MHW as the reference datum plane for determination of horizontal shoreline change. Let us select an average MHW value of +1.7 feet MSL and a maximum value for MHW of +3.0 feet MSL, both of which are representative of Florida conditions (from Table 1). Using these data, three cases of combinations of MHW and foreshore slope values are illustrated in

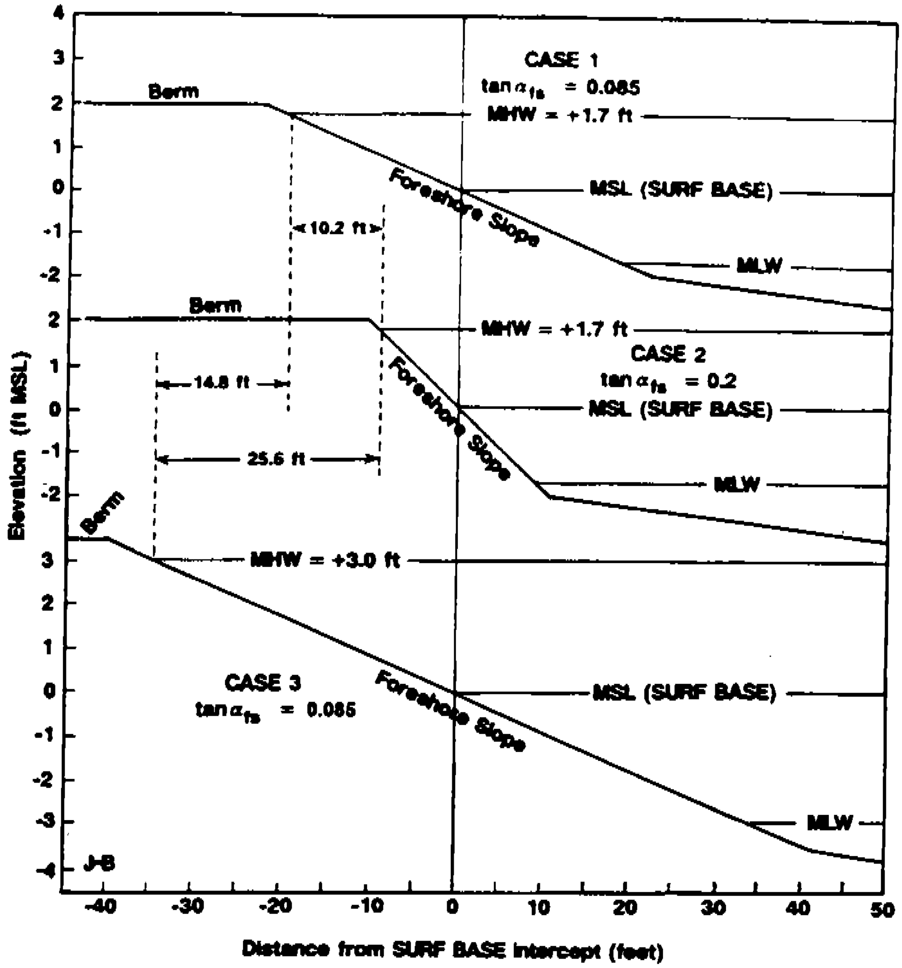

Figure 7. Long-term shoreline shift analysis.

Figure 7. Additional data could have been selected as well as additional combinations; however, the three illustrated cases will more than suffice for our purposes. The profiles of the three examples are plotted so that the MSL (Surf Base) intercepts define the origins of the plots that they may be compared. Horizontal differences of MHW intercept locations are identified by vertical dashed lines. Deviations range from 10.2 to 25.6 feet, all of which are significant illustrating the inappropriate nature of using MHW for such a purpose. Again, as with extreme event impact and seasonal shoreline change, MHW shoreline shifts are not comparable from locality to locality (the same would hold true for other datums such as MHHW, MLW, MLLW, etc.). In fact, if we evaluated long-term beach changes volumetrically, MHW or any of the other site specific extremal variable datums would result in precisely the same non-comparability problems of the extreme event and seasonal shoreline shift examples previously given.

We can approach the subject from a different perspective. If MSL is not used as a reference Surf Base plane, then what should be used? If one selects an extreme tidal datum plane such as MHW, does it represent a base to which aktological force and response elements can be based? Does it have spatial continuity? Is it applied in a conceptually correct sense? All of these questions need be directed toward coastal processes.

THE SURF BASE

The preceding application/use examples, while rigorously identifying inconsistencies resulting from the use of extreme datum planes for coastal science and engineering purposes, have not specifically addressed coastal processes in terms of the forces that cause beach responses.

In order to understand how the ***surf base*** applies, one needs a basic understanding of how wave statistics are derived and applied. At a given water depth a ***wave train*** is a near-periodic set of waves with a characteristic average wave crest height H, wave length L, period T, and having a specific direction of propagation. Where water depths are such that waves remain relatively stable, the wave record (such as that measured by a wave gauge) will represent all wave trains (*i.e.*, multiple trains) passing the gauge. Multiple wave train height and period measurements are termed the ***spectral wave record*** or ***wave field***. ***Shore-breaking waves***, however, do not conform to spectral wave statistics. This occurs because in nearshore waters, waves are ultimately limited by water depth according to $d_b = 1.28\ H_b$ (McCowan, 1894; Balsillie, 1983a; Balsillie, 1999b; Balsillie and Tanner, 1999) where H_b is the wave crest height at shore-breaking and d_b is the water depth where the wave breaks. Hence, shore-breaking waves engender moment wave statistics for ***single wave trains*** since a wave train with larger waves will break further offshore than one with smaller waves.

