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Volumetric Beach and Coast Erosion Due to Storm and Hurricane Impact

by

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VOLUMETRIC BEACH AND COAST EROSION DUE TO STORM AND HURRICANE IMPACT

by

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ABSTRACT

Prior to the initial work of the author during the early 1980s, methods to predict nearshore, beach, and coastal erosion due to storm and hurricane impact were based on theoretical applications and estimation. However, with the acquisition of actual field data quantifying storm and hurricane erosive impacts, it became clear that, in addition to the combined storm tide (commonly termed the storm surge), the length of time that an event has to erode the beach and coast is a highly significant factor that could be quantified (*i.e.*, given two events each producing identical storm tide hydrographs, the slower moving event will result in greater beach and coast erosion). Hence, based on actual field data, the ***event longevity parameter (ELP)*** was introduced (Balsillie, 1985c, 1986) which incorporates both the combined storm tide and its rise time, the latter of which can be computed from the event forward speed.

Since the published work of the mid-1980s, additional field data (a three-fold increase) have become available to further verify the ELP approach, and to introduce new developments. It has, for instance, become apparent that in addition to the design peak storm tide elevation, the design erosion event requires attention in many coastal engineering design applications if they are to be successful. In fact, aside from design soffit elevations which are determined from the peak combined storm tide elevation and superimposed storm waves propagating upon the storm tide surface, it is the design erosion event that quantifies the final expression of all other impacts. Hence, probability density functions are defined for both erosion above mean sea level and peak storm tide level. In addition, it has been found that the pre-impact offshore bed slope can be used to indicate the "efficiency" or "receptiveness" of the offshore sediment sink to accept sand eroded from the beach and/or coast (termed the ***offshore sink efficiency parameter (OSEP)***. Incorporation of the new data, and quantification of the two additional developments and an amended Saffir/Simpson hurricane damage potential scale constitute the subject matter of this paper.

INTRODUCTION

Although, in the seasonal and long-term sense, beaches are constantly being remolded by waves, tides and winds, the most dramatic changes occur as the result of extreme event (*i.e.*, short-term impacts from storms and hurricanes). The consideration of short-term, seasonal, and long-term impacts (*i.e.*, force elements such as astronomical tides, storm tides, waves, *etc.*) and the resulting outcomes (*i.e.*, response elements such as beach and coast erosion, longshore bar formation, and structural damage) are matters of standard coastal engineering practice. In this paper, short-term impacts define the subject of interest.

For many years, only the peak combined storm tide (also commonly termed the storm surge) was employed in determining and assessing nearshore, beach, and coastal engineering design solutions. Consideration of the storm tide alone, however, does not provide a realistic measure of impact potential. For instance, given two extreme events with identical storm tides, the slower moving event will result in greater beach and coast erosion.

The peak storm tide elevation plus superimposed storm wave activity propagating upon the storm tide surface is useful in determining deck, floor, *etc*. (termed "soffit") elevations, provided that any shift or erosion of the bed is known, since increased water depth results in higher waves. All other design solutions are more nearly related to erosion responses, such as pile tip penetration, seawall and bulkhead panel embedment elevations, *etc*. In addition, since storms cause nearshore erosion and bed shifts in response to longshore bar formation accompanying beach and coast erosion, resulting increased water depths can significantly affect both horizontal and vertical wave impact potentials which require consideration in design solutions and assessments.

The need for methodology to predict beach and coast erosion due to the impact of storms and hurricanes has been an issue of ongoing and increasing concern. Moreover, it is one which, for the majority of the history of the discipline of coastal science, has eluded satisfactory quantifying solutions. The lack of methodology is not surprising considering the complexities involved in quantifying littoral processes. Ultimately, however, only through the acquisition of field data will confident, successful solutions be realized. This paper provides a significant update (in terms of the number of hurricane and storm events) to previous work by the author (Balsillie, 1985c, 1986).

EXTREME EVENT EROSION AND ITS RELATION TO THE TYPE OF PRE-IMPACT COASTAL PHYSIOGRAPHY

In this paper erosion is considered to be the overall term encompassing horizontal and vertical recession components of beach and coast response due to storm and/or hurricane impact. Depending on the type of coastal physiography, these components can result in quite different outcomes. Horizontal recession is important in determining siting of coastal development activities. It is, however, the maximum vertical recession produced during event impact (Balsillie, 1984c, in manuscript) which is needed to assess structural design constraints (*e.g.*, piling tip penetration, "first floor" soffit elevations, *etc.*) based on hydraulic forces such as shore-breaking wave impact pressures (Balsillie, 1985b). Vertical recession should include effects due to both scour, and sediment liquefaction (Zeevaert, 1983, 1984).

It is also important to bear in mind the differences between the nearshore, beach (or shore), and coastal subzones of the littoral environment (Figure 1). Under normal hydraulic littoral conditions, processes are clearly different within each subzone (discussed in detail in later sections). Whether or not the storm rises above the beach, or if not, has the longevity to erode

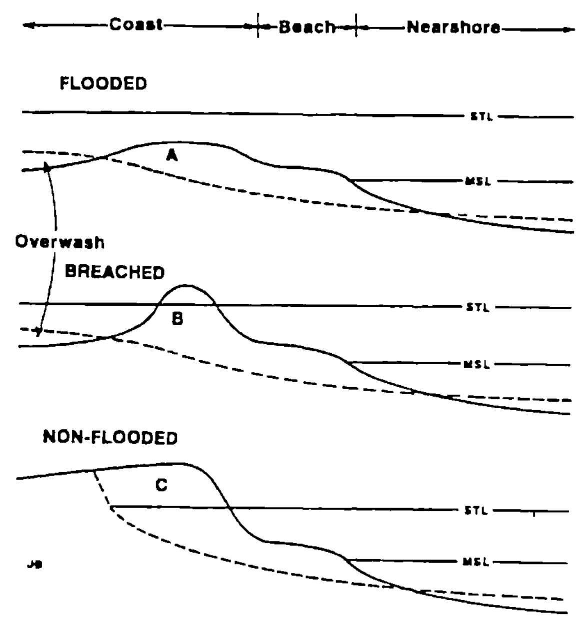

Figure 1. Idealized pre-storm (solid lines) and eroded (dashed lines) profile scenarios for the three basic types of coastal physiography (STL = peak storm tide level, MSL = mean sea level).

the beach and begin to erode the coast, and post-storm beach recovery, are important issues which shall be addressed later.

Considering initial coastal physiography and responses due to extreme event impact, three general types of geomorphic scenarios are suggested: non-flooded, flooded, and breached profiles (Figure 1). In assessing these profile types, several assumptions are made: 1) the beach and coast are composed of relatively unconsolidated sand-sized sediment, 2) onshore-offshore sediment transport processes prevail and alongshore processes are assumed static, and 3) "shallow water" hydraulic processes are approximately constant for a given water depth, noting that a change in wave conditions (principally shore-breaking and broken waves) will cause a shift in bathymetry which, in turn, will affect the waves.

Where the coast is higher than the peak storm tide and is wide enough not to be breached (*i.e.*, the non-flooded condition), only the offshore "sink" is available for deposition of sand eroded from the beach and coast. A major contributing erosional mechanism is gravitational mass wasting, because only a relatively few waves are required to cause an unstable, steep sand face to collapse. As the sediment escarpment increases in height, increasingly more sediment is potentially available for introduction to the prevailing littoral hydraulic environment for redistribution.

The barrier islands of the lower Florida Gulf Coast may in many places be inundated by 1 to 2 meters of water due to impact of a 100-year return period peak combined storm tide event (see Table 1 for definition). This does not include the added hydraulic elevation due to shore-breaking wave activity which propagates upon the storm tide surface. Therefore, the contribution of gravitational mass wasting, important to the non-flooded scenario, may not be of special consequence for relatively low-lying barriers. It does, however, introduce the aspect of an additional "sink" for eroded sand due to overwash processes (Leatherman, 1976, 1977, 1979, 1981; Leatherman and others, 1977; Schwartz, 1975). Combination of the preceding two physiographic-hydrographic scenarios leads to the breached profile condition illustrated in inset B of Figure 1 in which the overwash sink again occurs.

It is also apparent from the literature that the success of grain-by-grain onshore-offshore sediment transport mechanics under littoral wave activity as yet remains to reach the status of satisfactory quantification (Balsillie, 1984c, 1986). That existing attempts at quantification may be fraught with insensitivities is further exaggerated when dealing with a rising and falling storm tide and with storm-generated littoral wave activity. Hence, pursuit of alternative approaches is desirable. One such approach is investigation of field data quantifying actual storm and hurricane impact upon our shores.

DATA

This subject has received much attention in previous work, dating back for about 3 decades. Perhaps the most compelling work is that of Caldwell (1959) just preceding the infamous U. S. east coast Ash Wednesday storm of 1962 (Bretschneider, 1964; Harrison and Wagner, 1964; and O'Brien and Johnson, 1963), with a resurgence of interest occurring with the works of Edelman (1968, 1972). There have, in addition, been many studies reported in the literature providing descriptive accounts of the erosive power of extreme occurrences. However, until this work was originally published (Balsillie, 1985c, 1986), there were insufficient types and quantities of field data on which to quantify beach and coast erosion due to storm and hurricane impacts. This work has increased the size of the field data base by a factor of three.

Fourteen erosion events for 11 hurricanes, and 22 erosion events for 20 storms (Table 1) provides the largest field data compilation amassed to date for the purpose of quantifying beach and coast erosion due to extreme event impact. Seven events (H4, S17, S18, H7,H8, H9 and H10) were assessed through field data collection of the State of Florida, Department of Natural Resources (DNR, now the Department of Environmental Protection, DEP), Division of Beaches and Shores (now the Bureau of Beaches and Coastal Systems); field data collection techniques have been discussed elsewhere (Sensabaugh and others, 1977; Balsillie, 1985a, 1985c, 1985e, 1986, 1988). Thirteen events (S2 through S11, S14, S15 and S16) are the direct results of the efforts of the Coastal Engineering Research Center (CERC); field data collection techniques are discussed by Birkemeier (1979); Birkemeier and others (1988). A more recent event has been reported by Kana and Jones (1988) and Jones and Kana (1988). Hurricane Hugo (H11) information is presented by Birkemeier and others (1991) and Stauble and others (1991). A tropical storm (S20) was reported by Beumel and Campbell (1990). Ferriero (1994) reported erosion from a Portuguese storm event that occurred in 1989. Remaining events are from independent studies (references are listed in Table 1) that were previously analyzed by the author (Balsillie, 1985c, 1986).

Of the aspects concerning the data, it is important to note for management purposes that there are two types of erosion (Balsillie, 1985a, 1985e). One is the measure which represents those sampled profiles where erosion only occurred (TYPE I erosion measure). The other (TYPE II) is that which includes all profiles regardless of gain or loss. TYPE II erosion is important in assessing actual beach and coast economic losses. For design applications, TYPE I erosion is the better measure, since for design work we are interested in locations only where erosion has occurred. Hence, in this paper, TYPE I erosion volumes are used. Using the data from events H4, H5, S17, S18, H7, and H8, Balsillie (1985e, p. 33-34) found that, on the average, TYPE II erosion is 73% of TYPE I erosion ($n = 13$, sampled for over 200 profile pairs, $r = 0.9515$).

