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Assessing the hurricane-related coastal erosion hazard

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ABSTRACT

Caribbean countries are well-acquainted with the hazards of hurricanes and tropical storms which may produce significant coastal erosion resulting in great losses on coastlines. Hurricanes are typically classed into various orders of magnitude, and a similar discretization of extreme events is used to perform a simple coastal erosion analysis. Seven categories of extreme events provide the basis for the erosion assessment, and each model storm is represented by an assigned set of deep-water parameters. Representative values of various parameters, in each category, are assigned using established parameter ranges, or calculated using existing mathematical models. Parameters that can not be considered a constant for each model storm, such as storm duration and wave directions, are randomly described during the erosion analysis. Once the nearshore bathymetry is known up to the deep water limit, the predicted shoreline following the model storm event can be ascertained. This prediction is accomplished using an existing morphological model in its deterministic mode. Expectedly, probabilities of occurrence are associated with each likely outcome. Therefore, given the topography of the coastal region and the vulnerability of elements at risk, expected losses can be obtained which will provide a guide to coastal managers.

Keywords: hurricane, tropical storms, shoreline change, numerical model, natural hazard

1. INTRODUCTION

1.1 THE CARIBBEAN SETTING

Caribbean coastlines have long been plagued with coastal erosion hazards that reduce the amenity value of beach areas, thereby affecting the revenue generated from tourism-related activities. Since most of the Caribbean island-nations depend on tourism to augment revenues, it is imperative that the region find a reliable yet inexpensive means of assessing the erosion risk associated with these events for planning and disaster preparedness. For certain coastlines, these erosion events are clearly evident during storm events, but other coastlines may reflect an erosion trend during non-storm periods. Generally, however, the most rapid and profound erosion events are associated with tropical storms and hurricanes. In 1995, Hurricane Luis, a category 4 event, affected many islands. The resultant beach erosion appeared to be related to the distance between the storm centre and the shoreline. In Dominica, where the storm centre was a minimum of 180km from the coast, the average shoreline retreat was 3m. Where the eye of the hurricane passed directly over the island, which was the case for the islands of Barbuda and Anguilla, the retreat was more significant. In Barbuda, the average shoreline retreat was 18m, with a maximum measured retreat of 30m. In Anguilla, the average shoreline retreat was 9m with a maximum measured retreat of 30m occurring at Meads Bay Central. At Vigie Beach in St. Lucia, which was affected by both Hurricane Luis and Tropical Storm Iris, there was a cumulative retreat of 11m (CSI, 1998). Ideally, beaches should recover after storm events, but do not always return to pre-storm levels (Cambers, 1998). The cumulative effect of storms on a beach may produce significant long-term erosion. Global climate changes also impact on the erosion hazard, as factors such as rising sea levels and increased storminess may exacerbate erosion events on coastlines. In order to produce detailed analyses of risk, comprehensive data sets are required that are not always readily available in the Caribbean islands. This represents a significant prohibitive factor for many countries willing to engage in meaningful planning activities. Data sets are required which can conclusively demonstrate long-term trends, and provide the basis for the generation of coastal erosion hazard maps.

1.2 Features of Tropical Cyclones

Tropical cyclones, at the lower boundary, are tropical depressions which may subsequently acquire enough energy to become a tropical storm with maximum sustained winds between 63kph and 118kph. Tropical storms may become more severe weather systems called hurricanes which attain and exceed wind velocities of 119kph. In the Atlantic Ocean, a 10-year survey from satellite observations for 1968–1977 (Simpson and Riehl, 1981), has demonstrated that the number of rain systems with potential for hurricane development is close to one hundred per season, with little change from year to year. The number of storms, not all of which were hurricanes, averaged only 8 per season, or 8%, with a considerable variability of 50%.

Hurricanes form over the ocean where the sea surface temperature exceeds a threshold of 26°C to 27°C, down to a depth of at least 60m below the water surface. Their formation also requires the atmosphere at the location to be without temperature inversions, and to be at a constant humidity of between 75 to 80% (Alexander, 2001). Subsequently, the North Atlantic hurricane season occurs during the months of June through November, with September having the greatest number of storms (Simpson and Riehl, 1981). Hurricane magnitudes are expressed by a category number ranging from 1 to 5 according to the Saffir-Simpson scale. Each category describes an event in terms of the wind velocities, central pressures and storm surge. The direction of movement of a hurricane relative to the coastline affects the magnitude of destructive forces; perpendicular landfall being the most destructive situation (Williams and Duedall, 2002). The direction of approach of the hurricane is important because the hurricane wind field is typically asymmetric. In the North Atlantic, the strongest winds are generally found within the right front quadrant of a north-westerly tracking hurricane since the forward motion of the weather system augments the wind speeds in this quadrant of the storm.