It follows, then, that moment wave statistics vary depending upon whether they represent the spectral wave record or single shore-breaking wave trains. The most commonly applied nearshore wave height statistics are the average wave height H, root-mean-square wave height H_{rms}, significant wave height H_s (average of the highest 30 per cent waves of record), H_{10} (average of the highest 10 per cent waves ofrecord), and H_1 (average of the highest 1 per cent waves). Each of these moment measures is applied in the design of coastal engineering solutions by defined prescription. Relating moment measures for spectral and shore-breaking wave cases are listed in Table 4 to illustrate the variability of relating coefficients.

Let us look at an example of tide conditions to which we might superimpose certain wave conditions. Figure 8 illustrates 6 days of an astronomical tide record. Suppose one inspects the case where MHW and H_s are, for whatever reason(s), selected for use. From the plots, each peak of the tide might be considered to be maintained, say, for 1/2 to 1 hour. Doubling this value, since two highs occur in each tidal day for the semidurnal tide, then MHW is actually maintained for about 4 to 8 per cent of the time (*e.g.*, 14 and 28 days a year). Superimposed upon MHW is the significant wave height which, by definition, neglects 70 per cent of the wave record (assuming that H_s adequately includes any significant zero wave energy component; Balsillie, 1993b). Clearly, such an application would be inappropriate for one applying such force elements to annual or long-term conditions. Unfortunately, however, such misapplications, of which this is just one example, are commonplace. On the other hand, such an application might have more viable application if it included a storm surge (*i.e.*, peak combined storm tide minus the astronomical tide) to represent the peak combined storm tide and attendant wave activity which occurred coincident with the peak astronomical tide. This latter case, however, has application only to identify a conservative design elevation for a structure (*e.g.*, perhaps a pier) which is a monergistic tidal datums application, but certainly not to profile response which constitutes a synergistic application.

Previously discussed use/application examples have already led to the elimination of extreme datum planes (i.e., MHHW, MWH, MLW, MLLW) as has the preceding example, and MSL and NGVD remain for consideration. The NGVD reference is not, of course, a tidal datum. It is rather, for all practical purposes a geodetic datum for computational reference, that although for open-coast gauges has a departure generally less than 0.5 of a foot from MSL for Florida, the long-term primary departure of MSL and NGVD is subject to influences of sea level rise or fall (shorter-term natural deviations have been discussed above). Hence, it should not be utilized as a datum, particularly where global data are involved (*i.e.*, where the non-tidal vertical reference

Table 4. Moment Wave Height Statistical Relationships (after Balsillie and Carter, 1984a, 1984b).

Portion of Wave Record Considered	Spectral Relationships	Shore-Breaking Relationships
All Waves	*Average Wave Height* $= H$	*Average Breaker Height* $= H_b$
All Waves	$H = 0.885\ H_{rms}$	$H_b = 0.98\ H_{brms}$
Highest 30%	$H = 0.625\ H_s$	$H_b = 0.813\ H_{bs}$
Highest 10%	$H = 0.493\ H_{10}$	$H_b = 0.73\ H_{b10}$
Highest 1%	$H = 0.375\ H_1$	$H_b = 0.637\ H_{b1}$

Definitions:

$$\text{Average Wave Height} = H = \frac{1}{N}\sum_{i=1}^{N} H_i$$

$$\text{Root-Mean-Square Wave Height} = H_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} H_i^2}$$

H_s = *significant wave height*

NOTE: Formulas apply to both H and H_b; H_s, H_{10}, and H_1 are calculated using the form of the equation as for the average wave height.

represents a conceptual plane not located and/or not calculated such that it is not necessarily comparable to NGVD). The remaining tidal datum is, then, MSL. Other than its identification by elimination of other datums, there are strong motivating reasons why MSL is the proper tidal datum reference to use when dealing with coastal processes (*i.e.*, force and response elements). As we have already learned, principal force elements include astronomical tides, storm tides, and waves. Astronomical tides are, by definition, already accounted for when using MSL, and storm tides are extreme events though accounted for as described in the preceding section. Waves, however, constitute an ubiquitous phenomenon near constant in nearshore coastal waters (except for coasts with a substantial zero wave energy component).

Therefore, by the process of elimination MSL is defined as the ***surf base*** (it is also the tide base, not to be confused with the concept of the ***wave base***). Upon inspection of Figures 1, 2, and 3, it is readily apparent that MSL, like the other datums, has variability. Why, then, would we select it as a convention for reference? Water levels are not globally coincident in the vertical sense for very real reasons. However, MSL is a measure representative of the entire distribution of the metonic astronomical tide, and is the only one of the tidal datums that has statistical continuity and comparability of results from place to place. Noting that for open coastal waters MSL is equivalent to MTL (Swanson, 1974, p.4), then the MTL measure remains to represent the central tendency of the tide distribution since metonic measures of highs and lows are used in its determination. The