Where possible, profiles were selected to represent known extreme event impact magnitudes. For instance, only DNR (now DEP) ranges R-33 through R-125 in Walton County, Florida were selected for Hurricane Eloise, since it was this area that coincided with the first quadrant of Eloise in terms of the combined storm tide height (see Balsillie, 1983a). In other cases, one could only consider what pre- and post-storm profile data were available; an example is the Ash Wednesday storm of 1962.

ANALYTICAL RESULTS

Two reference water levels have commonly been used, above which volumetric erosion is determined: 1. the peak storm tide still water level (STL), and 2. mean sea level (MSL).

The first water level (STL) is considered here because it has been used in other work. It is particularly accurate for non-flooded profiles since erosion volumes represent single process losses above the reference water level due to gravitational mass wasting, and include none of the complexities occurring below the reference level due to interactive hydraulic and sediment transport processes. It should be clear, however, that this reference water level has no applicability in determining volumetric erosion for breached or flooded profiles and, therefore, its use results in only partial success in volumetric erosion determination.

The mean sea level reference will, on the other hand, provide for volumetric erosion determination for all three

Table 1. Characteristics of storms and hurricanes used in this study.

I. D.	Event and Location	Peak Storm Tide (m MSL)	Event Forward Speed (km/hr)	Storm Tide Rise Time (hrs)	Information Sources
H1	Hurricane Audrey, June 1957, Louisiana Gulf Coast	3.66	19.0	11.7	Morgan and others, 1958
H2	Hurricane Carla, Sep. 1961, Texas Gulf Coast	2.30	6.3	51.0*	Reid and others, 977; Neumann and others, 1981; Schwerdt and others, 1979; U. S. Army, 1962
S1	Ash Wednesday Storm, Mar. 1972, U. S. East Coast	3.05	---	28.0*	Bretschneider, 1964; Harrison and Wagner, 1964; O'Brien and Johnson, 1963
S2	Nov. 1962 Storm, U. S. East Coast	1.50	---	7.5*	Birkemeier and others, 1988
S3	6 Nov. 1973 Storm, U. S. East Coast	1.40	---	18.6*	
S4	13 Jan. 1964 Storm, U. S. East Coast	1.50	---	12.4*	
H3	Hurricane Betsy, Sep. 1965, Mississippi Gulf Coast	2.26	16.0	18.0*	Wanstrath, 1978; Neumann and others, 1981; Schwerdt and others, 1979; U. S. Army 1979
S5	16 Sep. 1967 Storm, U. S. East Coast	1.40	---	12.4*	Birkemeier and others, 1988
S6	12 Mar. 1968 Storm, U. S. East Coast	1.20	---	6.1*	
S7	12 Nov. 1968 Storm, U. S. East Coast	1.60	---	15.0*	
S8	2 Feb. 1970 Storm, U. S. East Coast	1.10	---	6.1*	
S9	17 Dec. 1970 Storm, U. S. East Coast	1.60	---	12.4*	
S10	19 Feb. 1972 Storm, U. S. East Coast				
S10a	New Jersey	1.80	---	6.1*	
S10b	New York	2.00	---	6.1*	
S11	17-22 Mar. 1973 Storm, U. S. East Coast				
S11a	New York	1.40	---	12.2*	
S11b	New Jersey	1.30	---	12.2*	
S12	Nov-Dec. 1973 Events, German North Sea Coast	3.57	---	---	Erchinger, 1974
S13	23 Sep. 1974 Storm, U. S. East Coast	1.45	---	9.0	Kana, 1977
H4	Hurricane Eloise, Sep. 1975, N.W. Florida Gulf Coast	3.15	42.6	5.0*	Balsillie, 1983a; Burdin, 1977; Chiu, 1977; U. S. Army, 1976

Table 1. Characteristics of storms and hurricanes used in this study (cont.).

I. D.	Event and Location	Peak Storm Tide (m MSL)	Event Forward Speed (km/hr)	Storm Tide Rise Time (hrs)	Information Sources
S14	14 Oct. 1977 Storm, U. S. East Coast	1.80	---	17.0*	Birkemeier and others, 1988
S15	19 Dec. 1977 Storm, U. S. East Coast	1.40	---	35.0*	
S16	6 Feb. 1978 Storm, U. S. East Coast	1.70	---	19.9*	
H5	Hurricane Frederic, Sep. 1979 Alabama Gulf Coast	3.66	24.1	11.0*	Balsillie and Clark, 1979; Parker and others, 1981; Penland and others, 1980; Schramm and others, 1980
H6	Hurricane Allen, Aug. 1980, Texas Gulf Coast	2.74	32.2	6.0*	Dahl and others, 1983; U. S. Army,1980
S17	No Name Storm, 17-18 June 1982, Lower Florida Gulf Coast	1.68	40.2	8.0*	Galvin, 1983; Trescott, 1983
H7	Hurricane Alicia, Aug. 1983, Texas Gulf Coast	3.86	12.0	18.0*	Dupre, 1985; Garcia and Flor, 1984
S18	Thanksgiving Holiday Storm, 21-24 Nov. 1984, Florida East Coast	1.83	---	21.0*	Balsillie, 1985a
H8	Hurricane Elena, Sep. 1985, Florida Gulf Coast				Balsillie, 1985e
H8a	Pinellas County	1.37	14.5	20.0*	
H8b	Franklin County	2.32	16.1	13.4	
H8c	Gulf County	2.10	16.1	13.4	
H8d	Escambia County	2.29	25.7	8.0*	
H9	Hurricane Kate, Nov. 1985, N. W. Florida Gulf Coast	2.60	---	9.2	Balsillie, 1986
S19	1 Jan. 1987 Storm, U. S. East Coast	1.50	---	12.0	Kana and Jones, 1988; Jones and Kana, 1988
H10	Hurricane Gilbert, Sep. 1988, Cancun, Mexico	3.81	---	9.5	Unpublished Florida Department of Natural Resources data.
S20	Feb. 1989 Storm, Portuguese Atlantic Coast	3.53	---	45.0	Ferreira, 1994
H11	Hurricane Hugo, Sep. 1989, U. S. East Coast	3.80	32.2	5.0	Birkemeier and others, 1991; Nelson, 1991; Stauble and others, 1991
S21	Tropical Storm Marco, Oct 10-11, 1990, Lower Florida Gulf Coast	1.13	16.1	9.0	Beumel and Campbell, 1990

Notes: Peak storm tide is the combined peak storm tide level above NGVD including the astronomical tide and dynamic wave setup; Peak storm tide for event S12 was measured from the local datum; * indicates the measured storm tide rise time, all other are predicted using equation (2).

physiographic scenarios of Figure 1 (except, perhaps, for extreme cases such as inlet formation where erosion occurs below MSL). For breached or flooded profiles, overwash is eliminated from erosion volumes, so that volumetric erosion for non-flooded profiles (where only the seaward sink is available for deposition) and for flooded and breached (where the seaward and upland sinks are available, but eliminated) profiles are comparable. Elimination of upland and seaward sinks is desirable since, on the average, the sum should be equivalent to the amount eroded. While 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 from Balsillie, 1985c), the analytical method is fairly unbiased since it is applied equally to all profiles investigated.

For erosion volume determinations and applications, any datum other than MSL (*i.e.*, mean lower low water (MLLW), mean low water (MLW), mean high water (MHW), and mean higher high water (MHHL)) is not to be employed. Their departure from MSL is not constant from locality to locality (Balsillie and others, 1998). Hence, volumes will not be comparable.

It should be noted that volumetric changes were investigated which included offshore profile data. The results, however, introduced significant scatter. It is to be understood that offshore profiling requires considerable time and resources (Sensabaugh and others, 1977; Balsillie, 1985a, 1985e). Post-storm field measurements are most useful when the response time is swift, since any delay increases the possibility of post-storm beach recovery which can be faster than previously thought. Based on the preliminary analysis alluded to above, the inclusion of offshore profile bathymetry does not yet appear to be justifiable.

There have been a number of extreme event erosion studies in which volumetric erosion calculations are based on single averaged or composite pre-storm and post-storm profiles, even though multiple profiles were measured. In this study, however, pre- and post-storm profiles are surveyed from precisely located coastal monuments, along azimuths established for each monument. Hence, volumetric changes have been calculated for each profile pair, and resulting data have been then statistically treated to obtain point estimators and probability density functions (PDFs).

The Event Longevity Parameter (ELP)

Average Erosion Quantity Above Mean Sea Level and Probability Density Function (PDF)

The most complete set of field data amassed to date is now available to quantify beach and coast response due to extreme event impact. However, such data have little value if there does not exist a methodology for predicting future occurrences of erosion. In fact, until recently, there has been no consolidated methodology by which to realize such prognostication. Recognizing that the amount of erosion is significantly dependent upon the length of time that an extreme event affects the beach and coast (Hayes, 1967; Hayes and Boothroyd, 1969), the author (Balsillie, 1985c, 1986) developed the event longevity parameter (ELP). In terms of the average TYPE I erosion quantity above MSL, $Q_{e\ avg}$, the relationship is given by:

$$Q_{e\ avg} = 1622^{-1}\left(g^{1/2}\ t_r\ S^2\right)^{4/5} \qquad (1)$$

where g is the acceleration of gravity, S is the combined peak storm tide elevation (see note of Table 1 for definition), and t_r is the storm tide rise time. The relationship and data on which equation (1) is based are plotted in Figure 2 and listed in Table 2. The data

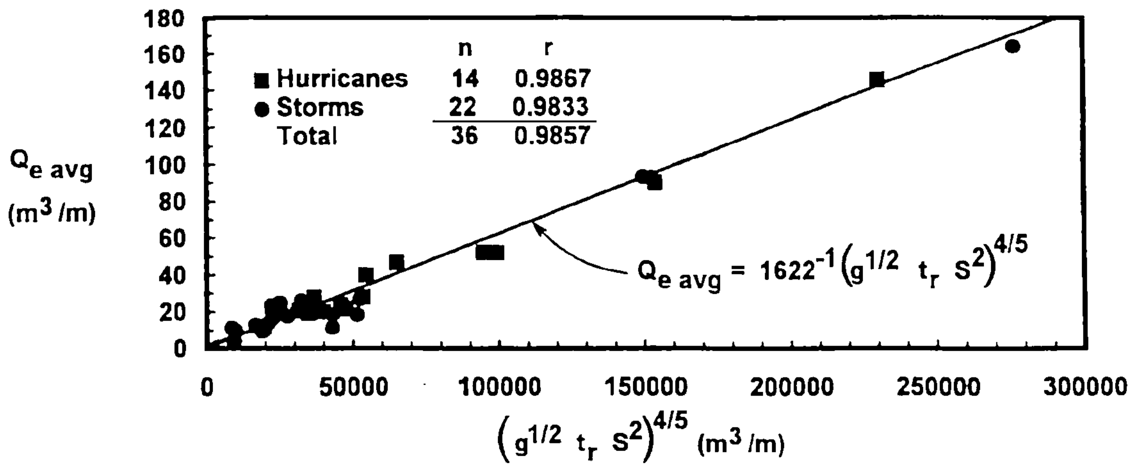

Figure 2. Relationship between the measured TYPE I average erosion volume above mean sea level and the event longevity parameter (n = number of events; r = Pearson product-moment correlation coefficient).

sample on which equation (1) is founded is three times larger than that available to Balsillie (1985c, 1986) in the original development of the relationship, which allowed for refinement of the dimensionless constant. The coefficient of equation (1) is, however, but 2.5% smaller than that reported in the earlier work.

