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Extreme Waves and Coastal Erosion in the Pacific Northwest

Peter Ruggiero[1], George M. Kaminsky[1], Paul D. Komar[2] and William G. McDougal[3]

Abstract

The extreme wave climate of a Pacific Northwest littoral cell has been characterized by examining four long-term databases of measured wave parameters. Winter waves in the region average 3.0 m in significant wave height and 12 s in period, while summer waves average 1.5 m and 8 s, respectively. There is a distinct seasonality in monthly mean wave direction, with winter storm waves arriving from the southwest and the milder summer waves arriving from the northwest. Projections of the 50-year design wave height vary greatly, depending on the data source, ranging from 8.5 m to 12.2 m. A probabilistic model, combining these long-term measurements of waves with measurements of tides and local beach morphology, has been applied to a sub-region of the littoral cell. The model quantifies the susceptibility of coastal properties to erosion by predicting the frequency with which wave runup impacts either sea cliffs or sand dunes. The coastal erosion model is based on wave runup measurements obtained on high-energy dissipative beaches typical of the Pacific Northwest. Statistics of wave runup maxima are well correlated with simple relationships between commonly measured wave and beach parameters. Measurements of extreme tides have been shown to be greater than predicted due to a variety of factors, particularly the occurrence of El Niño events. The 1997/98 El Niño has produced some of the highest water levels on record, increasing the potential for erosion within the region.

[1] Washington Department of Ecology, Coastal Monitoring & Analysis Program, P.O. Box 47600, Olympia, WA, 98504-7690, USA, tel 360-407-6230, fax 360-407-6535, prug461@ecy.wa.gov (Ruggiero), gkam461@ecy.wa.gov (Kaminsky)

[2] College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, pkomar@oce.orst.edu

[3] Ocean Engineering Program, Civil Engineering Department, Oregon State University, Corvallis, OR 97331, mcdougal@engr.orst.edu

Introduction

This study focuses on the 160-km long Columbia River littoral cell in the US Pacific Northwest, extending from Tillamook Head, Oregon to Point Grenville, Washington. Much of this littoral cell is characterized by wide dissipative beaches, typically backed by sand dunes or sea cliffs. Although this region is well known for its severe wave climate, much of the littoral cell has been historically accreting with few coastal development problems. However, recent sustained erosion at a number of sites (Figure 1) has damaged infrastructure and threatened local economies; now millions of Federal and State dollars are scheduled to be spent for shore protection. In many areas, long-term accretion appears to have slowed or reversed, indicating a regional trend toward erosion. In order to predict coastal behaviour at management scale, *i.e.* decades and tens of kilometers, a regional study of long-term coastal evolution and shoreline response has been initiated to investigate the sediment dynamics, regional sediment budget and natural and anthropogenic influences on the system (Kaminsky *et al.*, 1997).

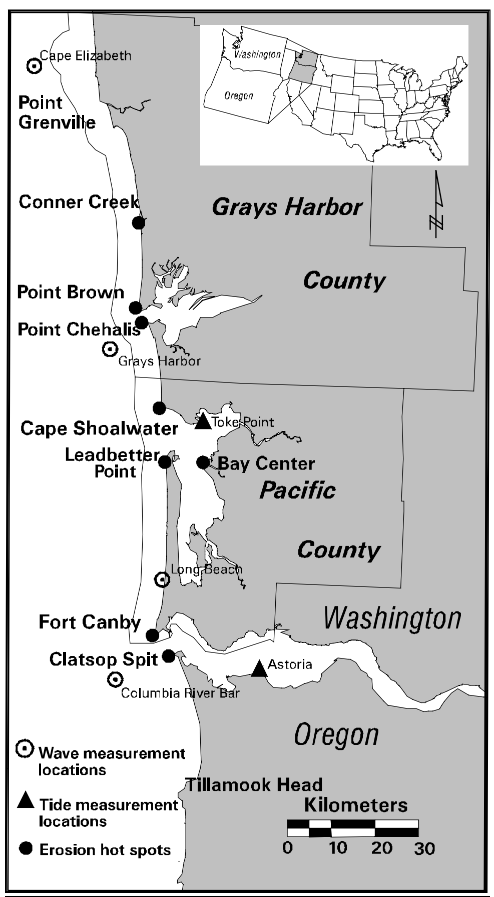

Figure 1. Erosion hotspots in the Columbia River littoral cell and the locations of long-term wave and tide measurements.

From a coastal management perspective, it is of great interest to be able to predict the frequency and intensity of erosion events. Long-term coastal planning and hazard mitigation, such as determining setback distances and the appropriateness of coastal protection structures, requires this information. Therefore, as a component of the Southwest Washington Coastal Erosion Study, a model based on the probabilities of extreme storm waves and extreme water levels (Ruggiero *et al.*, 1996 and Ruggiero, 1997) has been applied to a sub-region of the littoral cell. The goal of this work is to evaluate the susceptibilities of coastal properties to flooding and erosion. Results from the model, originally developed for the Oregon coast to provide for scientifically based coastal management decision-making, compared well with observations of erosion.

