CHAPTER 216

EXTREME WATER LEVELS, WAVE RUNUP AND COASTAL EROSION

P. Ruggiero[1] , P.D. Komar[2] , W.G. McDougal[1] and R.A. Beach[2]

ABSTRACT

A probabilistic model has been developed to analyze the susceptibilities of coastal properties to wave attack. Using an empirical model for wave runup, long term data of measured tides and waves are combined with beach morphology characteristics to determine the frequency of occurrence of sea cliff and dune erosion along the Oregon coast. Extreme runup statistics have been characterized for the high energy dissipative conditions common in Oregon, and have been found to depend simply on the deep-water significant wave height. Utilizing this relationship, an extreme-value probability distribution has been constructed for a 15 year total water elevation time series, and recurrence intervals of potential erosion events are calculated. The model has been applied to several sites along the Oregon coast, and the results compare well with observations of erosional impacts.

INTRODUCTION

Much of the Oregon coast is characterized by wide, dissipative, sandy beaches, which are backed by either large sea cliffs or sand dunes. This dynamic coast typically experiences a very intense winter wave climate, and there have been many documented cases of dramatic, yet episodic, sea cliff and dune erosion (Komar and Shih, 1993). A typical response of property owners following such erosion events is to build large coastal protection structures. Often these structures are built after a single erosion event, which is followed by a long period with no significant wave attack. From a coastal management perspective, it is of interest to be able to predict the expected frequency and intensity of such erosion events to determine if a coastal structure is an appropriate response. Predicting the frequency and magnitude of the most extreme erosion conditions is also important for the establishment of setback lines for coastal developments.

Field studies have been undertaken along the Oregon coast to better understand the processes involved in wave-induced sea cliff and dune erosion. The

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[1] Ocean Engineering Program, Civil Engineering Dept., Oregon State Univ., Corvallis, OR 97331

2 College of Oceanic and Atmos. Sciences, Oregon State Univ., Corvallis, OR 97331

goal is to develop simple methods for estimating the susceptibilities of coastal properties to wave attack. Wave-induced property erosion generally occurs when wave runup reaches the junction between the beach face and the sea cliff or dune. However, depending on a number of wave, water level and morphological parameters, both the elevation attained by wave runup and the elevation of the beach-face junction are highly variable. This paper presents a simple probabilistic method for predicting the frequency of occurrence of cliff or dune erosion. The predicted frequencies are then compared with the observed shoreline stability for several beaches along the Oregon coast.

Other researchers have attempted to determine the risk of coastal properties to flooding using probabilistic techniques. For example, Gares (1990) demonstrates a method for using runup to determine flooding risk on the New Jersey shoreline. Runup is calculated using the composite slope technique presented in the *Shore Protection Manual* and probability curves are produced assuming that maximum runup occurs at times of maximum storm surge. In the current work, an attempt is made to characterize extreme runup statistics on the high energy, yet dissipative beaches common in Oregon where the storm surge is small. Extreme total water levels, hence erosion risks, are then predicted utilizing a long term data base consisting of both measured tides and measured wave characteristics.

MODEL DEVELOPMENT

There are two main components, in Figure 1, which combine to generate total water levels (Shih *et al.*, 1994). The first is the tide elevation, ζ; all tidal and land elevations presented in this paper will be referenced to the U.S. National Geodetic Vertical Datum (NGVD) of 1929. Superimposed on the measured tide level is the vertical component of wave runup, R, which consists of both wave setup, $\overline{\eta}$ and the swash fluctuations, S, about the setup. Wave induced erosion of a sea cliff or dune will occur only when the total elevation of the water at times of maximum runup exceeds the elevation of the beach-face junction ($\zeta + R > E_j$). Once again, the objective of this study is to predict the frequency with which the total water level, E, reaches or exceeds the elevation E_j of the junction between sea cliff, dune or coastal protection structure and the beach face. To achieve this goal, we construct extreme-value probability distributions (e-v pdf) for water levels measured by tide gauges, water levels due to wave runup, and finally for the combined total water levels.