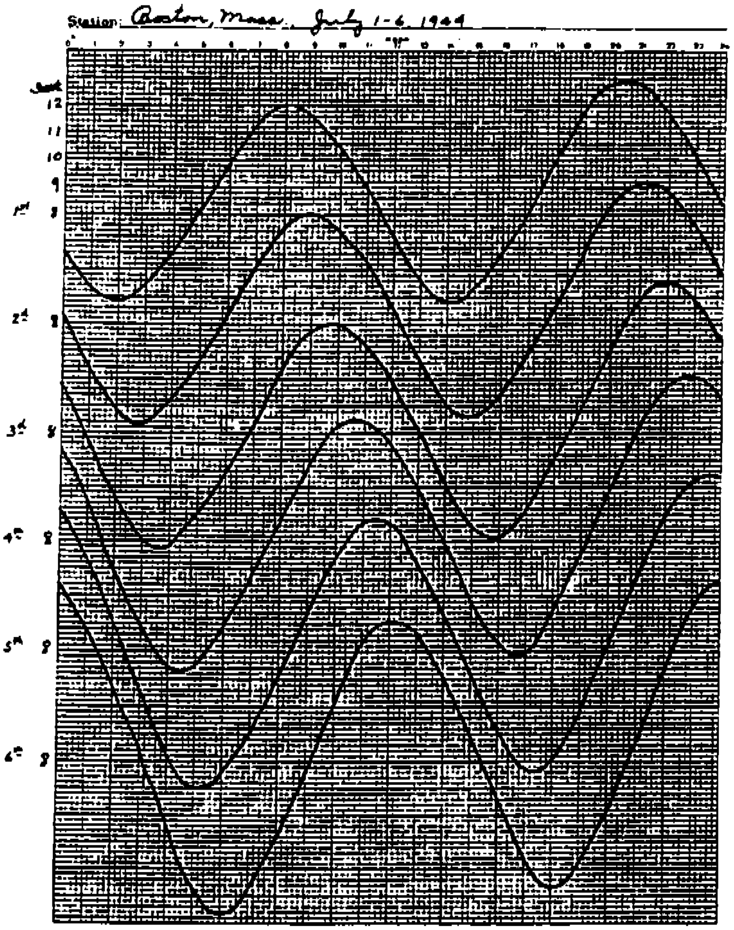

Figure 8. Semidiurnal tide curves for 6 tidal days (from Marmer, 1951).

issue becomes particularly poignant from inspection of Figure 1 where the behavior of low waters (*i.e.*, MLW and MLLW) and high waters (*i.e.*, MHW and MHHW) are anything but symmetrical in their relationship to MSL (or MTL), signifying a need for an average surf base measure. Statistically extreme average point measures providing numerical values of upper (*i.e.*, MHW and MHHW) and lower (*i.e.*, MLW and MLLW) tidal datums are robustly founded. Corresponding extremes of such physiographic features as the foreshore may not be so robustly founded, since its formation and maintenance has not been rigorously defined in terms of forces and responses (*e.g.*, Kraus and others, 1991, p. 3). Given the manner in which we currently define the foreshore, one should view it in the statistical sense where we know more about its central tendency than we do about the behavior of the lower foreshore (corresponding to MLW or MLLW) or higher foreshore (corresponding to MHW or MHHW). When we approach the extremes of the slope, exceptions due to physiographic irregularities can occur. Hence, one needs to view the surf base - foreshore slope intersection as a focal point about which the foreshore rotates. In this context, the focal point is directly related to incoming force elements. Furthermore, it is conceptually not subject to variations to which the upper and lower parts of the foreshore are subject, since it is an origin both common and comparable to the focal point at other localities.

From a slightly different viewpoint, one argument proffered by a colleague who took the "devil's advocate" position, is that the MHW intercept represents the most stable portion of the foreshore slope. While this may appear appropriate to the layman, from the geological perspective it is not. It is, in fact, the least stable in terms of representing a normal slope. The most stable position of the foreshore is probably at the MSL intercept (i.e., relative to other submerged portions of the profile) since it is reflective of average, ongoing force elements to which it is modified as a response element. By comparison, the foreshore in the vicinity of the MHW or MHHW intercepts is affected only during high tide stages and can be reflective of extremal impacts (*e.g.*, storm wave events). Extreme impacts affecting the MHW foreshore are likely to result in relict features which persist until continual average force conditions finally return the upper portions of the slope to normal slope status.

What point estimator of wave parameters, representing the appropriate force element, does one subscribe for an extreme average measure of the astronomical tide, say for MHW? One does not apply such point estimators for wave transformation synergistic applications, because none would be appropriate. Hence, unless an average sea level (MSL or MTL) is combined with an average wave height, one is mixing "apples and oranges". It is imperative when undertaking such a task, we render the task to simplest terms. For instance, when transforming waves to the point of shore-breaking, including any wave reformation and rebreaking, the waves should be expressed as an average wave height or, perhaps, root-mean-square wave height since these measures include all waves of record. Do not use the significant wave height, average of the highest 10 per cent of heights, average of the highest 1 per cent of wave heights, etc. Whether or not a significant zero wave energy component is included depends on the purpose of the work (Balsillie, 1993b). Any conversion of the average wave height to extreme wave height measures of Table 4, say for design purposes, is accomplished by converting the average measure, but only after wave transformation as an average height has occurred. Kraus and others (1991) note the importance of the average wave height and tout its use to be the "... "Rosetta stone" for conversion ...", no less important is the proper application of the surf base (MSL) which becomes the Rosetta Stone for referencing tide and wave phenomena. Another good reason for using averages throughout any numerical transformation process is because one is often unable to determine from published results if the transformation methodology is truly commutative.