Wave induced erosion of beachfront property, whether in foredunes or on sea cliffs, depends on the water elevation reached relative to the fronting beach-face junction elevation. The water level depends on the tidal variability influenced by many oceanographic and atmospheric processes that alter the mean water level from the predicted tidal elevation (*e.g.*, the occurrence of an El Niño). In addition, there is an increase in water level produced by waves, including the setup that elevates the mean shoreline position and the runup of individual waves above that mean level.

In this paper, we first characterize the extreme wave climate of the Columbia River littoral cell by analyzing records from four different sources. Wave measurements are then used to determine extreme runup elevations for the observed morphology along a sub-region of the littoral cell. Wave runup is superimposed on measured tides to simulate a total water-level time series. Predictions of erosion frequency are derived by combining extreme-value probability distributions of this simulated total water level with measured beach morphology characteristics. Model results provide objective information to coastal managers for planning and decision-making efforts. The effects of the 1997/98 El Niño on the wave and water level climate of the Columbia River littoral cell are also discussed throughout the paper.

Extreme Waves

The importance of maintaining long-term wave measurement records has been recognized in Washington State for some time. The Washington State Department of Ecology and the U.S. Army Corps of Engineers cooperatively managed and funded the Washington Coastal Data Information Program consisting of a network of nearshore wave climate monitoring stations (Kaminsky, 1993). There are four long-term wave gages distributed throughout the Columbia River littoral cell as shown in Figure 1. The data from these measurement sources have been accessible to coastal managers via the Washington Wave database (WWDB) (Earle and Eckard, 1993) and are now available via the World Wide

Web. Table 1 summarizes the differences among the various gages, including system type, water depth, and length of data record.

Table 1. Wave measurement systems within the Columbia River littoral cell.

Program	System	Location	Water Depth (m)	Period
NDBC	3-meter discus buoy	Columbia River Bar, OR	62	1984-present
CDIP	Slope array	Long Beach, WA	11	1983-6/96
CDIP	Waverider buoy	Grays Harbor, WA	43	1981-present
NDBC	3-meter discus buoy	Cape Elizabeth, WA	48	1987-6/97

Significant wave heights and dominant wave periods have been obtained from each of the wave gages. The 3-meter discus buoys operated by the National Data Buoy Center (NDBC) have been recording hourly data since inception. The Coastal Data Information Program (CDIP) stations began recording at 6-hour intervals, changing then to 3-hour intervals. The Grays Harbor buoy has been recording hourly since April 1996. Table 1 lists the available data period for each source; however, there are many data gaps in each record, some of which extend for a year or more. Wave direction measurements are available from the Long Beach slope array for its entire project life, from the Grays Harbor buoy since August 1993, and from the Columbia River Bar buoy since September 1995.

Figure 2 shows the average monthly significant wave height, H_s and the average monthly wave period, T, from each of the four sources. Wave measurements have been transformed to the equivalent deep-water wave height using linear wave theory. Winter waves are typically 3.0 m in height and 12 s in period, while summer means decrease to 1.5 m and 8 s respectively. The monthly mean wave heights from each of the sources reveal no apparent north-south trend. However, the wave heights from the 3-m discus buoys, operated by the NDBC, are slightly larger than those from the CDIP gages. Wave periods also vary between gages, with the NDBC sources reporting higher values than those from the CDIP. These results compare favorably to an earlier characterization of the Pacific Northwest wave climate by Tillotsen and Komar (1997). Wave records from a variety of sources were examined, including buoys, slope arrays, wave hindcast records and a microseismometer. They determined that the average monthly deep-water wave climate conditions are essentially uniform throughout the region, although daily variations may be substantial. Tillotsen and Komar (1997) also found that buoys operated by the NDBC reported wave heights 8 to 13 percent higher than buoys operated by the CDIP. Significant wave heights derived from Wave Information

Study (WIS) hindcasts (Corson *et al*., 1987) were found to be 30 to 60 percent larger than wave heights derived from direct measurements, and have therefore not been included in the present study. Tillotsen and Komar (1997) analyzed wave records through 1994. The present work extends these analyses through 1997 and includes measurements from two additional buoys, the Columbia River Bar and Cape Elizabeth buoys. Figure 2c shows the monthly mean wave direction, θ, from three sources, revealing that waves arrive predominantly from the southwest in the winter and from the northwest in the summer. Due to wave refraction to the relatively shallow water location of the array, this directional seasonality is not as pronounced in the Long Beach measurements. A detailed analysis of wave direction and sediment transport within the Columbia River littoral cell is currently underway.