Extreme Water Levels

Measured tides are often greater than predicted due to the occurrence of a storm surge, or the effects of water temperatures, currents and atmospheric disturbances such as an El Niño. A 24 year time series of hourly measured tides taken from a tide gage in Yaquina Bay, Oregon, has been analyzed to investigate some of these processes. The yearly maxima have been fitted to a Fisher-Tippet Type I extreme-value probability distribution, commonly known as the Gumbel extreme value distribution, and return intervals have been computed for extreme tides. A

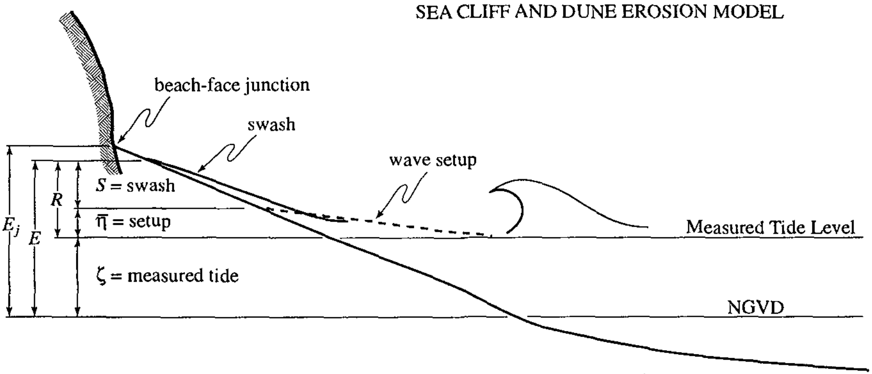

Figure 1: The basic model for the quantitative assessment of the susceptibilities of sea cliffs and dunes to wave-induced erosion.

predicted tide time series has been generated for the same 24 year period, and the predicted yearly maxima have also been fit to a Gumbel distribution. Shih *et al.* (1994) noted that for long return periods there are significant differences, on the order of 0.5 m, between predicted and observed extreme tides.

The difference between measured and predicted tides has been computed for the entire 24 year data set. The auto-correlation of this raw residual time series shows a roll off in correlation at a lag of approximately 48 hours. This lag corresponds well with the typical storm duration on the Oregon coast. The raw residuals were then filtered using a 48 hr low pass filter, eliminating measurement noise from the signal. The standard deviation of the low pass filtered residual time series is approximately 13 cm, giving a typical elevation for storm surge on the Oregon coast. Figure 2 shows the 24 year residual time series after applying a 1 month low pass filter in which single storms as well as spring and neap tides have been averaged out. Surprisingly, there is no distinct seasonal pattern in the figure. The extreme residuals evident in the smoothed time series, those in 1973, 1977, 1982-83, 1992 and 1993, all correspond to times of well-documented El Niño events. Although these events are usually associated with increased wave energy, both the residual and the measured tide are not significantly correlated with wave height throughout the period of overlap between the tide and wave data, a period of approximately 15 years. This observation, along with the relatively low contribution of storm surge to extreme total water levels on the Oregon coast, suggests that models such as that proposed by Gares (1990) may not be applicable to the Oregon coast. Models in which extreme measured water levels and extreme runup occur at the same time, although well suited for coastlines which experience hurricanes and Nor'Easters which generate significant storm surge, are not generally suitable to conditions typical of the Oregon coast.

Wave Runup

The second water-level component in the sea cliff and dune erosion model, superimposed on the measured tide, is wave runup. It is necessary to have the