As the hurricane approaches a coastline, the high winds produce not only high waves, but also increases water levels near the shore, known as storm surges. These storm surges create water depths that are larger in the nearshore area and thus decrease the energy lost through wave transformation processes as waves approach the shoreline. Therefore, storm surges create more energetic and destructive waves near the shore. Storm surge levels are site specific, requiring a number of parameters for its estimation. They vary considerably and result from a combination of direct winds, generated waves and low atmospheric pressure. Additional factors include rainfall, bottom topography and shoreline configuration. Generally, storm surge can be estimated using a combination of wave set-up, wind set-up and increased water levels due to the lower barometric pressures associated with hurricanes. The tide at the time of landfall of the storm can also exacerbate conditions at the shore during these events. High tides imply deeper water levels and result in even larger waves being able to penetrate the nearshore region. Battan (1961) has stated that a consistent property of all tropical storms is that, once formed, they follow paths that carry them poleward. In general, Atlantic hurricanes initially have only a small poleward component, following nearly an east-west path; however they always curve towards the north. Hurricanes tend to have paths that follow a parabolic curve, but to make such an assumption for all hurricanes is grossly incorrect (Simpson and Riehl, 1981).

2. Objective

One fundamental requirement for a coastal erosion hazard assessment is the generation of probabilities for:

- The occurrence of any storm on a given coastline, **p(B)**, and
- The occurrence of a storm of a given intensity provided that a storm has occurred, **p(A)|p(B)**.

The random behaviour of tropical cyclones implies that the characteristics of a storm, at a given time, cannot be predicted with a high degree of accuracy. However, historical data sets can provide some insight into hurricane features and patterns, and generate statistics for the storm wave climate. Furthermore, the storm parameters that define a given storm intensity must be identified and assigned numerical quantities for each magnitude event using methods that provide reliable estimates. The coastal erosion hazard may be described by the probabilities of occurrence of an event, at a given coastal site, the magnitude of the parameters that characterize that storm event, and the beach characteristics.

3. METHODOLOGY

In order to predict the magnitude of the coastal erosion after a storm, the hurricane wave climate was simulated and used as input into a shoreline change model. This stochastic numerical model was developed to predict long-term shoreline changes and simulates both high-energy and low-energy wave events in order to predict shoreline change. The numerical model was used in its deterministic mode to obtain results for the high-energy events only. These high-energy wave events were categorized into seven possible discrete storm events, namely: Tropical Depression (TD), Tropical Storm (TS), Hurricane Category 1 (H1), Hurricane Category 2 (H2), Hurricane Category 3 (H3), Hurricane Category 4 (H4) and Hurricane Category 5 (H5). These categories represent the least number of discrete events possible to fully describe the high-wave energy climate.

The extent of beach erosion was assumed to be dependent on two main factors: beach and storm-wave characteristics. Beach characteristics include, inter alia, beach sediment grain size, bed porosity, beach geology, beach planform, nearshore and offshore bathymetry, beach type (e.g. pocket beach or open coast) and the presence of coastal structures. For this analysis, the beach was considered to be a sandy beach on an open coast, and only the sediment grain size, bed porosity and the bathymetry were pertinent variables. The beach was considered to be homogenous, where the sediment grain size and porosity were constant for any distance offshore and at any depth of bed. The relevant storm-wave parameters to be assigned for each extreme event category were wave period, wave direction, wave height, storm duration and storm surge. Other relevant parameters considered included velocity of forward movement and spatial scale. Although, beach erosion is also expected to be a function of the distance of the storm centre from the shoreline, this variable was not considered in this analysis. It was assumed that the defined storm sea-state existed at the deep-water limit of the nearshore region. The beach erosion that ultimately results from real storms is unpredictable, even for storms of similar strengths. However, the most critical offshore storm-wave state was determined and used in this analysis for beach erosion prediction. For each category storm, values for each of the relevant storm parameters were assigned. The storm wave height and period are determined based on storm central pressures, using critical values of spatial scale and forward velocity. The storm duration is cumbersome, as storms can last from a few hours to a few days, at a given coastal site. In the stochastic shoreline model, a storm duration was randomly selected after assigning the parameters of wave height, wave period, and storm surge. Storm durations varied in magnitude from 1000 to 7500 waves inclusively, given at 500 wave increments and each given storm duration was considered to have equal likelihood of occurrence. However, this erosion analysis used a constant value of storm duration. In the stochastic shoreline model, a randomly selective approach was also used for choosing each wave direction. During a storm, the sea state becomes quite disordered and to simulate this state, the direction of each individual storm wave was randomly selected from directions ±0º, ±20º, ±40º, ±60º and ±80º, with each wave direction having an equal likelihood of occurrence. For this deterministic analysis, all waves were assumed to be normally incident. Finally, storm surge levels were assigned using expected values found in the Saffir-Simpson scale.