MSL is, therefore, the only datum plane that is relevant to the surf base. For a relatively short experiment or field study, MWL or SWL references are suitable to represent the time frame of the experiment or study. Such referenced results, however, may not be comparable to results referenced to MSL at other localities. For this reason, all applicable datums ... MSL, MWL, and SWL, where known ... collectively termed Design Water Levels (DWLs), should be provided in documentation of results.

SEA LEVEL RISE

So far, we have but in passing mentioned the effects of sea level rise, recalling that the primary difference between NGVD and MSL (or MTL) is sea level rise. In an historical context, the effect of sea level rise on the current metonic period has, thus far, been insignificant from a surveying perspective. Its future effect, however, remains controversial (*e.g.*, Titus and Barth (1984) and Titus (1987) versus Michaels (1992), to mention but only several published works among a vast number on the subject). Other work indicates details of sea level reversals or pulses (Tanner, 1992, 1993), also characterized as crescendos (Fairbridge, 1989).

There are certain applications where temporal specifications of sea level rise are of potential consequence. Hence, from a data management and processing viewpoint, it becomes in certain cases necessary to start with NGVD and calculate the relative date-certain sea level rise component. The result, of course, becomes the date-certain MSL (or MTL). For the 1960-1978 National Tidal Datum Epoch, the following relationship assessed in British Imperial units is posited:

$$MSL_D = NGVD + c\,(D - 1969.5)$$

where MSL_D is the date-certain value for MSL (or MTL), $c = 0.0060$ for Florida's east Coast), $c = 0.0064$ for Florida's Lower Gulf Coast, and $c = 0.0069$ for the Florida

Panhandle Gulf Coast (Balsillie and others, 1987a, 1987b, and 1987c, respectively), and D is the survey date. Please note that the value of c changes with time and location; the current value of c for a particular coast is a representative regression value.

MONERGISTIC TIDAL DATUM PLANE APPLICATIONS

Thus far, the above application/use examples have been described as synergistic. That is, horizontal shoreline shift and volumetric change results are referenced to a datum so that they can be compared spatially within a North American or global context. The scientific need to do so has been robustly demonstrated. Even more, considerable analytical work is required to determine such synergistic results which cannot be simply recalculated to another datum.

As described in the introduction there are, however, other quite different conceptual applications of astronomical tidal datum planes. Some of these are not necessarily bound by the need for a spatial tidal datum convention. These are described as monergistic applications. The purpose, here, is to demonstrate several such examples.

DESIGN SOFFIT ELEVATION CALCULATIONS

"Soffit elevation" is a generic term meaning the elevation to the underside of the lowest supporting structural member excluding the piling foundation, say, for a pier or single- or muti-family dwelling. Such elevations are calculated for extreme elevations associated with the impact of extreme events (*i.e.*, storms and hurricanes). The goal is to raise the structure to an elevation so that it is above the destructive hydraulic force elements which will pass below the soffit and through the piling foundation. For a pier, for instance, a peak combined storm tide (super-elevated water level including contributions of wind stress, barometric pressure decrease, dynamic wave setup and astronomical tides) corresponding to a 50-year return period elevation is normally used for design calculations. Superimposed upon the storm tide still water level is a design wave height, normally a breaking wave height corresponding to H_{b10} or H_{b1}. As previously noted, where a wave shore-breaks is dependent on the water depth which, in turn, is dependent on patterns of sediment redistribution occurring during event impact. Sediment redistribution is largely a function of offshore sediment transport and longshore bar formation (Balsillie, 1982a, 1982b, 1983a, 1983b, 1983c, 1984a, 1984b, 1984c, 1985a, 1985b, 1985c, 1985d, 1985e, 1986; Balsillie and Carter, 1984a, 1984b, etc.). An example is illustrated in Figure 9.

Such design work calculations are site-specific because results will be influenced by the pre-impact site-specific profile configuration. There is no intention, nor at this time a need to compare such results to other localities. Should such an application need arise (*e.g.*, a generalized modeling effort or an accounting need to assure consistency in design application(s)), then the reference base should be MSL. However, such transformations to other datums can be easily accomplished, compared to much more involved recalculation of synergistic data (i.e., volumes or horizontal distances).

EROSION DEPTH/SCOUR CALCULATIONS

Site-specific design work such as minimum pile embedment requires knowledge of the design surface elevation. This elevation necessarily includes erosion depth (*e.g.*, longshore bar trough elevation or beach erosion elevation), additional scour caused by the pile, and sediment liquefaction. In essence these design elevation calculations are treated in the same manner as design soffit elevation