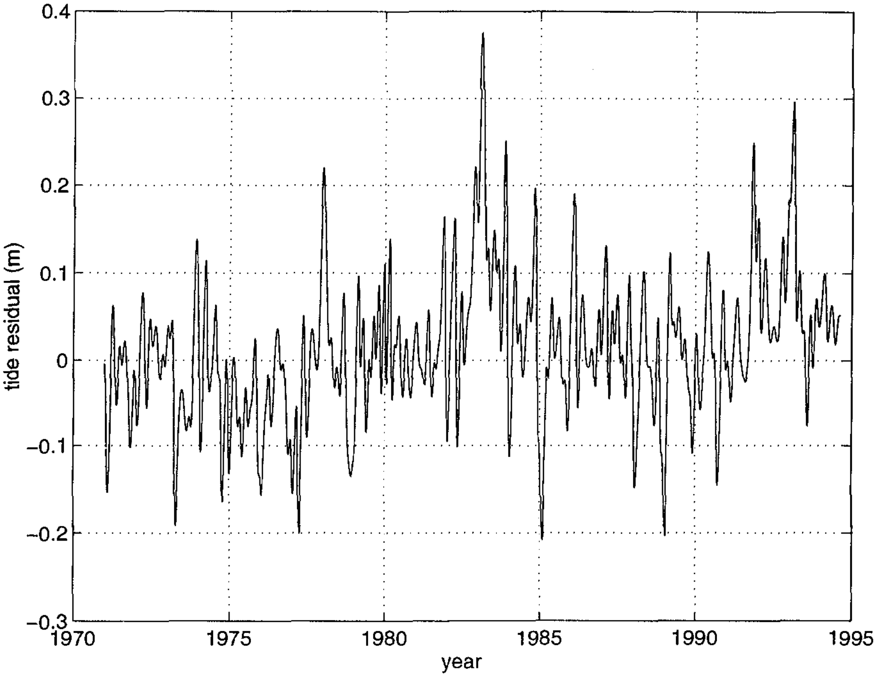

Figure 2: Thirty day low-pass filtered residual time series of measured minus predicted tides in Yaquina Bay, Oregon.

capability to predict extreme runup statistics utilizing measured wave parameters and beach morphology characteristics. Data bases containing a decade or more of measurements of wave heights and periods are now becoming readily available for use by engineers, scientists and planners, and much effort has been spent in finding simple relationships between deep-water wave parameters and runup on beaches. A well known data set of extreme runup statistics is that of Holman and Sallenger (1984) and Holman (1986), who measured wave runup using video techniques on the relatively steep beach of the Field Research Facility, Duck, North Carolina. Among other runup statistics, Holman (1986) examined the 2% exceedence elevation for runup maxima, non-dimensionalized by wave height, and found a dependence on the dimensionless surf similarity parameter, ξ_o, commonly referred to as the Iribarren number, the ratio of the beach slope to the deep-water wave steepness. The resulting relationship is

$$R_{2\%}/H_s = C\,\xi_o = C\,\beta/(H_s/L_o)^{(1/2)} \tag{1}$$

where C is an empirical constant determined by the measurements, β is the beach slope, H_s is the deep-water significant wave height, and L_o is the deep water wave length given by $L_o = (g/2\pi)T^2$ where g is the acceleration of gravity and T is the wave period. This result has been proposed by many researchers, including Battjes

(1971) and van der Meer and Stam (1992). In an attempt at further simplification, Holman's data were re-analyzed by Douglas (1992), who found that removing the beach slope term from Eq. (1) does not cause any reduction in the ability to predict runup on beaches. By analyzing a wide variety of Australian beaches, Neilson and Hanslow (1991) found that the relationship proposed by Holman explained results from field experiments on relatively steep beaches, $\beta > 1{:}10$, while for flatter more dissipative beaches with $\beta < 1{:}10$, runup depended only on the wave steepness. Many Oregon beaches are extremely dissipative with beach slopes much less than 1:10. The resulting Iribarren numbers are usually less than for beaches studied by other researchers, including the most dissipative in the Neilson and Hanslow (1991) study.

To test the dependence of extreme runup statistics on measured wave and beach morphology characteristics, video techniques were used to measure wave runup on several Oregon beaches over a broad range of dynamic conditions. Deep-water significant wave heights ranged from 1.9 to 4.6 m, periods from 7 to 17 seconds, and foreshore slopes from 1:100 to 1:20. This field program culminated in February 1996 at Agate Beach on the central Oregon coast, with a major investigation into the dynamics of high energy dissipative beaches. During this experiment, three video cameras were used to measure wave runup, and the overlap between the cameras allowed for continuous coverage of runup measurements over approximately 2 km of beach. Detailed analysis of the longshore variability of runup on dissipative beaches is underway. Runup elevation time series were extracted from all video data using image-processing techniques developed at the Coastal Imaging Lab of Oregon State University (Holman and Guza, 1984; Holland *et al.*, in press). For each data record, the tide has been removed and extreme runup statistics have been computed after identifying the local maxima of the shoreline elevation time series. Although there is a distinction in the processes which force wave setup and swash fluctuations, for most engineering applications the measure of interest is the extreme statistics associated with the total runup. Therefore, all runup statistics presented include both setup and swash.