A probability of occurrence for any storm event may be assigned for the coastal site using published data such as that of Sheets and Williams (2001) which provide the likelihood of hurricane events for various Caribbean islands (Table 1). These, however, apply strictly to the hurricane events only and cannot be used for the occurrence of all previously defined extreme wave events. In addition, probabilities of occurrence of each category event were determined based on historical data. Young and Burchell (1996) arguably provide the most extensive data set of each hurricane events found in the literature. This data consists of satellite observations of significant wave height and wind speed within mature hurricanes. The data set contains information on about 100 hurricanes "overflown" by the GEOSAT satellite during its 3-year mission. Young (1998) provided a smaller data set consisting of 16 tropical cyclones. This data was obtained over a 16-year period off the northwest coast of Australia. Simpson and Riehl (1981) also provided a data set consisting of 11 hurricanes, and generated a cumulative probability diagram for these hurricanes based on their central pressure. The data provided by Young (1998) and Young and Burchell (1996) was used, to generate the cumulative probability of hurricane events (Figure 1). These cumulative probabilities were used to obtain the probability space for each storm event.

Table 1: Hurricane probabilities for various Caribbean islands

Hurricane Probabilities (%)	Any Hurricane	Major Hurricane
Antigua	20	6.7
Barbados	8.3	2.3
Bonaire	2.2	0.6
Kingston, Jamaica	14.3	5.9
Nassau, Bahamas	22.2	9.1
San Juan, Puerto Rico	12.4	4.2
Santo Domingo, Dominican Republic	11.1	3.9
U.S. Virgin Islands	16.7	5.9