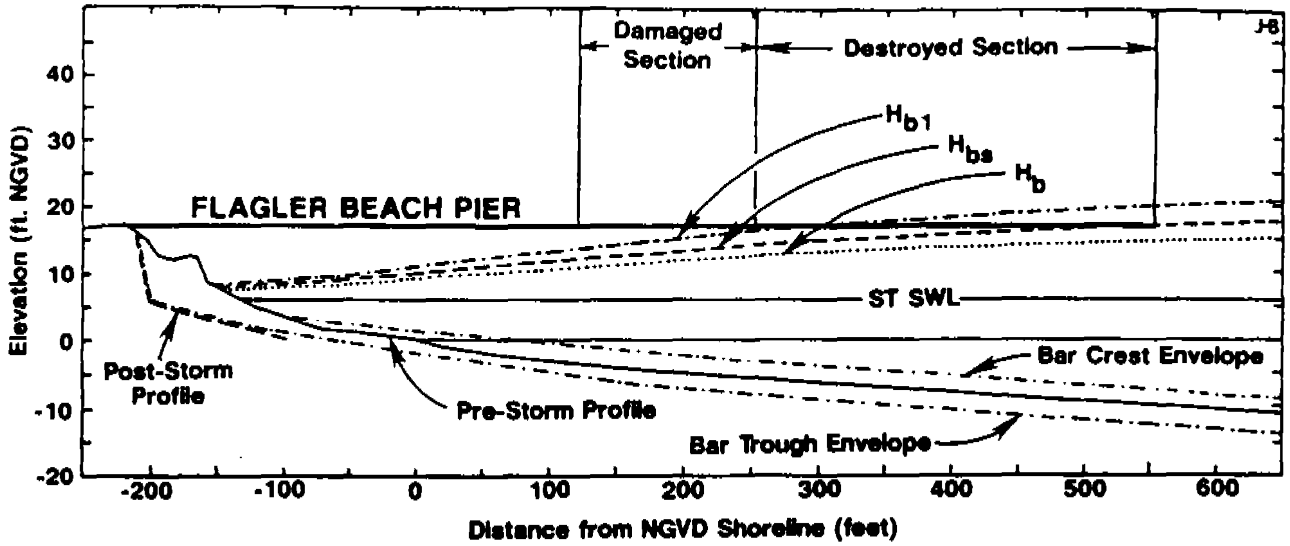

Figure 9. Actual damage to the Flagler Beach Pier from the Thanksgiving Holiday Storm of 1984 (Balsillie, 1985c) used to test the Multiple Shore-Breaking Wave Transformation Computer Model for predicting wave behavior, longshore bar formation, and beach/coast erosion (after Balsillie, 1985b).

calculations.

SEASONAL HIGH WATER CALCULATIONS

In addtion to short-term erosive impacts due to extreme events, our coasts are subject to long-term changes. In 1972, the State of Florida incorporated consideration of storm/hurricane erosion in affixing the location of Coastal Construction Setback Lines. In 1978, it adopted a posture in which quantitative extreme event erosion became the primary means by which Coastal Construction Control Lines were located. It was not until 1984, however, that long-term erosion was officially recognized by the State of Florida (Balsillie and Moore, 1985; Balsillie, State of Florida (Balsillie and Moore, 1985; Balsillie,1985f; 1985g; Balsillie and others, 1986; etc.,). In 1985, the Growth Management Amendment required assessment of erosion at any coastal site for which a permit application was tendered to be assessed for a 30-year period. Associated with 30-year long-term erosion projections is the local ***Seasonal High Water (SHW)*** defined as ... *the line formed by the intersection of the rising shore and the elevation of 150 percent of the local mean tidal range above local mean high water ...* (para. 161.053(6)(a)1, F. S.). That is:

$$SHW = (1.5\ MRT) + MHW$$

in which MRT is the mean range of tide (commonly referred to as the mean tide range). One might assume that the 30-year erosion projection is to be assessed at the SHW elevation. This is simply not true and, in fact, as we have seen earlier would be a misapplication leading to spatial discontinuity introducing computational error (Balsillie and Moore, 1985). Rather, the erosion projection needs to be assessed at MSL. The required methodology specified by rule (para. 16B-33.024(3)(h), F. A. C., republished as State of Florida, 1992, 62B-33.024(3)(h)1., F. A. C.) specifies NGVD as the assessment elevation. The original rule, however, was written before compilation of datum elevations, foreshore slope, and sea level rise information for the State. Subsequent work (Balsillie, Carlen, and

Watters, 1987a, 1987b, 1987c) has remedied the situation, and the rule needs to be reassessed. Following is an alternative for consideration.

BEACH-COAST NICKPOINT ELEVATION

In reality, Seasonal High Water is a misnomer. First, the components necessary for computation are metonically derived (*i.e.*, 19-year averages). Second, the results have not been demonstrated to represent seasonal variation in astronomical tide behavior. Third, it has been demonstrated that upon application, only about 13% to 15% of undeveloped beach property in Florida would be affected by the SHW application (Curtis and others, 1985).

An alternative consideration for such an application, and others, is the beach/coast nickpoint elevation. The nickpoint represents the point where the beach intersects the coast, normally identified as the base of a dune or bluff. Generation and maintenance of the nickpoint is primarily a function of direct extreme event impact. These elevations for Florida are probabilistically investigated; the results are plotted in Figure 10. Median (*i.e.*, 50th percentile) nickpoint elevations, N_e, for Florida are as follows: 1) East Coast: +7.15 feet NGVD (1929), 2) Lower Gulf Coast: +5.65 feet NGVD (1929), and 3) Panhandle Gulf Coast: +6.45 feet NGVD (1929).

The relationship between nickpoint elevations and SHW elevations for Florida is illustrated in Figures 11, 12, and 13. It is apparent from the figures that only the upper east coast is significantly affected by the SHW, attesting to the low impact figure of Curtis and others (1985).