The storm tide rise time, t_r, is the final continuous surge of the storm tide representing impact of the event at landfall. In some cases, pre-storm setdown (*e.g.*, particularly for alongshore hurricanes not considered here) and pre-storm setup can occur. These should be eliminated in determining the value of t_r, whose graphical determination is illustrated in Figure 3.

Values of the storm tide rise time are from measured storm tide hydrographs (references are given in Table 1). Such records are not always simple to interpret, depending on gauge siting, distance of gauges from event landfall, and relationship of the storm generated tide and the astronomical tidal cycle. Consideration of the combined storm tide rise time rather than the total tide history does, however, eliminate uncertainty, which may be introduced, when trying to interpret when the storm tide ends. The total value of t_r for a storm produced tide, maintained over multiple astronomical tides, is determined by adding the rise time components of each additional cycle.

For analytical purposes, t_r is an excellent quantitative measure of event longevity. However, for applied predictive purposes, for an approaching event, the measure is not useful because it is available only after event impact. However, it was found (Balsillie, 1985c) that the storm tide rise time and event forward speed, v_f (measured at the point when the radius of maximum winds, or a facsimile thereof for extratropical storms, makes landfall), are related (Figure 4) according to:

$$t_r = 0.00175\ \frac{g}{v_f} \tag{2}$$

where g is in units of km/hr^2 (*i.e.*, g = 9.8 m/s^2 = 127008 km/hr^2), v_f is in units of km/hr, and the coefficient 0.00175 is in units of hr^2.

The role of pre-storm setup as an

Table 2. TYPE I erosion volume above mean sea level.

I.D.	Event and Location	Average Erosion Volume (m^3/m)	Maximum Erosion Volume (m^3/m)	n	Event Longevity Parameter (m^3/m)	Φ	r_Φ	Elapsed Time (months)	Profile Type
H1	Hurricane Audrey, Jun. 1957, Louisiana Gulf Coast	51.7	89.0	6	99,461	5.55	0.8449	29-48	F
H2	Hurricane Carla, Sep. 1961, Texas Gulf Coast	89.8	---	8	153,710	---	---	5.3	NF,F
S1	Ash Wednesday Storm, Mr. 1962, U. S. East Coast	93.0	---	5	149,327	---	---	60-96	NF
S2	Nov. 1962 Storm, U. S. East Coast	12.9	28.9	31	16,724	1.80	0.9721	0.36	NF
S3	6 Nov. 1963 Storm, U. S. East Coast	20.5	47.3	28	30,970	2.95	0.9634	0.60	NF
S4	12 Jan. 1964 Storm, U. S. East Coast	25.0	56.9	21	25,037	3.55	0.9703	0.50	NF, MS
H3	Hurricane Betsy, Sep. 1965, Mississippi Gulf Coast	46.5	99.0	9	64,912	6.17	0.9939	4	F,B
S5	16 Sep. 1967 Storm, U. S. East Coast	16.6	43.6	18	22,420	2.72	0.9637	0.16	NF
S6	12 Mar. 1968 Storm, U. S. East Coast	9.7	24.9	18	9,919	1.55	0.9787	0.16	NF
S7	12 Nov. 1968 Storm, U. S. East Coast	26.2	55.8	41	32,285	3.48	0.9610	0.72	NF, MS
S8	2 Feb. 1970 Storm, U. S. East Coast	11.1	19.1	29	8,630	1.19	0.9404	0.52	NF
S9	17 Dec. 1970 Storm, U. S. East Coast	17.7	43.5	37	27,724	2.71	0.9906	0.41	NF
S10	19 Feb. 1972 Storm, U. S. East Coast								
S10a	New Jersey	9.5	18.8	34	18,977	1.17	0.9572	0.76	NF
S10b	New York	20.2	41.7	23	22,462	2.60	0.9630	0.82	NF
S11	17-22 Mar. 1973 Storm, U. S. East Coast								
S11a	New York	23.6	52.9	16	22,102	3.30	0.8923	0.69	NF, MS
S11b	New Jersey	10.3	25.3	17	19,630	1.58	0.9768	0.66	NF, MS
S12	Nov.-Dec. 1973 Event, German North Sea Coast	200.0	---	---	---	---	---	---	NF
S13	23 Sep. 1974 Storm, U. S. East Coast	12.0	---	10	18,328	---	---	0.07	NF
H4	Hurricane Eloise, Sep. 1975, N.W. Florida Gulf Coast	20.0	50.7	62	39,628	3.16	0.9735	24	NF

Table 2. TYPE I erosion volume above mean sea level (cont.).

I.D.	Event and Location	Average Erosion Volume (m^3/m)	Maximum Erosion Volume (m^3/m)	n	Event Longevity Parameter (m^3/m)	Φ	r_Φ	Elapsed Time (months)	Profile Type
S14	14 Oct. 1977 Storm, U. S. East Coast	18.5	34.8	22	43,085	2.17	0.9710	0.23	NF
S15	19 Dec. 1978 Storm, U. S. East Coast	11.6	37.9	17	42,979	2.36	0.9800	3.25	NF
S16	6 Feb. 1978 Storm, U. S. East Coast	11.6	37.9	17	42,979	2.36	0.9800	3.25	NF
H5	Hurricane Frederic, Sep. 1979, Alabama Gulf Coast	52.0	121.1	32	94,671	7.55	0.9738	6	F,B
H6	Hurricane Allen, Aug. 1980, Texas Gulf Coast	28.0	---	3	36,682	---	---	30	NF,B
S17	No Name Storm, 17-18 Jun. 1982, Lower Florida Gulf Coast	14.0	25.8	24	21,111	1.61	0.9917	3	NF
H7	Hurricane Alicia, Aug. 1983, Texas Gulf Coast	92.4	---	1	152,259	---	---	36	NF
S18	Thanksgiving Holiday Storm, 21-24 Nov. 1984, Florida East Coast	27.0	70.0	127	52,388	4.30	0.9077	3-20	NF
H8	Hurricane Elena, Sep. 1985, Florida Gulf Coast								
H8a	Pinellas County	21.0	48.3	44	31,704	3.01	0.9622	130	NF
H8b	Franklin County	40.0	75.4	35	54,456	4.70	0.9585	49	NF
H8c	Gulf County	24.0	44.1	54	45,579	2.75	0.9753	13-21	NF
H8d	Escambia County	19.0	38.3	112	34,653	2.39	0.9875	10	NF
H9	Hurricane Kate, Nov. 1985, N. W. Florida Gulf Coast	22.0	51.2	18	47,481	3.19	0.9617	2	F,NF
S19	1 Jan. 1987 Storm, U. S. East Coast	19.4	---	4	25,669	---	---	0.3	NF
S20	Feb. 1989 Storm, Portuguese Atlantic Coast	164.0	341.0	4	276,390	---	---	---	---
H10	Hurricane Gilbert, Sep. 1986, Cancun, Mexico	144.7	297.0	8	89,782 231,462*	18.52	0.9842	60	NF
H11	Hurricane Hugo, Sep. 1989, U. S. East Coast	28.0	52.5	19	53,501	3.98	0.9691	4	NF
S21	Tropical Storm Marco, Oct. 10-11, 1990, Lower Florida Gulf Coast	3.9	11.4	28	9,317	0.57	0.9755	1	NF

Notes: Elapsed time is the time between pre- and post-storm surveys; Profile types are: F = Flooded, B = Breached, NF = Non-flooded, MS = Multiple Storms; * adjusted value to account for increased offshore sediment sink efficiency, see text for discussion; data sources are listed in Table 1.

erosive agent deserves additional comment. If the general onshore physiographic scenario can be described as a beach that is backed by a coast comprised of a dune or bluff (see Figure 1 for graphical definition), then the elevation relative to MSL which identifies where the coast begins (*i.e.*, the beach-coast inflection point, or nickpoint), becomes an important measure. That is, if the storm tide is less than the beach-coast nickpoint elevation, then more time will be required to erode the beach before the coast is affected, relative to the case where the storm tide is higher than the beach-coast nickpoint elevation, so that both the beach and coast will be affected within time constraints of the event. Experience with identification of the beach-coast intersection for Florida beaches (*i.e.*, those for beaches preceding events listed in Table 1), tells us that it is the latter scenario which usually defines the design erosion condition. Current examples of average nickpoint elevations are +2.19 m MSL for Florida's upper East Coast (St. Johns County), +2.25 m MSL for the lower Gulf Coast (Charlotte County), and +2.1 m MSL for the northwestern panhandle Gulf Coast (Walton County). It is significant that of the events of Table 1 and those graphically reported by Harris (1963), none resulted in a pre-storm setup in excess of about +1.5 m MSL, well below the beach-coast nickpoint elevation for Florida. Hence, in combination with the observation that pre-storm setup is an anomalous feature, the above further substantiates that it should be deleted from consideration in erosion prediction.

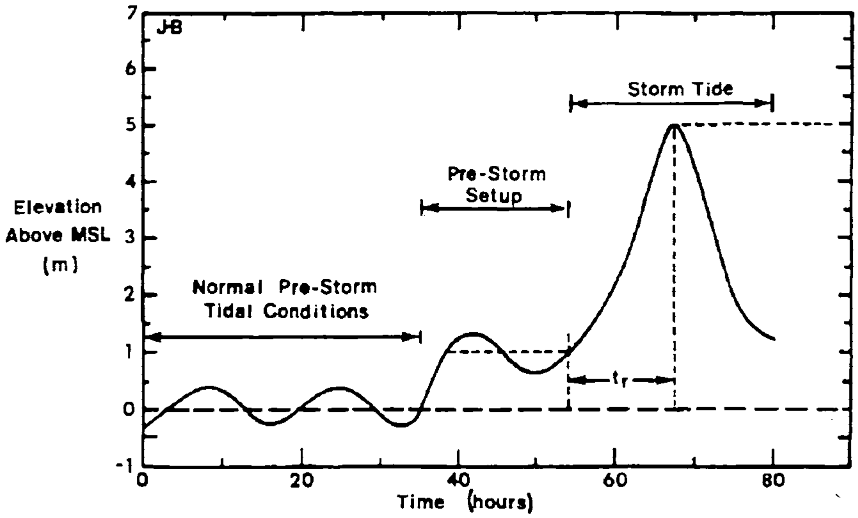

Figure 3. Example of water surface hydrograph through an idealized storm tide, and definition of storm tide rise time measure (after Balsillie, 1986).

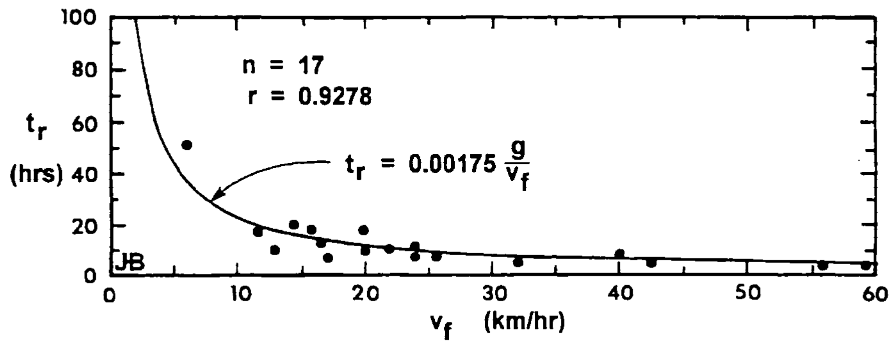

Figure 4. Relationship between the storm tide rise time and event forward speed, where the relating coefficient, 0.00175 is in units of hours squared (after Balsillie, 1986).