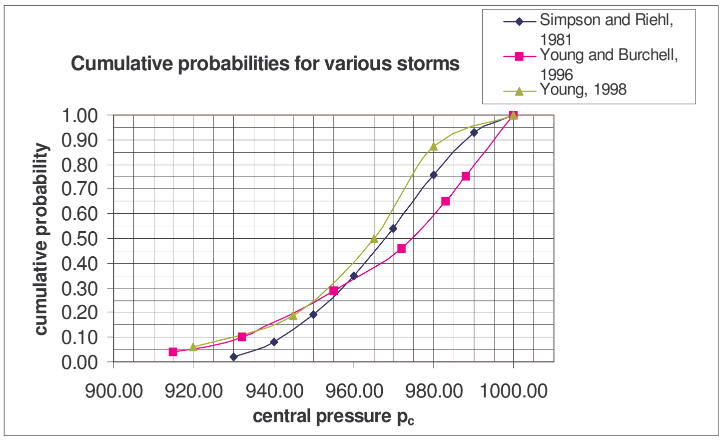

Figure 1: Cumulative frequencies from storm data sets

Since there are numerous models used for the prediction of waves within hurricanes, it is useful to define some of the parameters that are usually associated with these storm models. The wind velocity, $\mathbf{U_{10}}$ is defined as the wind speed at a reference height of 10m above the water surface. Further, U_{10} can be defined for any point within the tropical cyclone and is usually determined from the pressure found at the centre of the tropical storm, $\mathbf{p_c}$. Typical values of the central pressure are provided for each extreme event in Table 2. $\mathbf{p_n}$ is the peripheral pressure, or the barometric pressure at the periphery of the storm extent and is assumed to be 1013 mbars. The velocity of the forward movement, $\mathbf{V_F}$, is self-explanatory. $\mathbf{R_{mw}}$ is the radius of maximum winds and is defined as the distance from the centre of the cyclone to the radius at which the maximum winds are located. R_{mw} is a crucial parameter used in most of the hurricane models, yet is the most elusive to quantify. In nature, there is no defined circle where the maximum winds circulate around the storm centre. The maximum wind speed may be found in well-developed tropical cyclones within the intense rain bands or even an outer eye wall (Phadke et al., 2003). In addition, R_{mw} is not well defined for weak cyclones and varies throughout the life of the storm (Croxford and Barnes, 2002). One common approach is to use a constant value of R_{mw}, throughout the storm life, rather than changing R_{mw} during the storm. The method used in this analysis, however, assigns a constant value of 50km to the parameter, R_{mw}, for all storm events. Figure 2 shows R_{mw} versus p_c and the assumption of a R_{mw} value of 50km for all values of p_c appears to be justifiable, except for values of p_c greater than about 980 mbars.

There are several parametric wind models, each of which has been shown to be applicable to at least one tropical cyclone event in a given region (Phadke et al., 2003). All these parametric models represent the wind flow in an idealised stationary tropical cyclone by concentric circles. The wind speed is zero at the centre and increases to its maximum at the radius of maximum wind, and then decreases to zero at some large radius. Although, three parametric models are commonly used, namely the modified Rankine vortex, the SLOSH model and the Holland model, only the latter model was used in this analysis.

Table 2: Assigned values for the central pressure for each storm event

Category Storm	Central Storm Pressure, p_c (mbars)
TD	1000
TS	988
H1	983
H2	972
H3	955
H4	932
H5	915

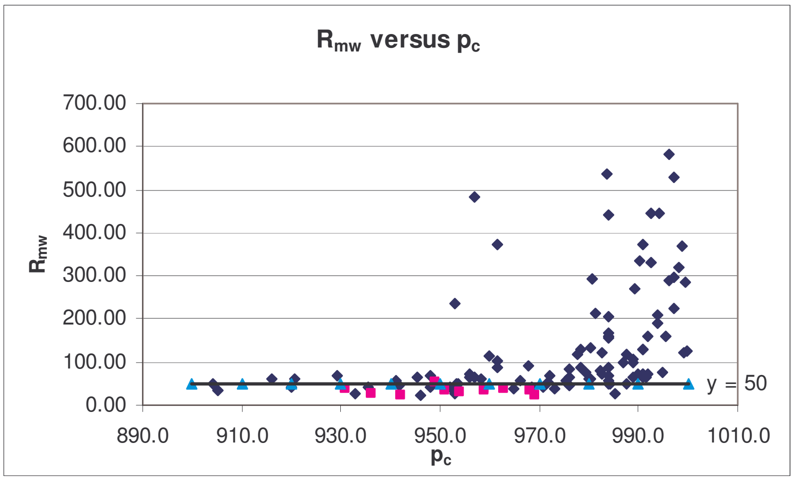

Figure 2: A diagram of radius of maximum winds, R_{mw}, versus the central pressure, p_c, (using the Young and Burchell 1996 data)

The Holland (1980) model provides a wind field directly from parameters R_{mw} and p_c:

$$U_g = \sqrt{\frac{B(p_n - p_c)}{\rho}\left(\frac{R_{mw}}{r}\right)^B \exp\left(-\left[\frac{R_{mw}}{r}\right]^B\right) + \frac{r^2 f^2}{4}} - \frac{rf}{2}$$ **Equation 1**

where ρ is the density of the air, 'f' is the Coriolis parameter and U_g is the gradient wind speed, with maximum value U_{gmax}.