The Oregon measurements of $R_{2\%}$ are non-dimensionalized in the form of Eq. (1), and compared with the data of Holman (1986) in Figure 3. The Iribarren number distinguishes between the dynamically different nearshore systems from which the data were taken. The Oregon data falls in the extremely dissipative range of Iribarren numbers, while the FRF data range from dissipative to reflective. Although the Oregon data are of the expected order of magnitude, any linear predictive model such as Eq. (1), derived from Holman's data, would tend to under predict $R_{2\%}$ on the flatter Oregon beaches, an observation noted earlier by Shih *et al.* (1994). The data from Oregon have been re-plotted in Figure 4a, which suggests that extreme runup statistics do not depend on the Iribarren number over this dissipative range. Figure 4b shows that the Oregon runup data has virtually no dependence on the beach slope, and Figure 4c shows a lack of dependence of $R_{2\%}/H_S$ on the wave steepness. Although not shown, the extreme runup also does not depend on the wave period. This is surprising, as runup has a first order dependence on the wave

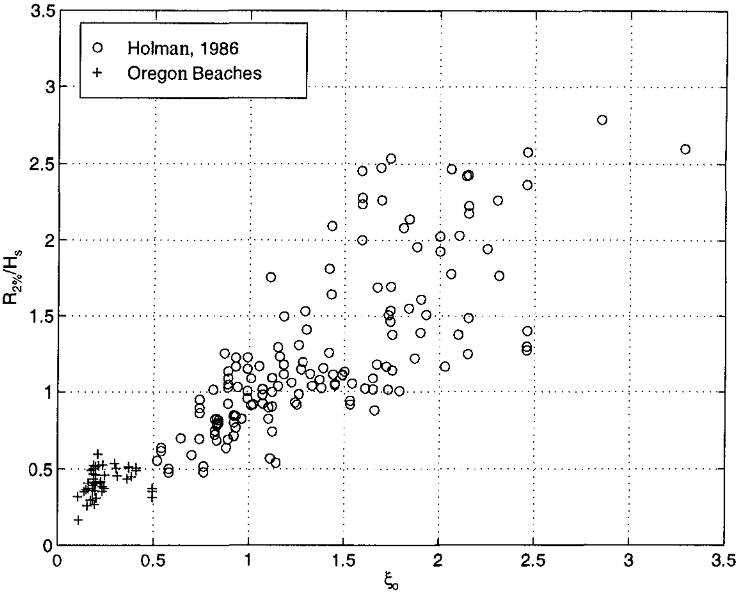

Figure 3: Comparison between non-dimensional extreme runup statistics obtained by Holman from the FRF and from Oregon beaches.

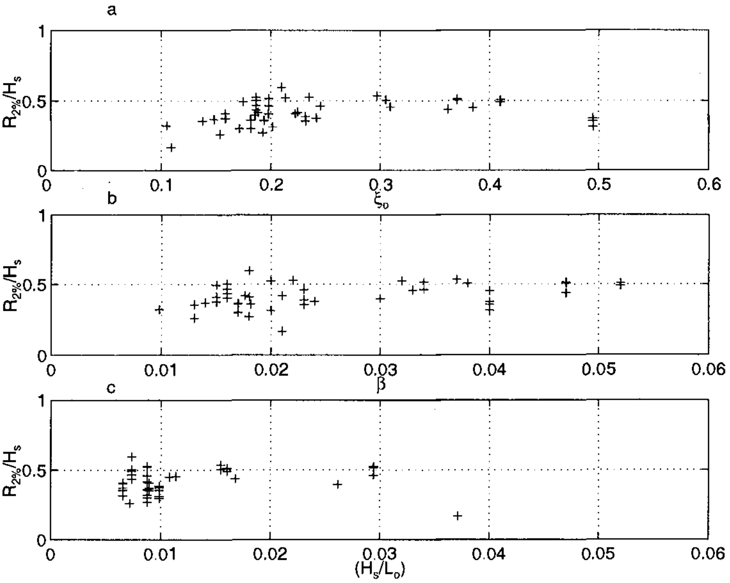

Figure 4: Relationships between non-dimensional extreme runup statistics and a) the Iribarren number, b) beach slope, and c) wave steepness.