It is to be noted that the ELP contains both the peak storm tide, S, and the storm tide rise time, t_r. It is the introduction of the latter which prompted the name ***event longevity parameter***. Utilizing stepwise regression (Krumbein and Graybill, 1965; Balsillie, in press; Balsillie and Tanner, in press), it has been determined that S results in a relative net contribution in predicting $Q_{e\ avg}$ of 76%, and t_r provides a net relative contribution of 24%. Even so, both are required in order to obtain the success of equation (1) evident in Figure 2.

There are 29 events that provide information on which to investigate an erosional probability density function (PDF). From 6 to 127 profiles represent each of the events (Table 2), and result in the following equation:

$$Q_e = \xi \, (e^{3P}) \left(g^{1/2} \; t_r \; S^2\right)^{4/5} \qquad (3)$$

in which Q_e is the volumetric coastal erosion quantity occurring above mean sea level corresponding to the erosion probability, P, which is the probability of erosion less than or equal to that stated, and ξ is a relating coefficient. Values of Φ (examples are plotted in Figure 5, results and correlation coefficients are listed in Table 2) are plotted against the ELP in Figure 6, showing remarkable agreement. The relating coefficient ξ becomes 12344^{-1}.

Correlation coefficients associated with Φ are all significantly large. Note that if we were to consider, say, median and larger erosion values in the PDFs (see Figure 5), rather than all values available, correlation coefficients would be even larger.

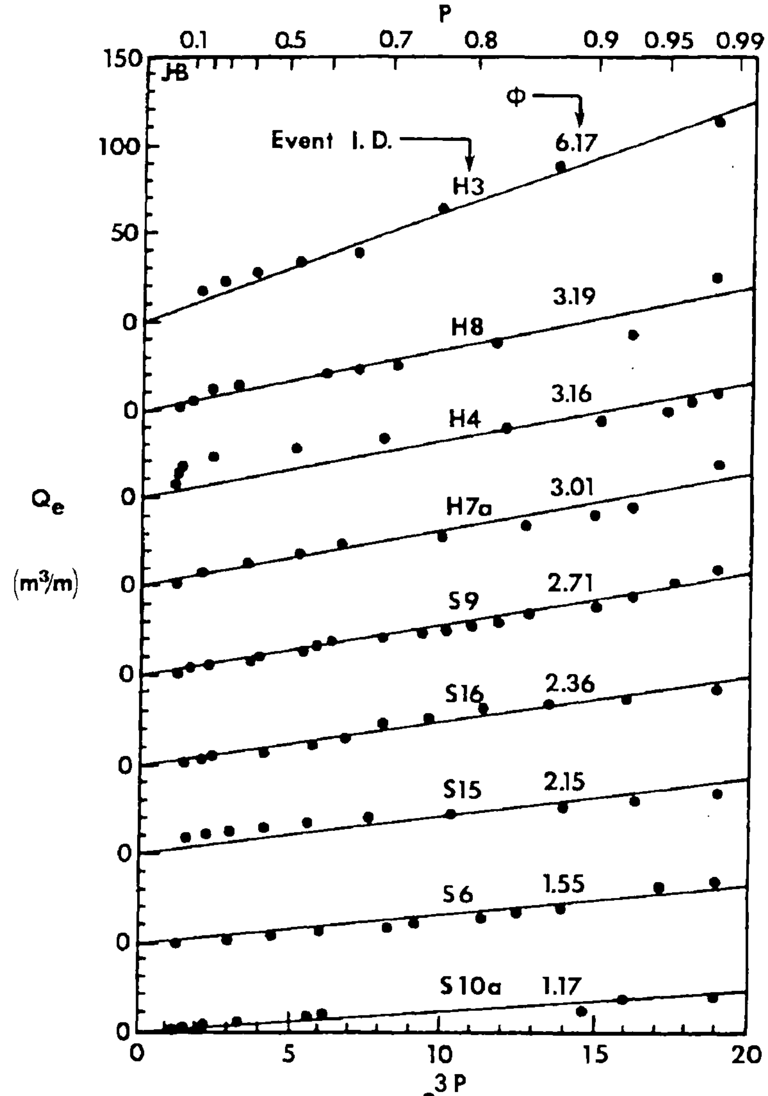

Figure 5. Typical examples of density distributions for determination of the slope Φ relating Q_e and e^{3P} (event I.D.s refer to Table 2).

Average Erosion Quantity Above the Peak Storm Tide Level and Probability Density Function (PDF)

The preceding has dealt with volumetric erosion occurring above mean sea level. While it has been noted that consideration of erosion above the peak storm tide elevation has no applicability for flooded or breached profiles, such a consideration does have validity for non-flooded profiles. Based on available data listed in Table 3, the following relationship based on 24 events, illustrated in Figure 7, surfaces:

$$Q'_{e\,avg} = 3299^{-1} \left(g^{1/2} \; t_r \; S^2\right)^{4/5} \qquad (4)$$

where $Q'_{e\,avg}$ is the TYPE I average erosion quantity occurring above the peak storm tide level.

Using data from 22 events (Table 3) a PDF may be proposed according to:

$$Q'_e = \xi' \, (e^{3P}) \left(g^{1/2} \; t_r \; S^2\right)^{4/5} \qquad (5)$$

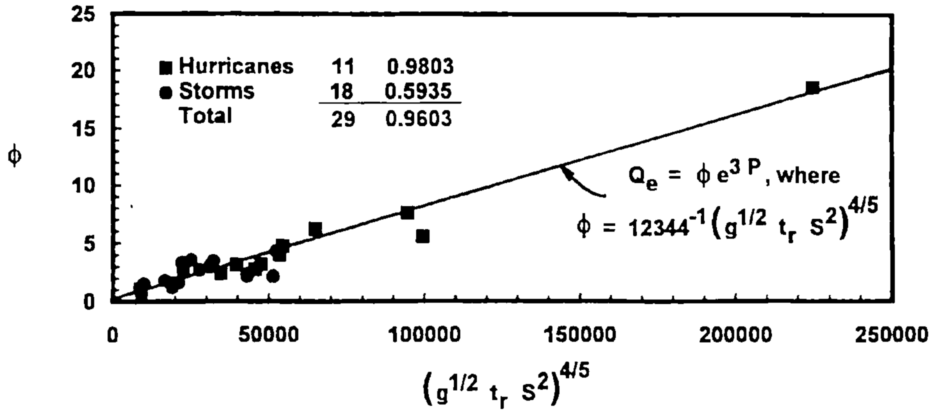

Figure 6. Relationship between the event longevity parameter and distribution coefficients for TYPE I average volumetric erosion above MSL.

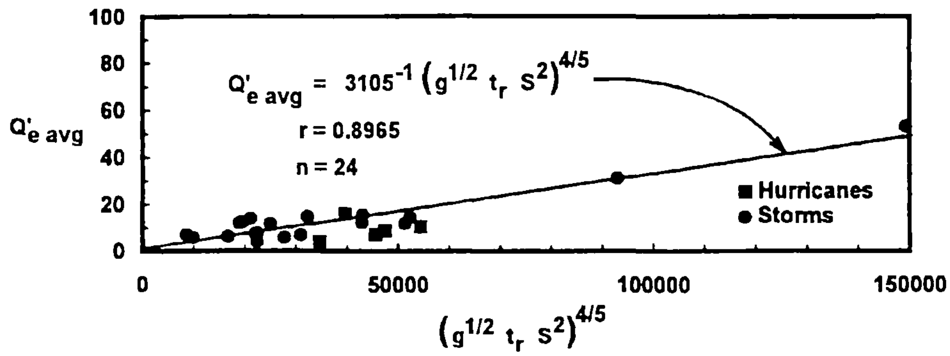

Figure 7. Relationship between the measured TYPE I average net erosion quantity above peak combined storm tide level and the event longevity parameter.

where the relating coefficient ξ from Figure is 23630^{-1}.

It is evident from results presented in Figure 8, that the correlation between variables is significantly less than those statistical assessments for analyses presented in Figures 2, 6, and 7. Even so, the probability that a random sample of this size could result in sample correlations so large, is very small.

Design Erosion Quantities

Now that we have established successful relationships that quantitatively predict average erosion volumes for events relative to MSL and the peak storm tide elevations, we can broaden our quantitative expectations. We know that for engineering design purposes, using TYPE I erosion volumes, an average measure is not responsible. For engineering design purposes it is always prudent to consider some upper measure of a destructive force, or response element. A highly useful measure from substitution of equations (1), (3), (4), and (5), where PDF linearity prevails, is given by:

$$\frac{Q_e}{Q_{e\ avg}} = \frac{Q'_e}{Q'_{e\ avg}} = 0.1314\ e^{3P} \qquad (6)$$

in which Q_e and Q'_e are erosion volumes for

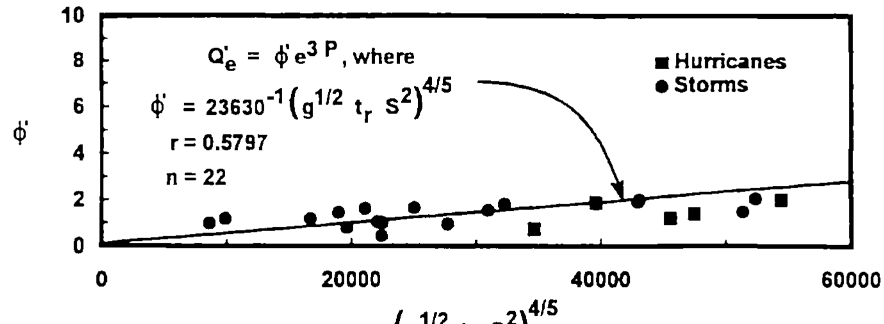

Figure 8. Relationship between the event longevity parameter and distribution coefficients for the TYPE I average erosion volume above the peak combined storm tide.

a specified exceedence probability P above MSL and peak storm tide, respectively. Hence, the TYPE I median erosion volume (*i.e.*, P = 0.5) is about 61% less than the TYPE I average erosion volume (for the average erosion volume P = 2/3), the third quartile TYPE I erosion volume (*i.e.*, P = 0.75) is 130% greater than the average TYPE I erosion volume, *etc.*

Noting that pre-storm profiles are seldom measured just prior to storm or hurricane impact, some physiographic deviation might be reasonable to levy on a PDF in assessing a design maximum erosion volume. This and purely random, anomalously high erosion volumes suggest that, perhaps, a probability P of between 0.9 and 0.95 would not seem inordinate to apply. Using a value of 0.925 and coefficients from equations (1) and (4), the application of equation (6) yields the following design relationships:

$$Q_{e\ max} = 770^{-1}\left(g^{1/2}\ t_r\ S^2\right)^{4/5} \qquad (7)$$

for the TYPE I erosion volume above MSL, and:

$$Q'_{e\ max} = 1473^{-1}\left(g^{1/2}\ t_r\ S^2\right)^{4/5} \qquad (8)$$

for the TYPE I erosion volume above the combined peak storm tide level. Both equations result in erosion volumes close to twice (*i.e.*, 2.1) the average erosion volume.