Near $r = R_{mw}$, the Coriolis force is relatively small compared to the pressure gradient and centrifugal forces. The above equation then becomes

$$U_{g\max} = \sqrt{\frac{B(p_n - p_c)}{\rho e}}$$ **Equation 2**

Holland (1980) has shown that

$$B = 1.5 + \frac{(980 - p_c)}{120}$$ **Equation 3**

However, more recently, Harper and Holland (1999) suggested that

$$B = 2 - \frac{p_c - 900}{160} \quad \text{for } 1<B<2.5$$ **Equation 4**

Gradient wind speeds, U_g, need to be reduced to U_{10} wind speeds. This can be done using the simple relationship

$$U_{10} = K_m U_g$$ where K_m is the correction factor **Equation 5**

Harper and Holland (1999) recommended that $K_m = 0.7$ for the Holland model, whereas Young (2003) used $K_m = 0.8$. It is the latter value of $K_m = 0.8$ that was assumed in this paper.

$$U_{10\max} = K_m U_{g\max}$$ **Equation 6**

For a stationary hurricane, U_{10max} is given using the equation above. However, for a moving hurricane, the wind speed increases in the right quadrant of the storm. Jelesnianski (1966) suggested adding the following correction term to the U_{10} values.

$$U_{corr} = \frac{R_{mw} r}{R_{mw}^2 + r^2} V_F$$ **Equation 7**

One other method uses a constant value of U_{corr}, which is added to U_{10max} to obtain the maximum wind velocity of any given moving storm system.

If $U_{corr} = \frac{V_F}{2}$, then

$$U_{10\max} = 0.8\left[\frac{B(p_n - p_c)}{\rho e}\right]^{1/2} + \frac{V_F}{2}$$ **Equation 8**

U_{10max} values for each of the storm categories were calculated using the above method, as was used in Young (2003). These results are shown in Table 3, where V_F is assumed to be zero and the central pressures used are those shown in Table 2.

Table 3: Calculated maximum wind speeds using the Young (2003) model

Category Storm	U_{10max} for a stationary storm m/s	mph
TD	19	42
TS	27	60
H1	30	66
H2	35	79
H3	43	97
H4	54	120
H5	61	135

A number of methodologies (Hasselmann et al., 1973; Shore Protection Manual, 1984; Ochi, 1993; Young and Burchell, 1996; Hsu et al., 2000; Kumar et al., 2003; Young, 2003;) have been proposed for the prediction of the significant wave height, H_s, and the peak wave period, T_p, under storm conditions. Only the methods of Hasselmann (1973), Ochi (1993), Hsu et al. (2000) and Young (2003) and are detailed below.

Ochi (1993) proposed that:

$$H_s(m) = 0.235 U_{10}(m/s)$$ **Equation 9**

Hsu et al. (2000) gave

$$H_s = 0.2(p_n - p_c)$$ **Equation 10**

Further, the Shore Protection Manual (1984) gave an approximate formula to obtain the significant wave period, T_s, provided H_s is known.

$$T_s = 12.1\sqrt{\frac{H_s}{g}}$$ **Equation 11**

Spectral peak period, T_p, was approximated by the following empirical relationship (Kumar et al., 2003):

$$T_p = 4.5 H_s^{0.48}$$ **Equation 12**

Young and Burchell (1996) and Young (2003) have proposed the following method for the estimation of H_s and T_p. The method was originally developed by Young (1988), and incorporates the concept of "extended fetch" in the model. The wave height was not only determined by the maximum wind speed, but also by the amount of time that the wave remains within the generating region. As U_{10max} increases, the speed at which the waves propagate also increases. Therefore, V_F must also increase for the most severe wave condition to occur. The equivalent fetch, x, is defined as:

$$\frac{x}{R'} = \psi\left(aU_{10\max}^2 + bU_{10\max}V_F + cV_F^2 + dU_{10\max} + eV_F + f\right) \qquad \textbf{Equation 13}$$

$a = -2.175x10^{-3}$, $b = 1.506x10^{-2}$, $c = -1.223x10^{-1}$, $d = 2.190x10^{-1}$, $e = 6.737x10^{-1}$ and $f = 7.980x10^{-1}$

R' is a spatial scale parameter defined as $R' = 22.5x10^3 \log R - 70.8x10^3$ and Ψ is a scaling parameter given as $\psi = -0.015U_{10\max} + 0.0431V_F + 1.30$.

Young (2003) assumed that the JONSWAP (Hasselman et al., 1973) relationships, originally developed for fetch limited conditions, could be applied in hurricane wind fields with the specification of a suitable equivalent fetch. Young (2003) provided the following equations to obtain H_s and T_p.

$$\frac{gH_s}{U_{10\max}^2} = 0.0016\left(\frac{gx}{U_{10\max}^2}\right)^{0.5} \qquad \textbf{Equation 14}$$

$$T_p = 0.045\frac{2\pi}{g}U_{10\max}\left(\frac{gx}{U_{10\max}^2}\right)^{0.33} \qquad \textbf{Equation 15}$$

The relationships described by Young and Burchell (1996) are not applicable outside the range of the parameters $U_{g\max}$ and V_F, given as: $20 \le U_{g\max} \le 60$, and $0 \le V_F \le 12$.