period in the dimensional form of Eq. (1). The best parameterization of $R_{2\%}$ for the Oregon data is a simple dependence on the deep-water significant wave height as shown in Figure 5. The best-fit straight line matched to the Oregon data is

$$R_{2\%} = 0.5\ H_s - 0.22\ (\mathrm{m}) \qquad (r^2 = 0.72) \qquad \textbf{(2)}$$

A linear relationship between runup elevation and wave height on relatively low energy dissipative beaches was also found by Guza and Thornton (1982) in Southern California, and by Aagaard (1990) in Denmark and Australia. Guza and Thornton (1982) found that the significant vertical swash excursion, defined as 4σ, where σ^2 is the total variance of the runup elevation time series, was approximately 70% of the significant wave height, a slightly stronger dependence on wave height than found for the Oregon data and the results presented by Aagaard (1990). The FRF data of Holman (1986) are shown again in Figure 5 to emphasize the fact that the data are derived from dynamically very different systems as the Holman data clearly falls above the Oregon data. More research is needed to identify regimes where different models for extreme runup statistics are applicable.

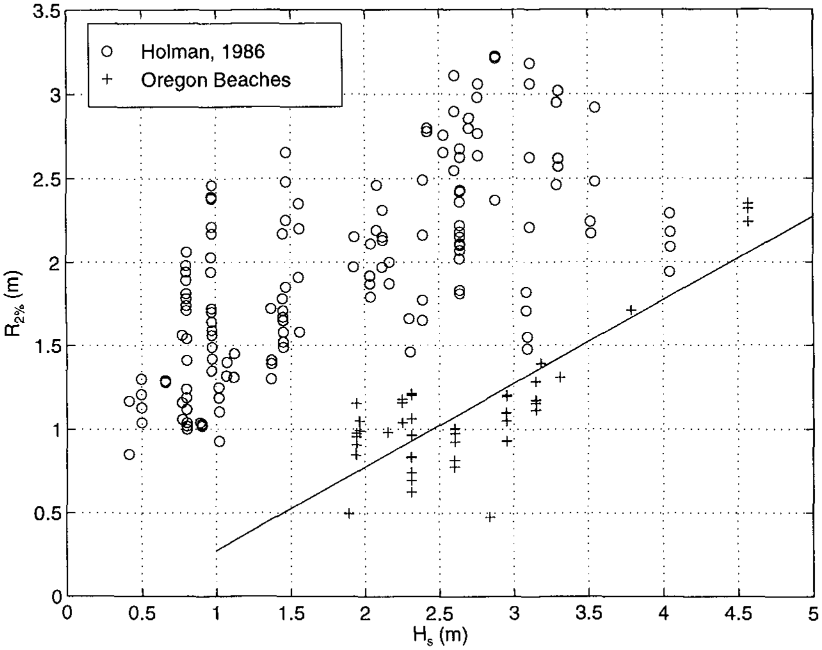

Figure 5: Dependence of extreme runup statistics on the deep-water significant wave height.

The extreme runup statistics presented here, as in the work done by other researchers, are monochromatic representations of spectral phenomena. In fact, all of the Oregon runup data, particularly that on the very low sloping Agate Beach, were dominated by infragravity energy ($f < 0.05$). Spectral peaks typically occurred at periods ranging from approximately 100 seconds to 200 seconds, and usually more than 90% of the runup elevation variance fell in the infragravity band. This infragravity dominance helps explain why runup statistics are independent of the incident band wave period. The incident band energy was saturated for most data runs, and the dependence on wave height shown in Figure 5 can almost entirely be explained by the infragravity band energy and its dependence on the wave height. Again, this is a similar result to that found by Guza and Thornton (1982).