It is to be noted that coefficients of equations (7) and (8) precisely agree with fitted coefficients describing the graphically estimated maximum erosion quantities of Tables 2 and 3.

The Offshore Sink Efficiency Parameter (OSEP)

The form of the event longevity parameter has invoked some controversy. While the combined peak storm tide height and storm tide rise time components have generally been well received, the appearance of the acceleration of gravity and the dimensionless proportionality constant have not.

If one compares erosion quantities above the combined storm tide to those above mean sea level, it is apparent that about half the eroded sand volume originates from above the peak storm tide level (50% if one compares coefficients from equations (1) and(4), and (3) and (5), and 55% from the data). This should not be surprising from a geomorphic viewpoint, considering that our beaches and coasts have certain constraining dimensions physiographically. It is recognized that the efficiency of gravitational acceleration is not only greater for steeper slopes when dealing with sand transport, but

Table 3. TYPE I erosion volume above combined peak storm tide.

I. D.	Event and Location	Average Erosion Volume (m^3/m)	Maximum Erosion Volume (m^3/m)	n	Event Longevity Parameter (m^3/m)	Φ	r_Φ
S1	Ash Wednesday Storm, Mar. 1962, U. S. East Coast	53.0	---	4	149,327	---	---
S2	Nov. 1962 Storm, U. S. East Coast	6.3	18.6	32	16,724	1.16	0.9953
S3	6 Nov. 1963 Storm, U. S. East Coast	6.9	24.2	26	30,970	1.51	0.9552
S4	13 Jan. 1964 Storm, U. S. East Coast	11.7	26.1	37	25,037	1.63	0.9841
S5	16 Sep. 1967 Storm, U. S. East Coast	3.9	7.1	19	22,420	0.44	0.8918
S6	12 Mar. 1968 Storm, U. S. East Coast	5.8	18.6	37	9,919	1.16	0.9590
S7	12 Nov. 1968 Storm, U. S. East Coast	14.8	28.7	43	32,285	1.79	0.9879
S8	2 Feb. 1970 Storm, U. S. East Coast	6.9	15.6	31	8,630	0.97	0.9559
S9	17 Dec. 1970 Storm, U. S. East Coast	5.8	15.1	42	27,724	0.94	0.9316
S10	19 Feb. 1972 Storm, U. S. East Coast						
S10a	New Jersey	12.0	22.8	23	18,977	1.42	0.9815
S10b	New York	7.6	15.7	38	22,462	0.98	0.9831
S11	17-22 Mar. 1973 Storm, U. S. East Coast						
S11a	New York	7.5	16.4	17	22,102	1.02	0.9758
S11b	New Jersey	5.3	12.5	16	19,630	0.78	0.9909
S12	Nov.-Dec. 1973 Events, German North Sea Coast	31.0	---	---	92,944	---	---
H4	Hurricane Eloise, Sep. 1975, N. W. Florida Gulf Coast	16.0	29.8	72	39,628	1.86	0.9557
S14	14 Oct. 1977 Storm, U. S. East Coast	15.5	31.6	22	43,085	1.97	0.9890
S15	19 Dec. 1977 Storm, U. S. East Coast	11.8	23.4	20	51,356	1.46	0.9890
S16	6 Feb. 1978 Storm, U. S. East Coast	12.3	30.5	17	42,979	1.90	0.9940
S17	No Name Storm, 17-18 Jun. 1982, Lower Florida Gulf Coast	14.0	25.8	24	21,111	1.61	0.9917
S18	Thanksgiving Holiday Storm, 21-24 Nov. 1984, Florida East Coast	14.6	32.4	128	52,388	2.02	0.9807
H8	Hurricane Elena, Sep. 1985, Florida Gulf Coast						
H8b	Franklin County	10.3	31.6	34	54,456	1.97	0.9661
H8c	Gulf County	7.1	18.9	30	45,579	1.18	0.9958
H8d	Escambia County	4.2	11.4	58	34,653	0.71	0.9459
H9	Hurricane Kate, Nov. 1985, N. W. Florida Gulf Coast	8.7	22.0	13	47,481	1.37	0.9247

Note: The time between pre-storm and post-storm surveys, and comments are given in Table 2; data sources are listed in Table 1.

due to inertial effects is less response oriented under lower slope subaqueous than steeper slope subaerial littoral conditions. The result is a partitioning of sediment transport between kinetic energy (*i.e.*, by virtue of low-slope, near horizontal motion due to shore-normal subaqueous sediment transport mechanics) and potential energy (*i.e.*, by virtue of subaerial elevation of dunes and bluffs and potential gravitational mass wasting due to wave impacts propagating upon an elevated water level). Based upon this logic, it would appear that the diminished effect of the acceleration of gravity is not unwarranted, because it probably relates more to spreading rates across the nearshore than to dune or bluff mass wasting. The latter is essentially instantaneous, while the former is time-consuming. In fact, the prototype wave tank results of Dette and Uliczka (1987) appear to provide some elucidating information. First, their results show that the pre-impact nearshore bed slope correlates with the magnitude of beach and coast erosion volumes and the rate of erosion. Specifically, the steeper the pre-storm nearshore bed slope, both the greater the erosion volume above SWL, and the faster the removal rate. Second, regular and irregular waves appear to erode the beach and coast at different rates.

Dette and Uliczka (1987) report prototype results for initial nearshore bed slopes of 0.25 and 0.05, and Saville (1957) for a slope of 0.0667. U. S. East and Gulf Coast natural nearshore slopes (*i.e.*, 300 to 800 m offshore) are, however, characteristically less than 0.02, averaging about 0.016 for Florida. Application of these data relative to ξ the PDF coefficient of equation (3), yields a dimensionless proportionality constant Ψ termed the ***offshore sink efficiency parameter (OSEP)***, according to:

$$\Psi = \xi^{-1} (\tan \alpha_i)^{\phi} \qquad (9)$$

where $\tan \alpha_i$ is the initial or pre-impact nearshore bed slope, and:

$$\phi = 2.07 + 13.2 \tan \alpha_i \qquad (10)$$

Data and fitted relationship leading to equations (9) and (19) are plotted in Figure 9. Results from equation (9) apply only where the initial or pre-impact nearshore bed slope is greater than 0.01638; where the initial bed slope is less than 0.01638 the value of Ψ is unity (*i.e.*, 1.0). The final form of equation (3) now becomes:

$$Q_e = \xi \, (e^{3\,P}) \, \Psi \, (g^{1/2} \, t_r \, S^2)^{4/5} \qquad (11)$$

The validity of Ψ can be tested using data obtained from Hurricane Gilbert which struck Cancun, Mexico in September, 1986. While the accuracy of data for Hurricane Gilbert is not touted to be of the standard for the remainder of the data base presented here (and in particular for the Florida data), the magnitude of the event was so overwhelming that it cannot be neglected; best known data are listed in Tables 1 and 2. A significantly important factor associated with the Gilbert data are the very steep

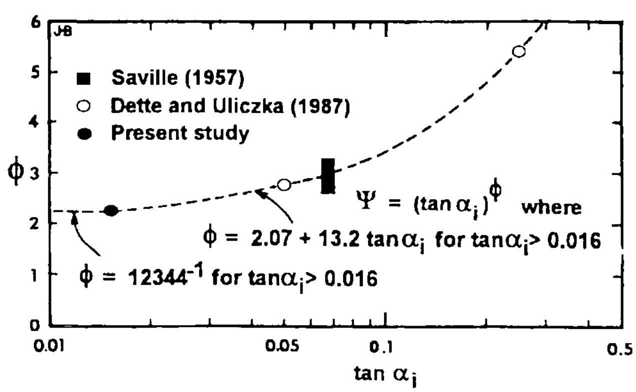

Figure 9. Tesselated relationship relating nearshore bed slope ($\tan\alpha_i$ which occurs from 300 to 800 m offshore of the MSL shoreline) to the ELP coefficient ξ.

nearshore slopes off of Cancun as illustrated in Figure 10. In fact, the nearshore slope is over twice (*i.e.*, 222%) as steep as slopes commonly found off U. S. East and Gulf Coast nearshores. Such a slope is steep enough that sand is not able to be transported back onshore during post-storm conditions. Hence, the steep offshore slope becomes, for all practical purposes, a sediment sink. Given the following data for Hurricane Gilbert:

$$\tan \alpha_i = 0.0363,$$

$$t_r = 9.5 \text{ hours},$$
$$S = 3.81 \text{ m},$$

$$P = 0.68 \text{ (average erosion volume)},$$
$$P = 0.925 \text{ (maximum erosion volume)},$$

then: $\quad \text{ELP} = 89{,}782 \text{ m}^3/\text{m},$
$\quad \text{OSEP} = 2.578,$

and: $\quad e^{3P} = e^{3(2/3)} = 7.3891,$

and,

$$e^{3P} = e^{3(0.925)} = 16.0386.$$

The adjusted ELP due to the effect of the steeper nearshore and increased value of the ***offshore sink efficiency parameter*** is the product of the ELP and OSEP, resulting in a value of 231,462 m^3/m. The goodness of fit of this result is illustrated in Figure 2. Moreover, equation (11) results in an average erosion volume (*i.e.*, P = 2/3) of 144.5 m^3/m which is very close to the measured amount of 144.7 m^3/m, and a maximum erosion volume (*i.e.*, P = 0.925) of 313.6 m^3/m which is within 5.6% of the measured value of 297 m^3/m.

The final form of equation (5) for volumetric erosion above the peak storm tide level becomes:

$$Q_e' = \xi' \left(e^{3P}\right) \Psi \left(g^{1/2}\, t_r\, S^2\right)' \qquad (12)$$

where by similitude, it is assumed that the OSEP applies straightforwardly as in equation (11) (field data are needed, however, for confirmation).

Nearshore geometry is now commonly quantified by a power curve (Dean, 1977; Hughes, 1978; Balsillie, 1982a, 1987) given by:

$$d = a_s\, x^{2/3} \qquad (13)$$

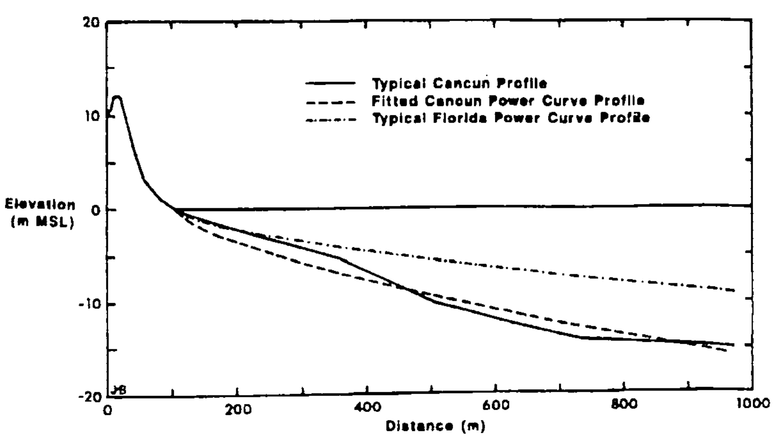

Figure 10. Comparison between a typical Florida nearshore profile and a typical Cancun, Mexico nearshore profile.

in which d is the water depth, and x is the distance offshore. Using the data of Saville (1957), Dette and Uliczka (1987), and average data for Florida, $\tan \alpha_i$ may be approximately related to the shape coefficient (Dean, 1977), a_s, according to:

$$\tan\alpha_i = 0.5\, a_s^{3/2} \qquad (14)$$

illustrated in Figure 11 (a_s in equations (11) and (12) has units of $m^{1/3}$; if a_s is in units of $ft^{1/3}$ multiply the value by 0.673 to obtain consistent S. I. units).