To obtain the most critical value of the forward storm velocity, V_{Fcrit}, that is, the value of V_F that yields the highest H_s for a given storm, the equation $H_s = f(V_F)$ was differentiated with respect to V_F and the value indicating the most critical H_s was obtained when $\frac{dH_s}{dV_F} = 0$.

Table 4 shows the U_{10max} wind speeds re-calculated, but incorporating the forward movement of the storm. The forward movement velocity was assigned a value equal to V_{Fcrit}, for that storm. Once V_{Fcrit} was obtained, then the highest value of H_s was calculated. The peak wave period, T_p, was then determined. Table 5 summarises the results of these calculations to obtain H_s and T_p for the various category storm events. The typical ranges given in the Saffir-Simpson scale were used for storm surge levels, during selected storm events. In those cases that could not be extracted from the Saffir-Simpson scale, extrapolated results were used based on the wind speed (Figure 3). The rounded lower-bound values of storm surge levels were added to the water depths for the duration of the storm. Assigned wave parameters and maximum storm surge values for the storms in the shoreline model are shown in Table 6. The storm surge was added in incremental values during the first half of the storm, and decreased by incremental values during the last half of the storm. Figure 4 shows how surge levels were adjusted for the storm duration. Values were changed at the time scale of the typical storm wave period.

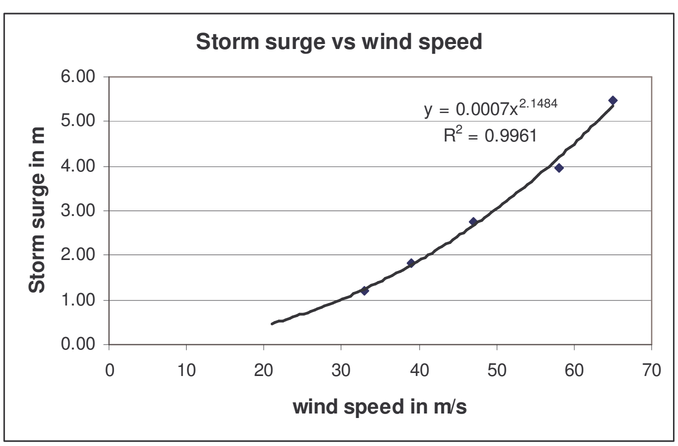

Figure 3: Storm surge values for extreme wave climate

Table 4: Calculated maximum wind speeds using the Young (2003) model and V_{Fcrit}

Category Storm	U_{10max} for a moving storm m/s	mph
TD	21	48
TS	30	66
H1	33	73
H2	39	87
H3	47	106
H4	58	129
H5	65	146

Table 5: Summary of the calculations for wave height and wave period for each storm

Category of Storm	JONSWAP		Hsu (2000)		Ochi (1993)
	H_s (m)	T_p (s)	H_s (m)	T_s (s)	H_s (m)
TD	5.64	10.71	2.60	6.23	5.02
TS	8.29	12.44	5.00	8.64	6.97
H1	9.23	12.95	6.00	9.46	7.67
H2	11.09	13.84	8.20	11.06	9.09
H3	13.48	14.78	11.60	13.16	11.08
H4	15.95	15.48	16.20	15.55	13.56
H5	17.25	15.68	19.60	17.10	15.30

Table 6: Storm parameters for extreme wave climate

Category of Storm	Deep water Wave Height (m)	Wave period (s)	Maximum Storm surge (m)
TD	5.64	10.71	0.49
TS	8.29	12.44	1.04
H1	9.23	12.95	1.28
H2	11.09	13.84	1.83
H3	13.48	14.78	2.74
H4	15.95	15.48	4.30
H5	17.25	15.68	5.49