Waves and Total Water Levels

In the previous section we showed that the best predictor of extreme runup on dissipative Oregon beaches is simply the deep-water wave height. A 15-year wave data set from the Coastal Data Information Program buoy offshore from Bandon, Oregon, has been used to estimate the extreme wave climate of the Oregon coast. This irregularly spaced data set has been interpolated to hourly measurements to match the measurement interval of the Yaquina Bay tide measurements. A Gumbel extreme-value distribution has been fitted to this data, and the resulting recurrence intervals for extreme waves are shown in Figure 6. This extreme value pdf has been produced by using all of the wave data above 6.5 meters, rather than just the yearly maxima (Muir and El-Shaarawi, 1986).

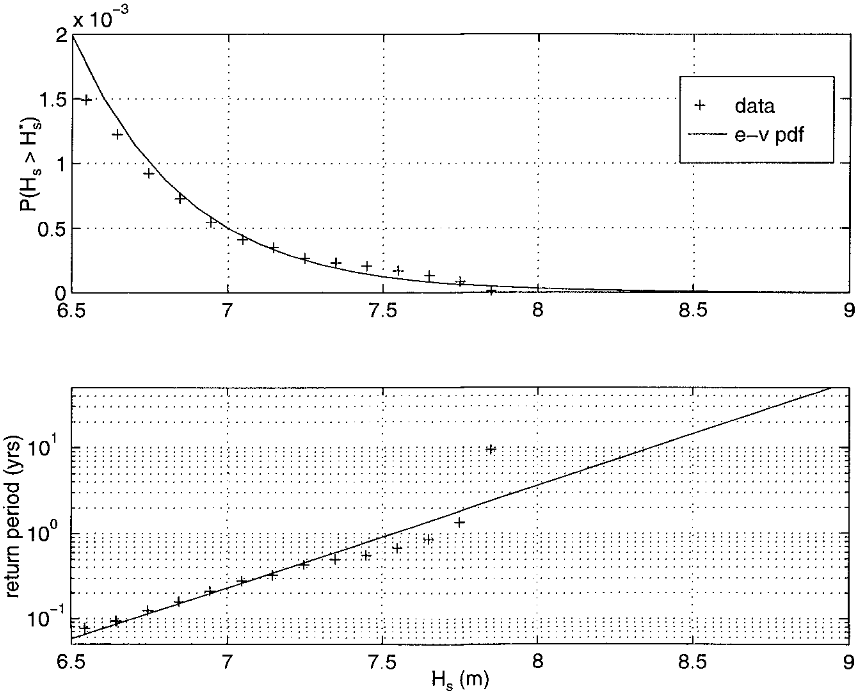

Figure 6: Extreme-value probability distribution and recurrence intervals constructed from 15 years of wave height data obtained by the CDIP buoy offshore from Bandon, Oregon.

Figure 6, as well as results presented by Tillotsen and Komar (in press), clearly demonstrate the intense nature of the wave climate experienced along the Oregon coast. The linear relationship between wave height and extreme runup statistics given in Eq. (2) can now serve as a transfer function to construct an extreme value distribution for $R_{2\%}$ from the distribution of wave heights, and is shown in Figure 7.