Return Period Volumetric Erosion Events

The incidence of extreme phenomena may require site-specific treatment. Such is the case with the determination of the return period storm tide which is dependent not only on historical storm/hurricane characteristics and water levels, but also, importantly, on local conditions such as offshore and nearshore bathymetries. A major problem in following such an approach for erosion responses is that site-specific quantitative erosion data are historically deficient. However, since uncertainties about erosion make simplified considerations the most appropriate (Hallermeier and Rhodes, 1986), and because of the apparent success of foregoing quantitative results, it is assumed that physiographic responses to storm attack need not be held to a site-specific treatment.

Further, it has been a major tenet of this and other works (Balsillie, 1985c, 1986) that the storm tide return period event and the storm erosion return period event are seldom coincident. Until now there has been insufficient information on which to specify the probabilistic erosion event.

The frequency P_e used in plotting the distribution is found (Gumbel, 1954) by ranking the erosion volumes from smallest to largest and then dividing the rank of each of the sample size plus one, *i.e.*:

$$P_e = m \frac{1}{n + 1} \qquad (15)$$

where m is the ranked value. If the theory does hold, the points should plot as a straight line on probability paper. The return period T_e is then given by:

$$T_e = \frac{1}{1 - P_e} \qquad (16)$$

Using equations (15) and (16), the plot of Figure 12 is constructed using data from Table 2. Only Atlantic Ocean events are considered in this analysis. There are 35 events listed in Table 2 which apply. These events occupy a 34-year period from 1957 through 1990. During this period some 324 tropical storms and hurricanes formed in the Atlantic. Of these, about 104 (or 32% of the total) landfalling or exiting events affected the Americas along the U. S. East Coast, and Gulf of Mexico coasts of the U. S. and Mexico. It is assumed that the applicable 35 events of Table 2 represent a random sample of erosion conditions. The 35 events, however, represent only one-third of the actual number of events that affected coastal reaches. Therefore, for analytical purposes, the 35-event sample is "triplicated" to yield 105 events (*i.e.*, tripled in size to more nearly represent the 104 events that actually occurred); only the mid-point of each "triplicate" is plotted to

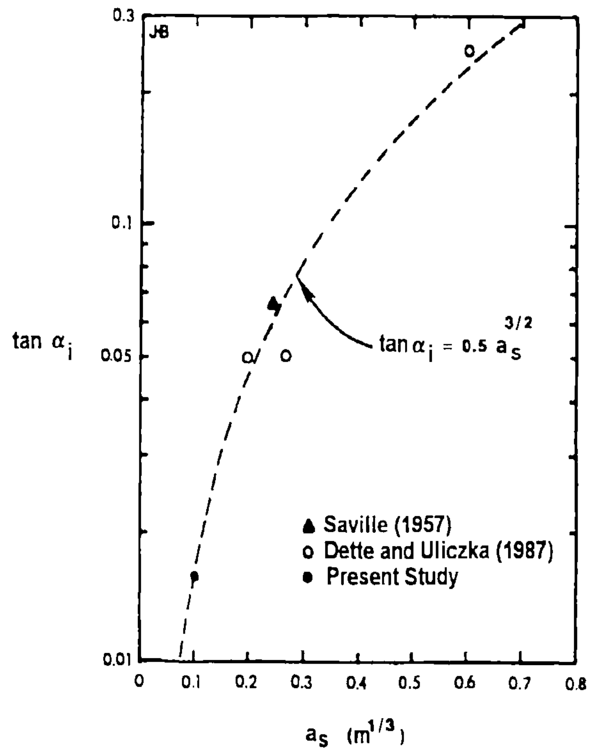

Figure 11. Relationship between the initial nearshore bed slope (tan α_i occurring 300 to 800 m offshore of the MSL shoreline) and the power curve fit shape coefficient, a_s.

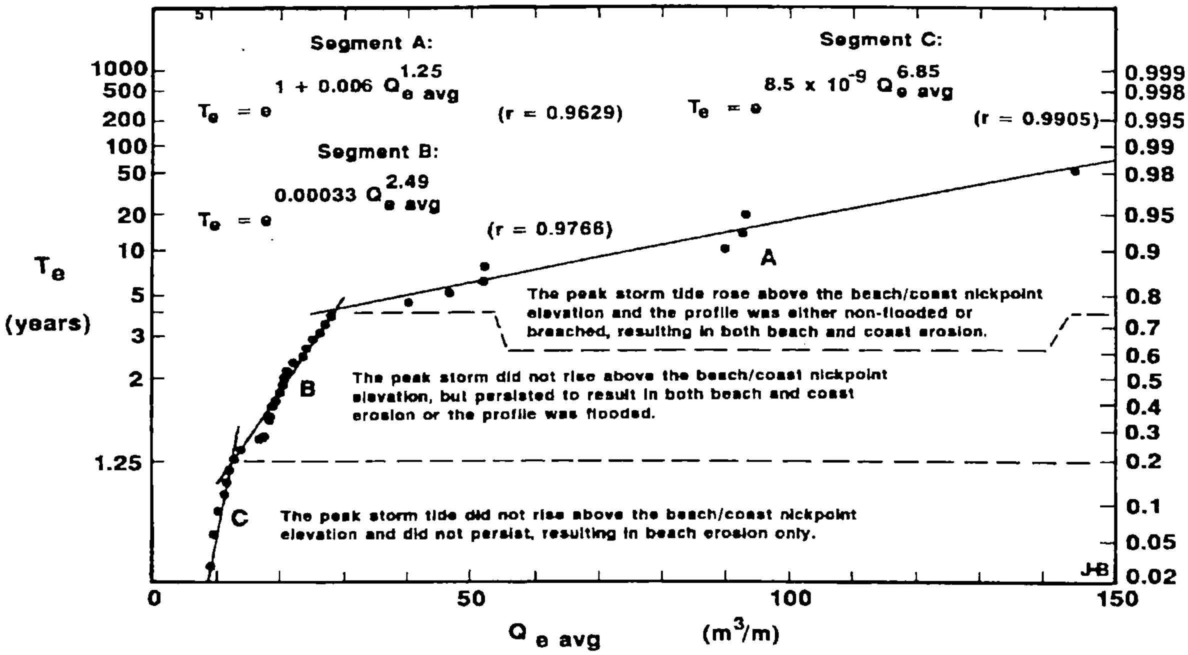

Figure 12. Relationship between exceedence probability P, return period T_e, and average TYPE I erosion volume above MSL.

represent the associated probability and return period. It is noted that three straight-line segments are apparent for which possible explanations have been suggested (see Figure 12). Equations of immediate interest for coastal construction design purposes are:

$$T_e = e^{1 + 0.006\,Q_{e\,avg}^{1.25}} \tag{17}$$

for segment A which describes extreme events with a frequency less than about a 4-year return period, where $Q_{e\,avg}$ is specified in cubic meters per alongshore meter of beach or coast (note: m^3/m = 2.508 (yd^3/ft)). Utilizing, by substitution, equation (6) the corresponding probability of equation (17) is given by:

$$P_e = 1 - \left(e^{1 + 0.006\,Q_{e\,avg}^{1.25}}\right)^{-1} \tag{18}$$

Further, by rearranging equation (17), the return period erosion quantity in m^3/m may be determined according to:

$$Q_{e\,avg} = 60\,\left[(\ln T_e) - 1\right]^{0.8} \tag{19}$$

By incorporating results from equation (6), the design maximum erosion volume (i.e., for P = 0.925) results in a factor of 2.1 and:

$$Q_{e\,max} = 126\,\left[(\ln T_e) - 1\right]^{0.8} \tag{20}$$

For segment B of Figure 12, which describes events between about 1.25- and 4-year return occurrences, the return period is given by:

$$T_e = e^{0.00033\,Q_{e\,avg}^{2.49}} \tag{21}$$

for which equations corresponding to (18), (19), and (20), become:

$$P_e = 1 - \left(e^{1 + 0.00033\,Q_{e\,avg}^{2.49}}\right)^{-1} \tag{22}$$

$$Q_{e\,avg} = 25\,\left[(\ln T_e) - 1\right]^{0.4016} \tag{23}$$

and:

$$Q_{e\,max} = 53.5\left[(\ln T_e) - 1\right]^{0.4016} \qquad (24)$$

Following this methodology, similar equations may be developed for segment C that represent events occurring more often than the 1.25-year return period (see Figure 12).

There is simply not yet sufficient field data to reliably determine return period volumetric erosion events for erosion above the peak combined storm tide level (in particular for that portion corresponding to segment A of Figure 12). However, statistics indicate that erosion volumes above the peak storm tide level, on the average are about one-half those above MSL. Hence, in the interim, a reasonable estimation may be determined by doubling the value of $Q'_{e\ avg}$ and using equations (17) through (24).

The quantifying equations developed in this section are of special consequence. Past return period damage elements have been assessed in terms of forces, specifically the combined storm tide elevation and wave heights. Now, for the first time, a return period response element in terms of erosion is provided which accounts for all the force elements, including longevity of the event. It is envisioned that these equations will be highly valuable in design and coastal management activities.

One might be inclined to believe that the developed approach is based upon broad assumptions (*e.g.*, global continuity in littoral physiography) and a limited sample size. Recognize, however, that errors creep into design computations due to assumptions about convoluted littoral processes. At present, and at a minimum, equations (17) through (24) would seem to provide information as a valuable check for the more involved design computations (methodology for application of volumetric erosion volumes is discussed in the conclusions).

It is, however, notable that Figures 11 and 12 support the significance of physiographic zonation between the beach and coast.

Post-Storm Recovery

There seems to be considerable interest among coastal scientists and engineers in post-storm littoral recovery, even though we are just now quantifying details about magnitudes of physiographic responses during the "height" of extreme event impact. While there exists some quantifiable representation of such recovery (Balsillie, 1985d, in manuscript), additional work remains. Generally, based on what is known about littoral processes, we can endeavor to find discernible and logical conclusions about such recovery. Again, it becomes of importance to delineate littoral subzones (see Figure 1), namely, ... 1. the nearshore, 2. the beach, and 3. the coast. It is these three subzones which interactively define the extent of both extreme event impacts and what are discernibly "normal" or "day-to-day" littoral processes.

The nearshore, which is always subject to the effects of astronomical tides and waves, is expanded when a rising storm tide encompasses the beach, and, under design conditions, the coast. That longshore bars are formed during extreme event impact has been a controversial issue. The problem is, of course, that nearshore subaqueous behavior has not been adequately monitored to yield confident quantification during extreme event impact. However, based on additional considerations and tested data (Balsillie, 1984c, 1985d), and field observations (Dette, 1980; Birkemeier, 1984; Sallenger and others, 1985), the formation of longshore bars during extreme event impact seems more nearly to be the case. Ramifications of the concept are not only essential towards a new understanding of coastal engineering design constraints that might be required, but of interactive littoral forces and responses that could occur during extreme event impact (bearing in mind that extreme prospects are probabilistic).