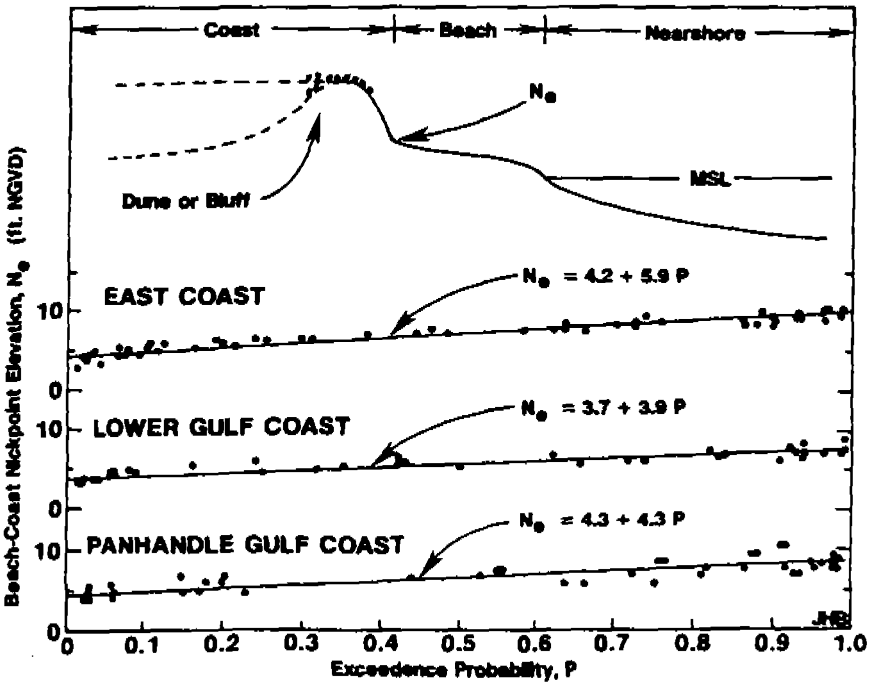

Figure 10. Beach/coast nickpoint elevations for Florida.

BOUNDARY OF PUBLIC VERSUS PRIVATE PROPERTY OWNERSHIP

The boundary between private (*i.e.*, upland) and public (*i.e.*, seaward) beach ownership is normally fixed by some commonly applied tidal datum. For most of the U. S. this boundary is determined by the plane of MHW which when it intersects the beach or coast forms the line of mean high water. However, unlike other riparian ownership determinations (*i.e.*, fluvial, lacustrine and estuarine), littoral properties must, in addition, contend with significant wave activity that seasonally varies. Hence, ocean-fronting beaches all too often experience cyclic seasonal width changes of a magnitude long recognized as problematic in affixing an equitable boundary (Nunez, 1966; Johnson, 1971; O'Brien, 1982; Graber and Thompson, 1985; Collins and McGrath, 1989).

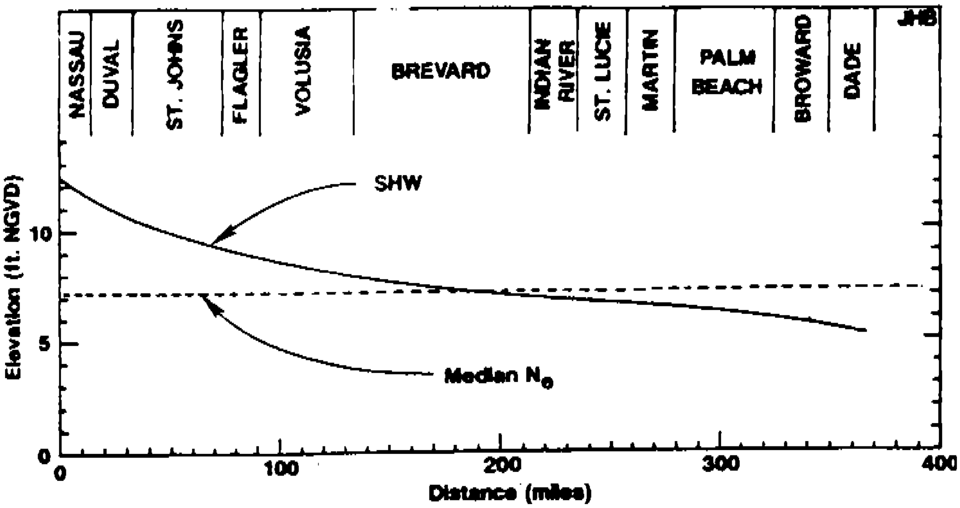

Figure 11. Comparison of Seasonal High Water (SHW) and Median Beach/Coast Nickpoint Elevation (N_e) for the Florida East Coast.

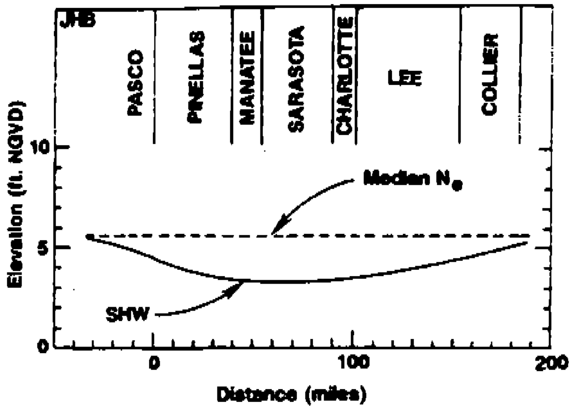

Figure 12. Comparison of Seasonal High Water (SHW) and Median Beach/Coast Nickpoint Elevation (N_e) for the Florida Lower Gulf Coast.