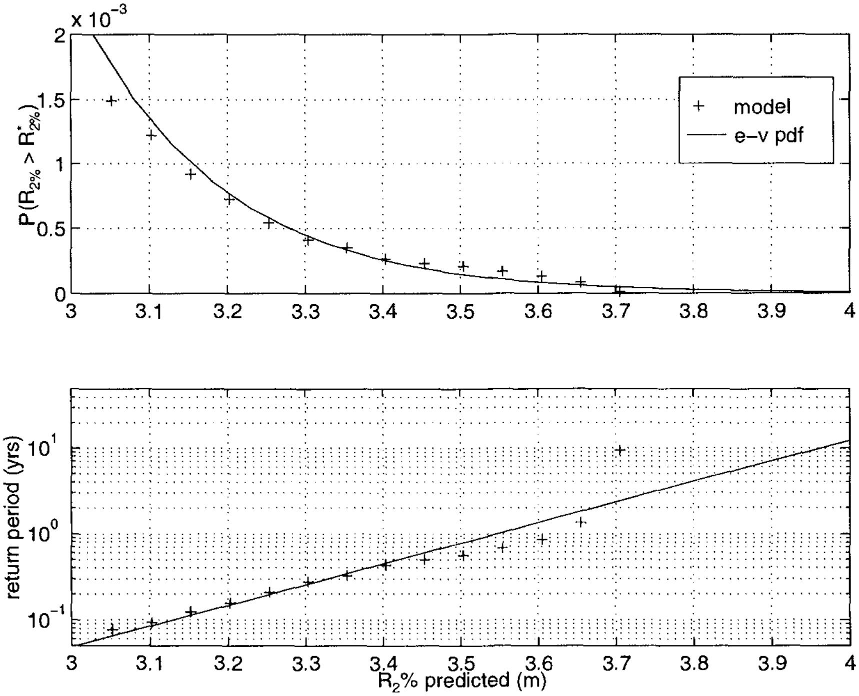

Figure 7: Extreme-value probability distribution and recurrence intervals for wave runup calculated from the wave height distribution in Figure 6.

Analytic probability density functions have been determined for both extreme measured tides and extreme wave runup, the two components of the sea cliff and dune erosion model. Assuming that runup and tides are statistically independent, the joint probability of tides and runup is easily calculated. This exercise has been completed, and contours of equal probability of occurrence have been generated. However, a more useful and direct method for determining the statistics of extreme total water levels is to apply the above model for wave runup to the wave component of the joint time series of waves and water levels. This joint time series is constructed from the time periods in which the wave data and tide data overlap. In doing this, we generate a runup time series which can be added to the measured tide to give a simulated total water level time series. An extreme value distribution is determined from this time series directly, using all total water levels above 2.8 m, and is shown in Figure 8. The recurrence intervals of the total water level reaching or exceeding any elevation can now be determined.

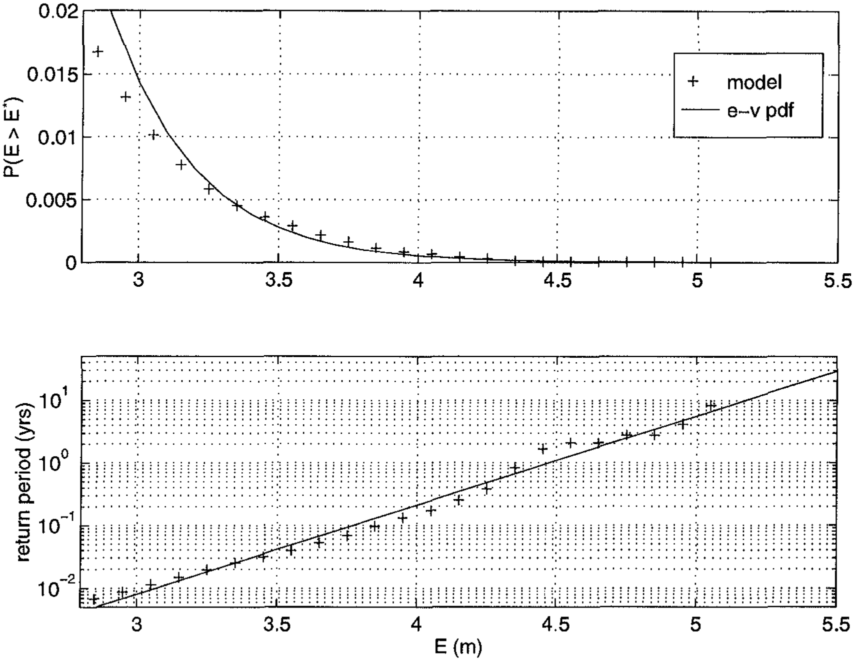

Figure 8: Extreme-value probability distribution and recurrence intervals for total water levels, measured tides plus wave runup.

MODEL APPLICATION

The Oregon coast is divided into a series of littoral cells, with beaches confined between large headlands. The elevation of the beach-face junction varies considerably between cells due to differences in sediment grain sizes, and the quantities of sand in a particular cell. This elevation can also vary within a cell due to local effects such as the lowering of the beach by rip current embayments (Shih and Komar, 1994). A number of beaches with varying morphologies are being monitored in Oregon to determine these elevations relative to NGVD, as well as to quantify typical summer and winter profiles and long term morphology changes. The model has been applied to 13 sites along the central Oregon coast, accounting for 9 of the 13 littoral cells. The beaches are backed by sea cliffs, dunes and shore protection structures and all have beach slopes within the range of applicability of the runup model. The model allows for the determination of the frequency with which the total water level exceeds the elevation of the beach-face junction, thus being a good indicator of potential erosion.