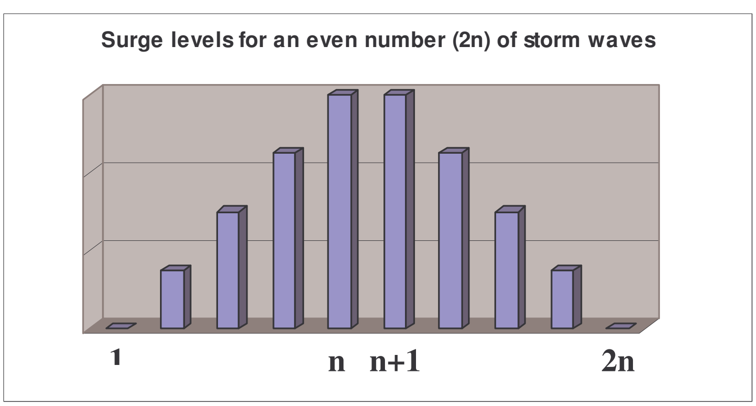

Figure 4: The incremental changes in surge levels for an even number of waves

4. RESULTS

The results of Young and Burchell (1996) in Figure 1 were used for a coastline having a probability of occurrence of any storm event of 0.6, in any given year. This probability of '0.6' was arbitrarily chosen to illustrate the proposed hazard assessment method. Two pre-storm bathymetries were assumed, and calculated storm parameters were input into the shoreline model to illustrate the methodology detailed above. Bathymetry 1 and 2 have beaches with a median grain size of 0.2mm, and are planar with mean slopes of $1/40$ and $1/20$ respectively. These slopes represent the mean slopes in the sub-aqueous zone of the beach, whilst both bathymetries have a sub-aerial mean slope of $7/50$. The storm event was considered to be an offshore storm, where waves were generated offshore and then propagated across the nearshore region towards the shoreline. A storm duration of 500 waves was assumed for all storm events, and all storm waves were propagated normally incident to the shoreline. Two significant processes affecting waves in the nearshore zone, namely wave reformation and the conveyance of energy from winds to waves, were not considered in this analysis. These results, correct to 2 decimal places, are summarised in Table 7 below.

Table 7: Summary of Results

Extreme Event	p(B)	p(A)lp(B)	p(B) x p(A)lp(B)	Extent of Erosion (m)	
				Bathymetry 1	Bathymetry2
TD	0.6	0.25	0.150	1.33	60.72
TS	0.6	0.10	0.060	11.00	86.41
H1	0.6	0.19	0.114	11.37	100.40
H2	0.6	0.17	0.102	9.00	110.50
H3	0.6	0.19	0.114	2.18	122.35
H4	0.6	0.06	0.036	0.06	162.24
H5	0.6	0.04	0.024	0.05	167.74

5. DISCUSSION

The predicted erosion was clearly sensitive to the initial bathymetry of the coastline. Therefore, when this methodology is applied, the sensitivity of the results to varying initial bathymetries must be assessed. For Bathymetry 1, the milder slope caused larger waves to break further offshore, and since waves did not reform or receive energy from the wind, the breaking wave energy dissipated across a larger nearshore distance. Subsequently, the unexpected results of milder conditions, near the shore, for H4 and H5 events were observed. The steeper slopes of Bathymetry 2 allowed greater wave energy to penetrate the nearshore region and resulted in much higher erosion episodes than Bathymetry 1. The probabilities obtained in column 4 (Table 7) represent the probability of that given storm event in any year. These probabilities, along with the corresponding predicted shoreline retreat, may be used to determine an annual expected storm-related erosion extent. This was determined as 3.33m and 60.82m for Bathymetry 1 and 2 respectively. These results have not been compared to storm-related field data, and this verification exercise is a necessary precursor in order to improve the reliability of this analysis.

6. CONCLUSION

This paper has demonstrated that developing countries can implement simplified strategies to ascertain the storm-related coastal erosion risk. These types of analyses can guide decision makers in developmental planning, and identify the need for mitigation strategies. Regionally, reliable data on the erosion effects of tropical cyclones is required to demonstrate long-term trends and extract statistical estimates. Additionally, the output of this assessment can be improved by use of an enhanced shoreline model that includes the effect of wave reformation and wind-to-wave energy processes. Furthermore, the storm parameters determined in this analysis represent the most critical values and were used to ensure a conservative approach. Alternatively, multiple runs would yield a range of likely erosion scenarios provided parameters, such as storm duration and wave direction, are selected randomly. Nonetheless, coastal managers can be guided whether employing a deterministic or probabilistic approach to this hazard assessment method.

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