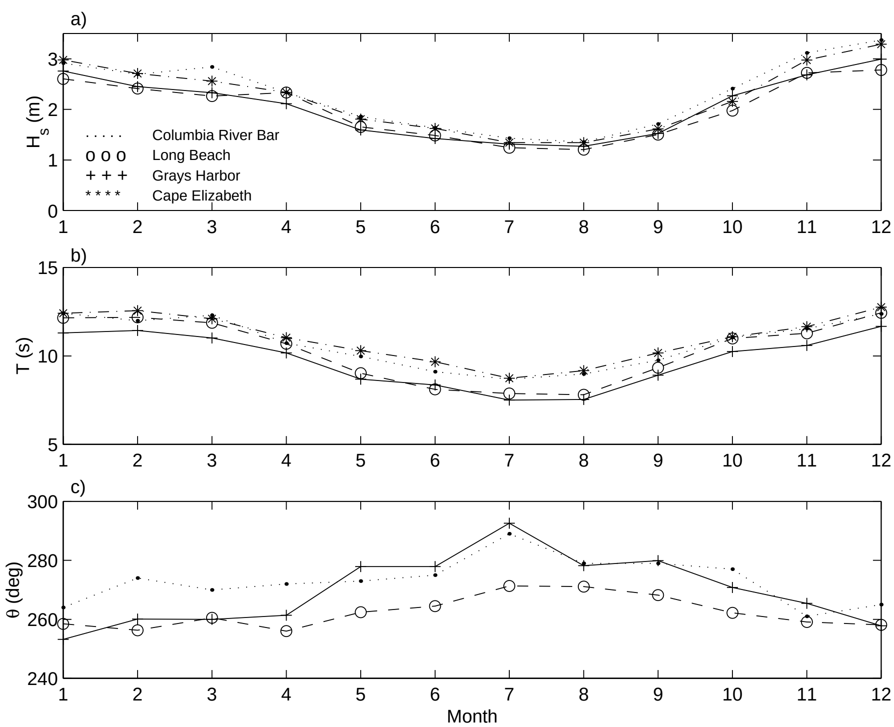

Figure 2. Monthly mean a) significant wave height b) period and c) direction. The Columbia River Bar buoy is denoted by a dotted line with small closed circles, Cape Elizabeth with a dash-dot line and asterisks, Grays Harbor with a solid line and pluses, and Long Beach with a dashed line with open circles.

The relatively long record of direct measurements, ranging between 10 and 16 years, allows for the determination of the extreme wave climate of the Pacific Northwest through the application of extreme-value probability distributions. The extremal analysis has been undertaken in two ways. First, the annual maximum wave height from each of the sources was fitted to a Fisher-Tippet Type 1 extreme-value probability distribution, commonly known as the Gumbel extreme-value distribution. This results of this method, shown in Figure 3a, can be potentially misleading, as it is possible to have several large storms within one calendar year and no large storms in subsequent years. The second method (Figure 3b) combines the Initial Distribution Method (IDM) with the Peak Over Threshold (POT) method (van Vledder *et al.*, 1993) by fitting all of the measurements above a threshold value of 6.5 m to a Gumbel extreme-value distribution.