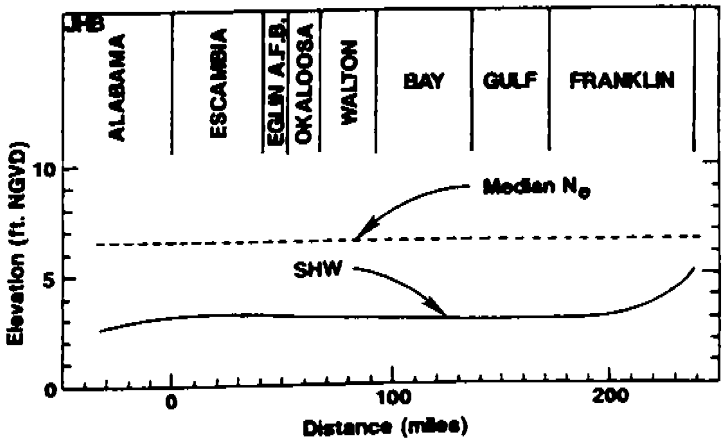

Figure 13. Comparison of Seasonal High Water (SHW) and Median Beach/Coast Nickpoint Elevation (N_e) for the Florida Panhandle Gulf Coast.

Many investigators have suggested that the legal boundary for ocean-fronting beaches should not be continuously moving with the seasonal changes, but should be the most landward or "winter" line of mean high water (Nunez, 1966). Selection of the "winter" MHW line would be the most practical to locate and would be the most protective of public interest by maintaining maximum public access to the shore (Collins and McGrath, 1989).

In Florida, the ocean-fronting legal boundary - seasonal fluctuation issue was deliberated upon in State of Florida, Department of Natural Resources vs Ocean Hotel, Inc. (State of Florida, 1974) as it related to locating the MHW line from which a 50-foot setback was to be required. Judge J. R. Knott rendered the following decision:

> ***This court therefore concludes that the winter and most landward mean high water line must be selected as the boundary between the state and the upland owner. In so doing the court has had to balance the public policy favoring private littoral ownership against the public policy of holding the tideland in trust for the people, where the preservation of a vital public right is secured with but minimal effect upon the interests of the upland owner.***

A 1966 California Court of Appeals decision rejected the application of a continuously moving boundary in People vs Kent Estate. However, no decision has been rendered as to what line to use (Collins and McGrath, 1989). More recently, Collins and McGrath (1989) report:

> ***The Attorney General's Office in California has offered its informal opinion that, if squarely faced with the issue, California courts would follow the reasoning in the Florida case and adopt the "winter and most landward line of mean high tide" as the legal boundary between public tidelands and private uplands ... (it should be understood that such a boundary, which relatively stable, would not be permanently fixed but would be ambulatory to the extent there occurs long-term accretion or erosion).***

The use of the MHW datum plane for the determination of a boundary is straightforwardly a monergistic application; one must be careful, however, to note that determination of the seasonal shoreline shift (or beach width) is not. This will require a synergistic application using MSL. Similarly, any periodic review and boundary relocation due to long-term shoreline changes will require the synergistic approach.

INLETS AND ASSOCIATED ASTRONOMICAL TIDES

It has been speculated that tidal inlets can significantly affect the character of open coast tide behavior. There are, however, insufficient alongshore data crossing inlets, both upcoast and downcoast, upon which to assess the effect of inlets (termed the "shadow effect"). In addition, flow characteristics vary from inlet to inlet and a multitude of such investigations would be required to investigate the alongshore influence of inlets. There are, however, some isolated open coast tide data near inlets or within inlet throats close to the shoreline. There are more data interior to inlets. Such information for 24 Florida tidal inlets and passes are plotted in Figure 14 from which some significant elucidating conclusions may be gleaned.

The data of Figure 14 are displayed in terms of the measured inlet tide data minus the open coast tide data of Balsillie and others (1987a, 1987b, 1987c). In this way the

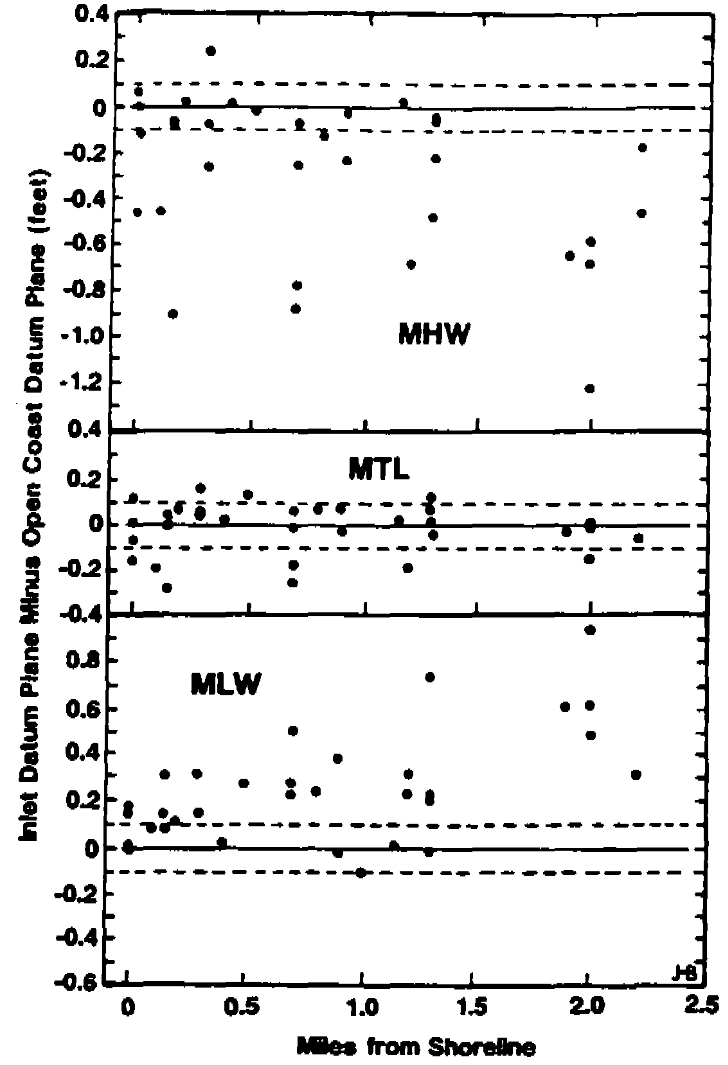

Figure 14. Departure of Florida inlet tide data and open coast tide data (measured tide data from DNR, Bureau of Survey and Mapping). See text for discussion.