Further, longshore bars are nature's own protective device. During storm action they not only are formed but move offshore (Short, 1979; Birkemeier, 1984; Mason and others, 1984, Sallenger and others, 1985), causing storm waves to break further offshore than would normally occur. By inducing breaking they cause the greatest amount of energy dissipation that water waves can experience and, should wave reformation occur, significantly reduce the elevation of destructive wave energy (*i.e.*, reformed wave heights are attenuated; Carter and Balsillie, 1983; Balsillie 1984b, 1985b).

During storm impact, the width of the surf zone dramatically increases. When, following impact, surf width again attains "normal" width the bar(s) within the "normal" surf zone move onshore in a few days. Outer bars either remain as relict features or disappear, although the latter requires months to occur (Birkemeier, 1984; Mason and others, 1984; Sallenger and others, 1985).

Beach (or shore) recovery appears to be considerably more rapid than has been presupposed by many coastal engineers. Although complexities occur (*e.g.*, longshore transport) which can produce a large range in values, it is now quite clear that beach recovery often occurs within days. Birkemeier (1979) found for the 19 December 1977 U. S. east coast storm (event S15) that from 38% to 100% beach recovery occurred within one or two days following event impact. Bodge and Kriebel (1985) also report rapid recovery for beaches following impact of Hurricane Elena in Pinellas County, Florida (event H7a). Such rapid beach recovery agrees with response time scales of post-storm nearshore profile changes.

The coast is of special interest because it is detrimentally affected only during extreme event impact (or man's activity). Where high sandy dunes or bluffs exist, the coast affords substantive protection to the upland. It is nature's physiographic reserve of particulate mass, drawn upon to replenish the more active beach subzone, when beach subzone dimensions are diminished.

Of the three sub-zones, the coast in its natural state can be expected to experience no immediate recovery. An example is Dauphin Island, Alabama struck by Hurricane Frederic in 1979, destroying dunes which attained heights of up to +10 m MSL. Average volumetric dune losses were about 50 m^3/m. Assuming the sand supply is available and that vegetation is instrumental in natural dune reconstruction, then based on the data of the U. S. Army (1984) and Dahl and others (1975), natural dune reconstruction would require 70 to 75 years for American Beach Grass and Sea Oats, respectively, and 180 years for *Panicum* (Balsillie, 1979a).

APPLICATIONS

The results of this work deal with volumetric erosion of the beach and coast due to extreme event impact. This comprises, however, but one aspect of interrelated natural processes in terms of force and response elements that occur within nearshore, beach, and coast subenvironments of the littoral zone. Other aspects include storm wave activity which is instrumental in causing the erosion, producing dynamic and impact loads on exposed structural members, and forming longshore bars that house sand eroded from the beach and coast. These various aspects are quantified and discussed in a series of papers, the sum total of which actually describe the entire Multiple Shore-Breaking Wave Transformation Erosion computer model (Balsillie, 1984c, 1985d). This approach allows one to more succinctly manage research by dealing with discrete or sets of discrete natural process units, and also facilitates updating of each manageable unit as new developments are made. Even so, it is recognized that some guidance would be helpful to describe how the predicted volumetric erosion can be practically applied.

Post-Storm Beach and Coast Physiography

The problem in applying volumetric erosion quantities, is the determination of the resulting physiography of the profile. For the two-dimensional case, the following simplified methodology is suggested as illustrated in Figure 13 (discussed by Balsillie 1984c, 1985d). Following determination of the design erosion volume, plot the pre-impact coast, beach, and nearshore profile. The nearshore profile shape in Florida can be determined using the power curve form according to Balsillie (1982a, 1982b, 1987). Plot the bar crest envelope, d_{bc} (*i.e.*, the line connecting the crests of longshore bars formed during the event) and the corresponding bar trough envelope, d_{bt} (*i.e.*, the line connecting the bar troughs, according to:

$$d_{bc} = \frac{2}{3}\left(S + a_s\, x_{bc}^{2/3}\right) \qquad (25)$$

where S is the peak combined storm tide, a_s is the shape coefficient given by Balsillie (1982b) for Florida, and x_{bc} is the distance offshore measured from the pre-storm MSL shoreline, and:

$$d_{bt} = S + \frac{6}{5}\, a_s \left(x_{bt} + 7\, S\right)^{2/3} \qquad (26)$$

where x_{bt} is the distance offshore measured from the pre-storm MSL shoreline.

Inspection of post-storm profiles indicates that the portion of the eroded profile above the peak storm tide (segment AB lying above the nickpoint of Figure 13) has a 1 on 1 slope. The segment BC is a slightly curved line smoothly continuing the bar trough envelope to the nickpoint (where the coast is flooded only segment BC applies). Starting at the pre-impact shoreline, segment ABC (or segment BC where the coast is flooded) is iteratively moved landward until the erosion volume is attained (shaded area of Figure 13).

Nearshore wave heights are determined using the bar crest envelope to represent the water depth at breaking, d_b (Balsillie, 1983b, 1984b, in press). The amount of the breaking wave height lying above the peak storm tide still water level, H_b', has been determined from field data (Balsillie, 1983d, 1985b, in press) to be given by:

$$H_b' = 0.84\ H_{bx} \qquad (27)$$

in which H_{bx} is the average height of the desired moment measure. The breaker height envelope illustrated in Figure 13, represents the significant height. Relating equations developed by Balsillie and Carter, 1984a, 1984b) for other moment measures commonly used in design work are:

$$H_{b\ rms} = 1.02\ H_b \qquad (28)$$

where $H_{b\ rms}$ is root-mean-square breaker height, and H_b is the average breaker height;

$$H_{bs} = 1.23\ H_b \qquad (29)$$

in which H_{bs} is the significant breaker height (*i.e.*, average of the highest two-thirds of the height record);

$$H_{b10} = 1.37\ H_b \qquad (30)$$

where H_{b10} is the average of the highest 10% of the wave record; and:

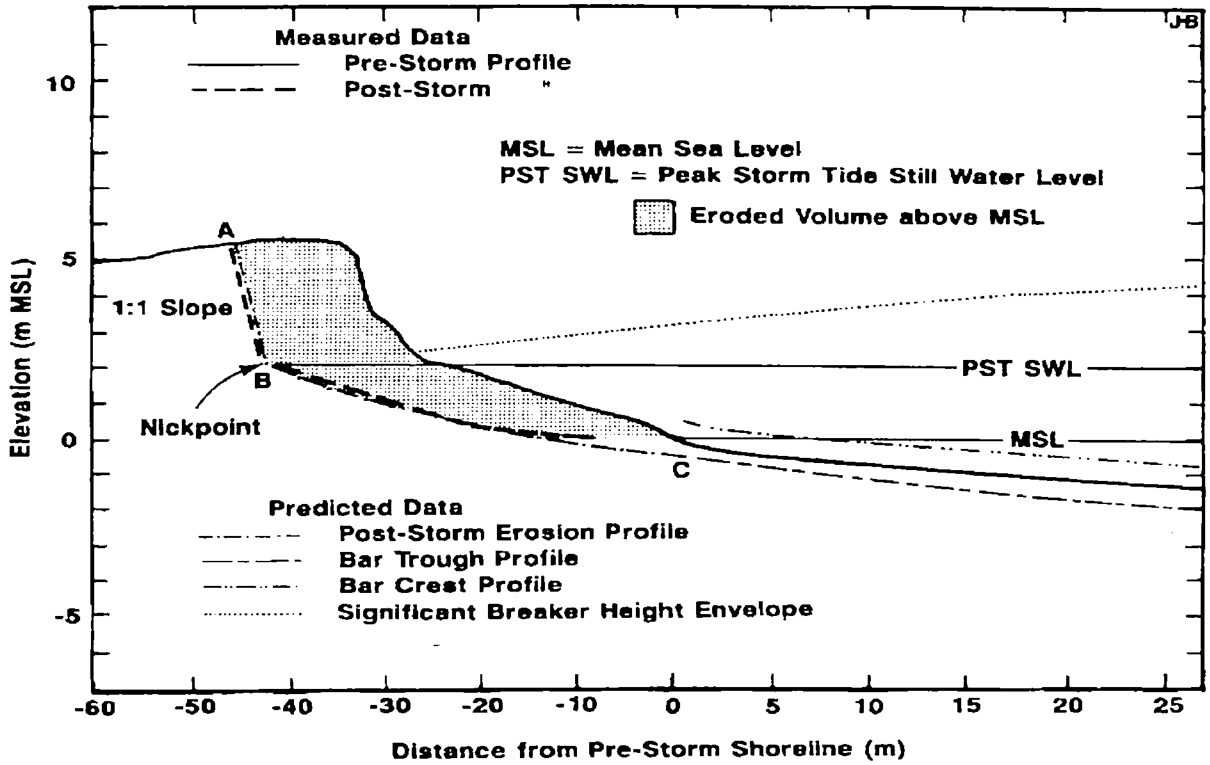

Figure 13. Example of application for determining two-dimensional post-storm physiography using volumetric data, and design wave conditions.

$$H_{max} \approx H_{b1} = 1.57\ H_b \qquad (31)$$

in which H_{b1} is the average of the highest 1% waves of record.

Encounter Period and Probability

A return period statistic is one providing a measure of the probability of annual occurrence. For instance, an event with a 100-year return period has a probability of 0.01 or a chance of 1% occurrence in any given year, an event with a 5-year return period has a probability of 0.20 or a 20% chance of occurrence in any given year, *etc*. Even if the return period occurrence occurs during an annual period, its probability of recurrence remains the same within the current annual framework.

The above often leads to confusion, particularly when one tries to relate such statistics to the design life of a project. What we really wish to do is transform the return period statistic to one of encounter probability, based upon a specified encounter period.

The solution is the use of Figure 14. The abscissa of Figure 14 gives the ***Encounter Period*** which is the period of time for which a project is to last (i.e., its design life). In the case of single-family dwelling design, the encounter period might be 50 years representing a depreciation period for tax purposes, *etc*. The ordinate of Figure 14 gives the ***Encounter Probability*** which represents the assigned return period equaled or exceeded during the selected ***Encounter Period***. Curves internal to the graph are for various ***Return Periods*** associated with the design event.