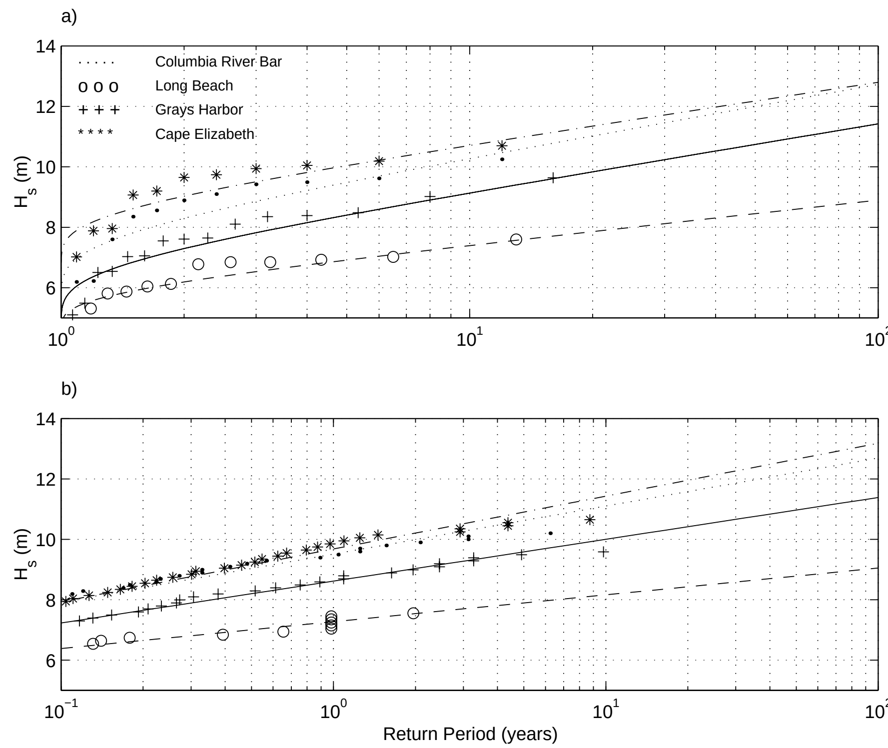

Figure 3. Extreme significant wave heights calculated using a) the yearly maxima and b) all data above 6.5 m. The Columbia River bar buoy is denoted by a dotted line with small closed circles, Cape Elizabeth with a dash-dot line and asterisks, Grays Harbor with a solid line and pluses, Long Beach with a dashed line with open circles.

Although the data sets are only long enough to reasonably project approximately 30 to 50 years (depending on the particular record length of the gage), the plots have been extended to the 100-year return interval. The results of these analyses further establish the severity of the wave climate of the Pacific Northwest coast, with the projected 50-year deep-water significant wave height in excess of 8 m. However, depending on the data source, extreme wave height projections vary substantially. There is a 3.7 m difference in the 50-year projections between the Long Beach gage, 8.5 m, and the Cape Elizabeth gage, 12.2 m. These differences can be attributed to several possible factors such as energy losses due to bottom friction and wave breaking, or simply due to the differences between the various measurement and data processing techniques among the gages.

Erosion Model Components

Wave-induced property erosion generally occurs when wave runup reaches the junction between the beach face and its backing feature, *eg.* a sea cliff, dune, or coastal protection structure. Figure 4 is a definition sketch of the two main components which generate total water levels (Shih *et al.*, 1994; Ruggiero *et al.*, 1996 and Ruggiero, 1997). The first is the measured tidal elevation, E_T, above a reference datum. The second is the vertical component of wave runup, R, consisting of both the super-elevation of the mean water level due to waves, wave setup, and swash oscillations about this setup water level. Depending on a number of wave, water level and morphological parameters, both the elevation attained by the wave runup and the elevation of the beach-face junction, E_j, can vary significantly. Wave-induced erosion of sea cliffs or sand dunes will occur only when the total elevation of the water, E, exceeds the elevation of the beach-face junction, $(E_T + R) > E_j$. The present model combines long-term databases of both measured waves and tides with field observations to predict extreme total water levels along a sub-region of the Columbia River littoral cell.

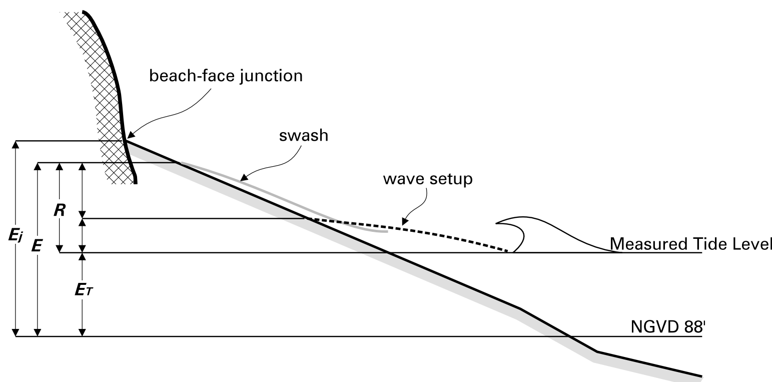

Figure 4. The basic model for the quantitative assessment of the susceptibilities of sea cliffs and dunes to wave-induced erosion.

Tides

Long-term data records of measured hourly tides have been obtained from the two operational water level stations within the Columbia River littoral cell. The locations of the Toke Point, WA and the Astoria, OR tide gages are shown in Figure 1. Although these gages have been maintained for extended periods, digital data has only been obtained since 1980 for this study. Short-term tide gages have occasionally been installed closer to the open coast in order to develop tide based vertical datums and calibrate tidal prediction models. For example, a tide gage was installed near Point Brown, WA between 19 May 1982 and 26 July 1982 allowing for a short-term direct comparison with the Toke Point gage. Tides at Point Brown were on average 0.27 m higher than those at the Toke Point gage during this period.

Tidal data are typically reported relative to tidal datums, such as Mean Lower Low Water (MLLW) or Mean Sea Level (MSL). These datums, derived locally based on water level measurements, can vary substantially along a coastline while land based datums are fixed in space. Therefore, regional coastal management applications are better served if tidal data are referenced to land based datums. The datum used in this study is the North American Vertical Datum of 1988 (NAVD 88). Geodetic control surveys utilizing Differential Global Positioning System (DGPS) techniques have been employed to determine the relationship between tidal datums and NAVD 88 for much of the southwest Washington coast. At Toke Point, the difference between MLLW and NAVD 88 is 0.24 m.