acceptability of the data within the dashed lines (*i.e.*, plus and minus 0.1 ft.) can be easily assessed. Data for MHHW and MLLW plot similar to MHW and MLW data with somewhat greater variability, and are not shown.

The first conclusion to be drawn from Figure 14, is that the amplitude of the tide is attenuated by the inlet (*i.e.*, MHW becomes lower in elevation and MLW gains elevation); this is illustrated in a different manner for two Florida inlets in Figure 15. Hence, if one were (as before) to use MHW as the reference plane for a synergistic application (e.g., storm impact, seasonal, or long-term beach changes), the amount of error introduced is potentially highly significant. It would, in addition, occur over a quite short segment of shoreline. For MHW, 39% of the data are acceptable (*i.e.*, lie with ±0.1 ft. of the open coast data) with 61% of the data being unacceptable. For MLW 76% of the data are unacceptable. However, for MTL almost 70% of the data are acceptable. This shift in data acceptability for MTL is not aberrant. Rather, it is to be a moderating expectation since MTL is the plane lying halfway between MHW and MLW and should, therefore much more closely approach open coast MTL values than any of the other extremal tidal datum planes. Therefore, depending on the application, the locally measured MSL (MTL) datum plane or the open coast MSL (MTL) datum plane should be used for synergistic applications in the vicinity of inlets (which is used should be clearly specified). Hence, MTL (or the MSL surf base) is, once again, the proper datum plane to use for inlets. In fact, O'Brien (1931) intentionally included in his definitions for tidal characteristics (e.g., flow area, tidal prism) that they be referenced specifically to MSL.

Ideally, the alongshore "shadow effect" of inlets on astronomical tides should be quantitatively assessed. Such work is, however, expensive and time consuming and is not expected to be forthcoming any time soon.

It is also of significance to note that Cole (1997, p. 38) has found that nth order polynomial equations precisely determine tidal datums within estuaries. The order of the best fit polynomial for an estuary was

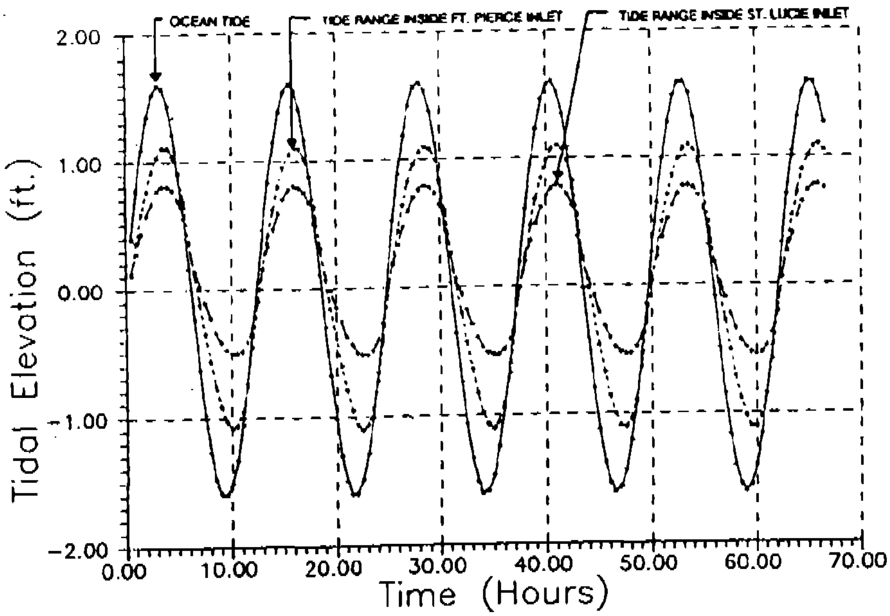

Figure 15. Open ocean and inside astronomical tides for Ft. Pierce and St. Lucie Inlets, Florida (from Anonymous, 1992).

found to be predictable based on the length of the estuary and the travel speed of the tidal wave within the estuary.

CONCLUSIONS

A considerable amount of information, hopefully simplified as much as possible, has been presented in the above application/use examples. It would not serve further purpose to restate conclusions here that could be more succinctly touted, other than to state that MSL (or open-coast MTL) is the proper datum to employ for synergistic coastal engineering applications. It is hoped that this work has rendered it apparent that how we perceive and treat such subject matter in a scientific context is sensitively critical. The considerations presented herein embody not just philosophy, but engender intellectual contemplation and deliberation necessary to arrive at a deductive, reasonable, and robustly correct convention for application. In this day and age, it is unfortunate that while we are finally realizing such enhanced data processing capabilities, we are fraught with misapplication that all-too-often render good data to inaccurate results.

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