Following is an example of how to use the figure. Suppose that you would like to

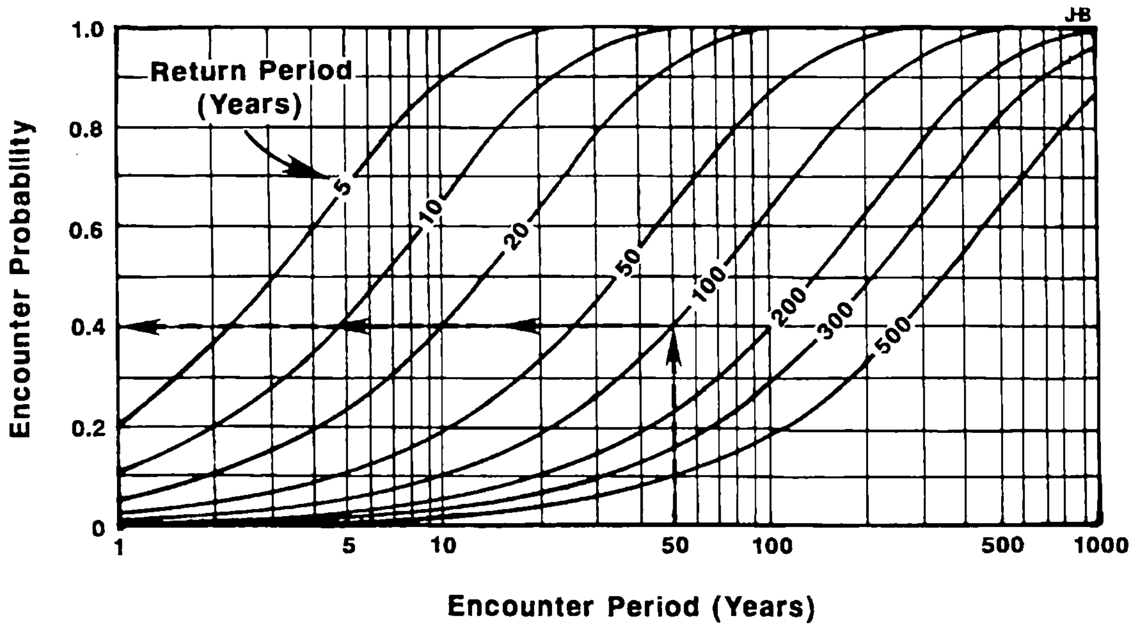

Figure 14. Nomograph for relating event return period, encounter period, and encounter probability.

build your single-family beach-fronting dwelling so that it is relatively safe from the 100-year return period erosion event. The probability of a 100-year return period occurrence being equaled or exceeded during the above assigned 50-year period (*i.e.*, Encounter Period) is 0.4, as illustrated in Figure 14. Hence, there is a 40% chance that the 100-year return period erosion event will occur in the planned life time of the home. Had the dwelling been designed for a 500-year return period erosion event, the structure would have a much better chance of surviving the critical event ... then only a 10% chance of occurrence during its planned life.

Using the figure in another manner, if a homeowner or prospective home owner is willing to take a 20% chance that the design erosion event will occur during the 50-year design life of the structure, then the ***Return Period*** of the erosion event that should be designed for is 250 years.

The above example uses the return period erosion event. However, Figure 14 can also be used for any other measure (*e.g.*, peak combined storm tide, wave event, event forward speed, *etc.*) provided that return period statistics are quantified.

An Erosion Damage Potential Scale

A beach/coast erosion damage scale for extreme events has not, here-to-fore, been proposed. Perhaps the best way in which to assess an erosion damage potential scale is to build upon the existing Saffir/Simpson hurricane damage potential scale (Table 4). Volumetric erosion is assessed using equation (1) for average erosion quantities and equation (7) for maximum erosion quantities. The assessment of Table 4 is, therefore, applicable to the U. S. Atlantic East Coast and the U. S. Gulf of Mexico Coast which have relatively low nearshore slopes (*i.e.*, where tan α_i is characteristically less than 0.02). Equations (1) and (7) were evaluated using the Saffir/Simpson peak storm tide (commonly termed the "storm surge") classes of values. Event forward speed classes were determined using the historical

Table 4. Amended Saffir/Simpson Hurricane Damage Potential Scale

Category	Central Pressure (mb)	Wind Speed (km/hr)	Peak Storm Tide Elevation above MSL (m)	Event Forward Speed (km/hr)	Storm Tide Rise Time (hr)	Average Erosion Volume (m^3/m)	Maximum Erosion Volume (m^3/m)	Damage Potential
1	>980	46-59	1.22-1.68	50-90	2.5-4.5	3-8	6.5-17	Minimal
2	965-979	60-68	1.68-2.60	30-50	4.5-7.5	8-25	17-53	Moderate
3	945-964	69-81	2.60-3.81	20-30	7.5-11	25-63	53-132	Extensive
4	920-944	82-96	3.81-5.49	10-20	11-22	63-188	132-395	Extreme
5	<920	>96	>5.49	<10	>22	>188	>395	Catastrophic

data of Schwerdt and others (1979). Storm tide rise time was then determined using equation (2).

The Saffir/Simpson scale assessed the damage potential in terms of the wind speed and peak storm tide. There is, in fact, sound reasoning for doing so, since both are largely dependent on event central pressure.

The same is not true of the event forward speed because the three-dimensional geometry of surrounding weather systems and conditions affect steering currents. Hence, factors other than central pressure have significant effect on the propagation of a hurricane.

There are two additional issues to be considered.

One is that it may be difficult to envision just what a volumetric erosion value means in terms of erosion damage for a specific coastal locality, unless cross-sections representing pre-storm and post-storm profiles are assembled. A horizontal recession value rather than a volumetric erosion value is an alternative, but this was found to result in many more problematic complexities than the volumetric approach (Balsillie, 1985c, 1986). Hence, while volumetric erosion values may not obviously identify the damage potential, they can be correlated to the Saffir/Simpson hurricane category and damage potential scale to provide a pragmatically useful addition to the scale.

The other issue centers about the fact that extreme events with much lower intensities than hurricanes (*e.g.*, tropical storms, which are here identified under the collective term "storms") can potentially result in as much or more erosion than many hurricanes (see Table 2). An example is a storm which essentially stalls just offshore for days. Hence, Figure 15 has been compiled which, based on event forward speed and peak storm tide elevation, can be used to assess erosion damage potential whether the event is a hurricane or a storm.

Table 4 and Figure 15 are transformed to British Imperial Units and given in the Appendix.

CONCLUSIONS

Analyzed information for storms (*e.g.*, Birkemeier and others, 1988; Kana and Jones, 1988; Jones and Kana, 1988; Beumel and Campbell, 1990; Ferriero, 1994) and more recent hurricanes (*e.g.*, Birkemeier and others, 1991; Stauble and others, 1991; Nelson, 1991) has increased the existing sample size of Balsillie (1985c, 1986) for field data quantifying beach and coast erosion due to extreme event impact. This additiona l data allows for testing of a

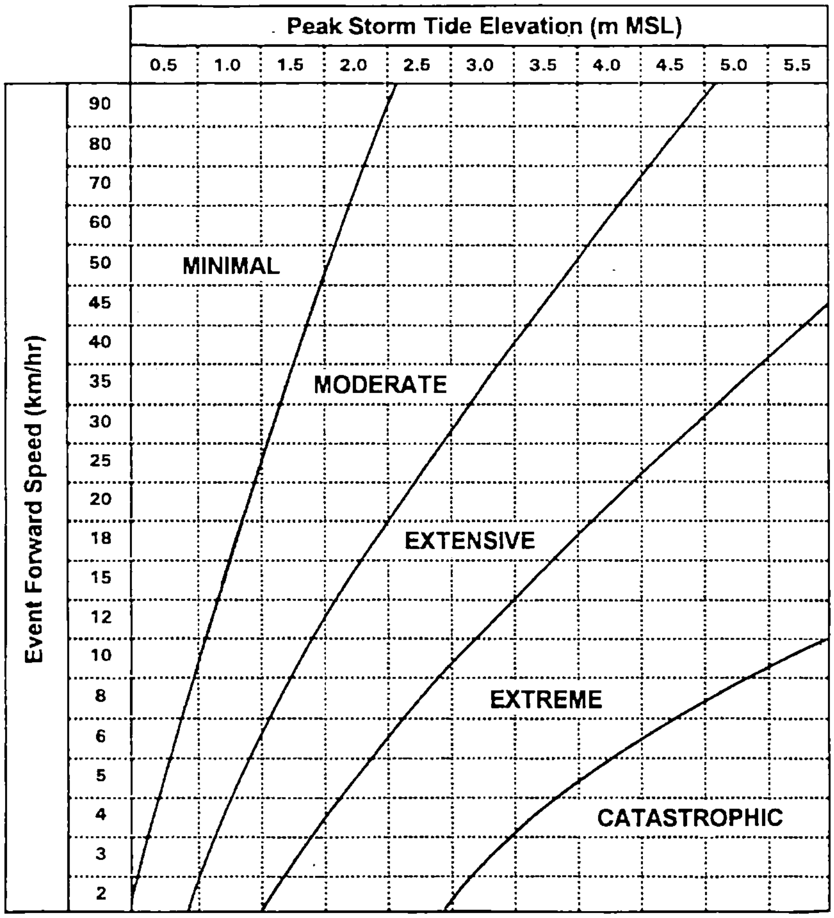

Figure 15. Beach and coast erosion damage potential scale as a function of event forward speed at landfall and peak storm tide elevation. Erosion volumes are based on peak storm tide elevation classes of Table 4; even so, results apply to storm events as well as hurricanes.

refinement of quantifying relationships.

A most important aspect of being able to predict beach and coast erosion due to storm and hurricane impact is the capability to assess profile geometry during and as a result of impact. By so doing, coexisting storm-generated wave activity propagating upon the storm tide surface can be assessed for management and design purposes. The fact remains, regarding waves and their modifying influence on a mobile bathymetry, that any change in wave characteristics induces an alteration in bathymetry but at a lag-time behind a change in wave characteristics. Because of the bathymetric lag-time, bathymetry can in turn impose significant influential effects on the character of littoral wave activity. Hence, in addition to erosive outcomes, it is the destructive potential of storm-generated wave impacts that also must be considered if a successful assessment methodology is to exist. Determination of profile geometry is then a matter of modeling interactive littoral processes, that is, both force (*e.g.*, water level rise and waves) and response (*e.g.*, profile modification) elements. A computer model exists (Balsillie, 1984c, 1985c, 1985d, 1986) in which a bulk onshore-offshore sediment transport mechanism, in terms of bedform movement has been developed (Balsillie, 1982a, 1982b, 1984b, 1984c), which is dependent on littoral wave activity (Balsillie, 1983a, 1983b, 1983c, 1983d, 1984a, 1984b, 1984c,1985b; Balsillie and Carter, 1984a, 1984b). It is the volumetric erosion methodology contained herein which allows for the real-time calibration of the combined assessment of combined storm tide, storm wave impact, horizontal and vertical physiographic recession force and response elements due to extreme event impact. In addition, there now appears to be enough information to make a statement about the return period erosion event. Least equivocal results given by equations (17) through (24) will, hopefully, be refined by future work. In the meantime, however, they are valuable as a check in design applications.

In addition, applications of the volumetric erosion methodology have been discussed, including the determination of post-storm beach and coast physiography, encounter period and probability, and an erosion damage potential scale.

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APPENDIX

Table 4 and Figure 15 of main text transformed to British Imperial Units of Measure

Amended Saffir/Simpson Hurricane Damage Potential Scale

Category	Central Pressure (Inches)	Wind Speed (mph)	Peak Storm Tide Elevation above MSL (ft)	Event Forward Speed (mph)	Storm Tide Rise Time (hr)	Average Erosion Volume (yds^3/ft)	Maximum Erosion Volume (yds^3/ft)	Damage Potential
1	>28.94 (>980)*	74-95	4-5.5	31-55	2.5-4.5	1.2-3.3	2.5-7	Minimal
2	28.50-28.91 (965-979)	96-110	5.5-8.5	18-31	4.5-7.5	3.3-10	7-21	Moderate
3	27.91-28.47 (945-964)	111-130	8.5-12.5	12-18	7.5-11	10-25	21-53	Extensive
4	27.17-28.88 (920-944)	131-155	12.5-18	6.5-12	11-21	25-75	53-158	Extreme
5	<27.17 (<920)	>155	>18	<6.5	>21	>75	>158	Catastrophic

*Central pressure in parentheses are in millibars.

Beach and coast erosion damage potential scale as a function of event forward speed and peak storm tide elevation, both at landfall. Erosion volumes are based on peak storm tide elevation classes of above table; results, however, apply to storm events as well as hurricanes.