Figure 5 displays monthly mean water levels since 1980 from the Toke Point gage. There is a distinct seasonality to the measurements, with winter water levels measuring as much as 0.3 m higher than summer measurements. Increased winter water levels can be attributed to oceanographic and atmospheric processes such as wind stress, barometric pressure gradients, and higher storm wave activity. Also shown on Figure 5 are the monthly mean water levels for 1997, widely recognized as having one of the strongest El Niño signals on record. For much of autumn and early winter of 1997, monthly mean water levels were approximately 0.15 m higher than normal for this period. The dashed lines on Figure 5 represent the maximum and minimum monthly means for the previous 18-year period. Monthly mean water levels in 1997 were the highest on record for four individual months. This increase in water level can be partially attributed to both elevated offshore water temperatures and a propagating sea-level wave trapped near the coast by the Coriolis force and wave refraction. This sea-level wave results from the cessation of trade winds in the southern hemisphere causing warm water to propagate along the equator until it hits South America, a portion of which then travels northward along the continental shelf. This increase in mean water level due to El Niño was documented in Oregon during the 1982/83 event (Huyer *et al.*, 1983). Observed water levels exceeded monthly means by up to 0.35 m during this event, playing a significant role in the resulting erosion along the Oregon coast (Komar, 1986; Komar and Good, 1989 and Peterson *et al.,* 1990). Unfortunately, the Toke Point gage was inoperable during the strongest period of the El Niño, October 1982 until March 1983, making a direct comparison of the two events impossible.

The annual maxima of hourly water level measurements from the 18-year Toke Point time series have been fitted to a Gumbel extreme-value distribution. Similarly, a predicted tide time series has been generated for the same 18-year period using National Ocean Service (NOS) methods, with the predicted yearly maxima also fitted to a Gumbel extreme-value distribution. Both distributions, shown in Figure 6, reveal significant differences, on the order of 1.0 m for long return periods, between the predicted and observed tides. This trend was previously observed by Shih *et al.* (1994) and Ruggiero *et al*. (1996) on the

Oregon coast, but extreme measured tides were only 0.4 m higher than extreme predicted tides. Potential factors that make up these differences include the existence of a storm surge, and the effects of water temperature, currents and atmospheric disturbances such as an El Niño. Recent studies have indicated that storm surge is a relatively small component of the total water levels experienced on Pacific Northwest coastlines and differences between measured and predicted tides are not significantly correlated with wave height. Therefore, models such as that proposed by Gares (1990) in which extreme measured water levels and extreme runup occur at the same time, although well suited for coastlines which experience significant storm surge, are not generally suitable to conditions typical of the Pacific Northwest.

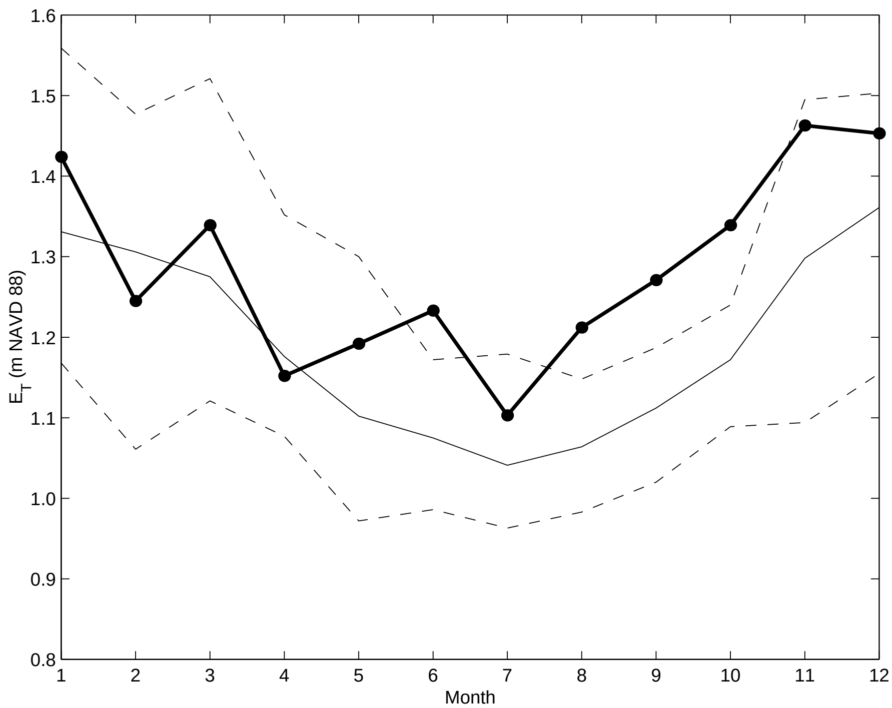

Figure 5. Monthly mean water levels for the Toke Point tide gage. The 1997 values, the heavy curve with closed circles, exceeded the mean, solid curve, and maximum ranges, dashed curves, for much of the autumn.