Table 1: Impacts per year as compared to beach stability observations.

Site	Backing Feature	β	E_j (m)	Impacts per year (hrs)	Observations
Jump off Joe	Sea Cliff	.034	2.90	173	severe erosion
Nye Beach	Sea Cliff	.034	3.70	13	stable
Beverly Beach	Sea Cliff	.043	4.02	4	erosion
Oceanside	Dune	.023	3.60	18	stable/erosion
South Beach	Dune	.026	4.12	3	accretion
Manzanita North	Dune	.025	4.20	2	stable/accretion
Manzanita South	Dune	.038	6.30	---	heavy accretion
Nestucca Spit	Dune	.046	6.50	---	heavy accretion
C&L Ranch	Sea Wall	.030	3.15	77	severe erosion
Pacific Shores	Sea Wall	.039	3.65	15	erosion
San Marine	Sea Wall	.030	3.75	11	erosion
Pacific Palisades	Sea Wall	.052	5.30	---	accretion
Driftwood Shores	Sea Wall	.033	7.50	---	heavy accretion

Table 1 summarizes the results as applied to the sites on the Oregon coast. The table lists the average winter beach slopes and the average elevations of the junction between the beach and the respective backing feature. The return interval, the fraction of time when the 2% exceedence elevation of runup maxima superimposed on the tide reaches or exceeds E_j has been calculated. However, since we have used all of the data above a threshold value from our simulated total water elevation time series to construct the extreme pdf shown in Figure 8, we can convert return intervals to the more convenient unit of hours of wave runup impact per year. This column in Table 1 gives an estimate of the number of hours per year in which $R_{2\%}$ exceeds E_j for a particular beach, thus being a reasonable proxy for potential erosion at the site. The final column in the table lists basic field observations concerning the morphologic stability of the particular site. The first site, Jump Off Joe, is backed by the remains of a massive landslide which protrudes out onto the active beach profile, hence the very low E_j. The toe of the landslide is actively eroding and is reached by swash during most higher high tides in the winter. Nye Beach, immediately to the south of Jump off Joe, is relatively stable and backed by a vegetated sea cliff. The model predicts that the sea cliff at Jump off Joe will be hit by wave runup much more often than any other site including the cliff at Nye Beach, agreeing well with observations.

SUMMARY AND DISCUSSION

With an appropriate model relating runup elevations to deep-water wave conditions, the frequency of occurrence of sea cliff or dune erosion can be predicted using historical wave and tide records. Coastal regulators, the anticipated users of the model, will have a quantitative method to determine the susceptibilities of properties to erosion and thus a rationale to establish setback distances for coastal developments. The model can also aid in the development of dune-management plans which balance the role of dunes in reducing future property losses versus the development pressure currently being experienced on the Oregon coast. For example, from this data set it appears that shorelines subjected to less than 1 hour of attack per year tend to be stable, while those with more than 10 hours per year tend to experience erosion. In its present form the model may be used to evaluate the need for shore protection structures and may potentially assist in their design. Future model development will attempt to include impact forces in order to predict erosion rates of both sea cliff and dune backed shorelines. The major weakness of the model is the simple relationship between extreme runup statistics and wave height. The model takes no account of the possibility that the functional relationship between runup and wave height may change under more extreme conditions than those measured. The model also ignores large-scale morphology, including offshore bars and bathymetry, as well as large-scale alongshore variability. More runup data are needed on beaches between the dissipative extremes presented here, and the more intermediate to reflective systems to help identify appropriate runup models for a particular beach state.

ACKNOWLEDGMENTS

We would like to thank Rob Holman for the use of his extensive data set. This work is a result of research supported by the NOAA Office of Sea Grant, Department of Commerce. The Agate Beach field experiment and data analysis was supported by ONR Grant # N000-14-94-11196.

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