Wave Runup

The Columbia River littoral cell consists of wide, dissipative beaches with foreshore beach slopes typically shallower than 1:50. A recent field campaign on the Oregon coast investigated wave runup dynamics on high-energy dissipative beaches (Ruggiero *et al*., 1996 and Ruggiero, 1997). This study utilized video image processing techniques (Holman and Guza, 1984 and Holland and Holman, 1993) to measure runup on a variety of beaches. During the experiments, beach slopes, β, varied from 0.005 to 0.047, deep-water significant wave heights varied from 1.4 m to 4.6 m, and wave periods varied between 7 s to 17 s. In all cases, infragravity energy dominated the runup signals.

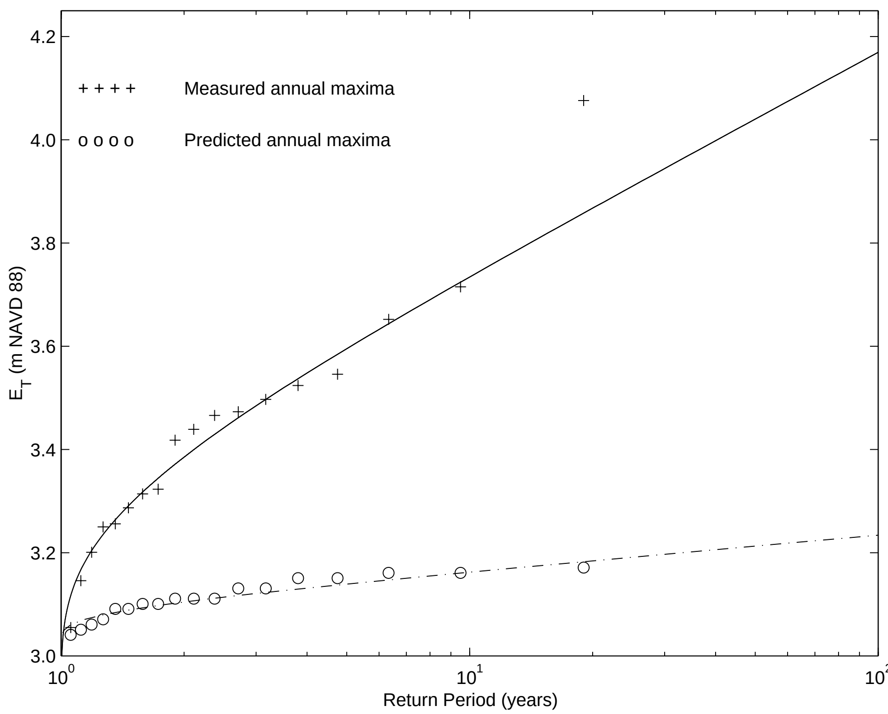

Figure 6. Extreme measured tides, solid line with pluses, and predicted tides, dash-dot line with open circles.

Extreme statistics of wave runup maxima on dissipative Oregon beaches have been shown to have a simple linear relationship with the deep-water wave height. Two other slightly more complicated relationships have also been derived by combining the Oregon runup data with measurements taken on an intermediate to reflective beach at the Field Research Facility of Duck, N.C. (Holman, 1986). The first relationship is a dimensional form of the Iribarren number,

$$R_{2\%} = 0.75\,\beta\,(H_s\,L_o)^{1/2} + 0.22\,H_s \qquad \textbf{(1)}$$

where $R_{2\%}$ is the two-percent exceedance elevation of wave runup maxima and L_o is the deep-water wave length given by linear wave theory as $(g/2\pi)T^2$. The second relationship does not do quite as well in describing the variance of the combined data sets, but does a superior job of describing the data from the dissipative beaches alone.

$$R_{2\%} = 0.27(\beta\,H_o\,L_o)^{1/2} \qquad \textbf{(2)}$$

The beach slopes in each of these relationships are taken to be the best linear fit of the measured beach surface within two standard deviations from the mean runup elevation. Estimates of $R_{2\%}$ in each expression include both wave setup and swash.

Extreme Total Water Levels

Analytic probability density functions have thus far been determined for both extreme measured waves and tides. Simple relationships between wave runup maxima and deep-water wave and beach morphology characteristics suggest a direct transfer function between long-term wave measurements and calculated long-term runup values. To determine the statistics of extreme total water levels, the empirical relationships for runup are applied to the wave component of the joint time series of waves and water levels. This joint time series is constructed from the periods in which the wave and tide data coincide.

For this application, the Grays Harbor wave buoy was used as it has the longest measurement record of the four possible sources. When necessary, the wave data records have been linearly interpolated to match the hourly measurement interval of the water level measurements at Toke Point. A wave runup time series is generated to be superimposed on the measured tide giving a simulated total water level time series. Extreme-value analysis is then directly applied to this new time series using all data above a 3.0 m threshold value. By performing the analysis in this manner, the projected return intervals of total water can be converted to the unit hours of wave runup impact per year. Figure 7 gives estimates of the number of hours per year in which two percent of the wave runup maxima reaches or exceeds a particular elevation. Both runup models (1) and (2) are examined, in Figures 7a and 7b respectively. The three representative beach slopes, β = 0.01, 0.03 and 0.05, revealed similar trends with the predicted susceptibility to erosion for a particular beach-face junction elevation increasing with beach slope. Of the two models, runup equation (1) is better suited for intermediate to steep beaches, which experience higher raw runup elevations, and yields higher values of impact hours per year for a given beach-face junction elevation. Model (2) is more applicable to dissipative beaches, and, therefore will be applied to the dissipative beaches found within the Columbia River littoral cell.

Model Application

As part of the Southwest Washington Coastal Erosion Study, a coastal monitoring and analysis program has been initiated for the Columbia River littoral cell. One component of the monitoring program is the collection of cross-shore beach profiles utilizing real time kinematic (RTK) DGPS surveying equipment. The inventory, installation, and observation of a dense network of geodetic control monuments along the coastal corridor has aided this data collection campaign. Beach profiles at over 45 locations, spaced at approximately 3-4 km intervals throughout the littoral cell, are being collected biannually with nominal horizontal and vertical accuracies on the order of 2 cm. Data collection began during the summer of 1997 and is planned to continue at least through the four-year life of the study.

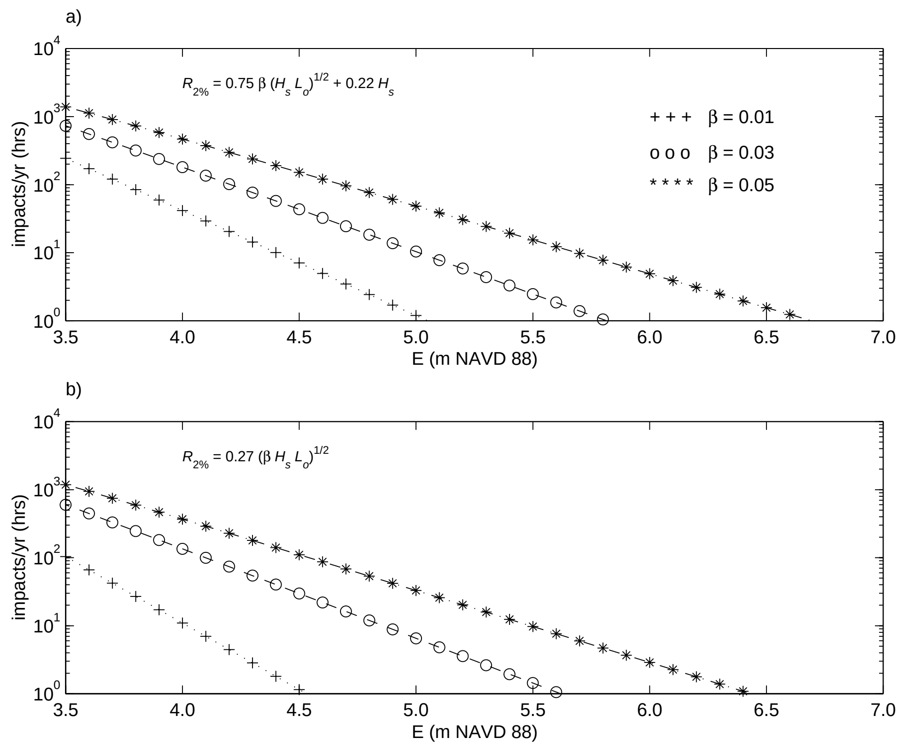

Figure 7. Extreme total water level probability curves calculated with a) runup model (1) and b) runup model (2) for three representative beach slopes, β = 0.01 (indicated by pluses), 0.03 (open circles) and 0.05 (asterisks).

One good test of model applicability is to calculate the total water elevation for a specific time, comparing model results with field observations. A cross-shore beach profile was collected at Ocean Shores, WA on 14 November 1997. Wave runup was observed to reach the beach-dune junction, in this case a severely eroding dune scarp, several times during the spring high tide occurring on that day. Some runup events impacted the scarp with such magnitude that small avalanching occurred. The mean tidal elevation derived from the Toke Point gage was approximately 0.25 m higher than predicted during the hour of high tide. After correcting for the difference between the tidal and land based datums and adjusting the measurement taken at Toke Point to this open coast site, the tidal level was 3.55 m NAVD 88. The wave height, 3.79 m, and period, 14.81 s, during high tide were taken from the Columbia River Bar buoy since the gages at Grays Harbor, Cape Elizabeth and Long Beach were not functioning at the time. The measured beach slope adjacent to the beach face junction was approximately 0.06, and the beach-dune junction elevation was 5.6 m. According to (2), two percent of wave runup maxima should have reached or exceeded the elevation 5.9

m, 0.3 m above the beach-face junction at this site. Therefore, model results have been confirmed with field observations. $R_{2\%}$ calculated with (1) gives a total water level value of 6.0 m for the same wave conditions. Two percent of wave runup maxima reaching or exceeding the beach-face junction elevation is assumed here to be a reasonable proxy for potential erosion.

Profiles from the summer of 1997 have been used to determine the elevations of the beach-face junctions and the beach slopes in order to apply the model to the northern sub-region of the Columbia River littoral cell (Point Brown to Point Grenville). Table 2 gives these data as well as model results for thirteen beach profiles. The model does a good job of predicting erosion susceptibility at the various sites, and model results compare favorably with qualitative beach stability observations. The sites predicted to be impacted by approximately 1 hour of wave runup per year are all currently accreting, while beaches being impacted by waves in excess of 50 hours per year are currently experiencing erosion. It is expected that beach profile data collected during the winter of 1998 will enhance model results.

Table 2. Wave runup impacts per year as compared to beach stability observations. Sites are listed from north to south for the sub-region between Point Grenville and Point Brown.

Site	Backing Feature	β	E_j (m NAVD 88)	Impacts per year (hrs)	Qualitative Observations
South	Dune	0.015	4.55	3.3	Stable
L443	Dune	0.016	4.10	22.7	Stable
B1	Bluff	0.014	4.20	10.7	Stable
A 1.5	Bluff	0.020	4.41	13.1	Stable
Pier RM1	Dune	0.027	4.05	88.8	Erosion
Gkam	Sea Cliff	0.015	4.10	18.9	Stable
Bhux	Sea Cliff	0.023	4.05	63.0	Erosion
GP-14109	Dune	0.010	4.57	0.8	Accretion
Diana	Dune	0.013	4.67	1.2	Accretion
Damons	Dune	0.013	4.56	1.9	Accretion
ET	Dune	0.015	4.77	1.4	Accretion
Butter	Dune	0.030	5.22	3.3	Stable
X1	Dune	0.080	5.60	77.8	Severe Erosion

Summary and Discussion

There have been two primary focuses of this study. First, the extreme wave climate of the Columbia River littoral cell has been characterized by examining long-term wave records from four sources. The projected 50-year wave was quite large in each case, varying from 8.5 m to 12.2 m depending on the source. These large differences in extreme projections make it difficult for engineers to determine accurate design waves for coastal engineering projects. Measured wave parameters demonstrate a distinct seasonality, in turn forcing seasonal trends in sediment transport throughout the littoral cell, a topic of ongoing study.

The second focus of this study has been to apply a model based on extreme total water levels to evaluate the susceptibilities of coastal properties to wave-induced erosion throughout a sub-region of the Columbia River littoral cell. The ability to quantitatively determine extreme values of mean water elevations and the wave runup during major storms is paramount in the application of this model. Empirical relationships between wave runup maxima and deep-water wave parameters have been developed through an investigation into the dynamics of wave runup on high-energy dissipative beaches. Combining historical wave, tide, and beach morphology records allows predictions of the relative frequency of occurrence of sea cliff or dune erosion. Model results have been shown to agree well with qualitative field observations. As more field data is collected the model will be applied to the entire littoral cell.

A major factor causing extreme measured tides is the occurrence of an El Niño such as the 1997/98 event occurring during the writing of this paper. Monthly mean water levels during autumn of 1997 were some of the highest on record, on the order of 0.15 m above normal. Wave conditions are also typically more intense during strong El Niño events. The monthly mean significant wave height for December 1997 was 3.8 m and the mean wave period was 12.4 s. A typical December has a mean wave height of 3.0 m with a period of 11.7 s. This increase in wave energy results in an increase in wave runup, which has been calculated to have been 0.24 m higher than usual for the month of December. Therefore, with the combined effects of both higher tides and higher wave runup, the total water level was 0.35 m higher than average for December. Elevated water levels greatly increase the potential for erosion, and, in fact, severe erosion has been observed at a number of sites throughout the Columbia River littoral cell during this winter.

Acknowledgements

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