State of Oregon
Department of Geology and Mineral Industries
Vicki S. McConnell, State Geologist

Open-File Report

OFR O-05-08

MORPHOLOGIES OF BEACHES AND DUNES ON THE OREGON COAST, WITH TESTS OF THE GEOMETRIC DUNE-EROSION MODEL

By

Jonathan C. Allan[1] and Paul D. Komar[2]

2005

[1]Oregon Department of Geology and Mineral Industries, Coastal Field Office, 313 SW Second Street, Suite D, Newport, OR 97365
[2]Consulting Oceanographer, 3520 NW Elmwood Drive, Corvallis, OR 97331

NOTICE

The Oregon Department of Geology and Mineral Industries is publishing this paper because the information furthers the mission of the Department. To facilitate timely distribution of the information, this report is published as received from the authors and has not been edited to our usual standards.

Oregon Department of Geology and Mineral Industries Open File Report
Published in conformance with ORS 516.030

For copies of this publication or other information about Oregon's geology and natural resources, contact:

Nature of the Northwest Information Center
800 NE Oregon Street #5
Portland, Oregon 97232
(503) 872-2750
http://www.naturenw.org

CONTENTS

LIST OF FIGURES

(List of Figures, continued)

LIST OF TABLES

1.0 STUDY OBJECTIVE

The objective of this study is to analyze beach survey data collected along the Oregon coast to respond to tasks required for developing and testing a dune-erosion model to be used by the Federal Emergency Management Agency (FEMA) to assess the susceptibilities of shore-front properties to erosion and flooding by ocean processes. The specific tasks of concern in this report include:

- Review the processes of waves and tides responsible for dune erosion along the Oregon coast;
- Compile surveys of the morphologies (elevations and slopes) of eroded beach profiles required in tests of the geometric dune-erosion model that is under consideration by FEMA in its methodology for the U.S. West Coast;
- Establish the configuration of the maximum eroded profile required in applications of the geometric dune-erosion model;
- Compile and analyze survey data for the main variables contained in the geometric model, namely, the beach slope immediately in front of the dunes and the elevation of the beach-dune junction;
- Directly test the proposed geometric dune-erosion model at foredune sites along the Oregon coast.

This report is limited to analyses of sites where the foredunes are fronted by a sand beach, the condition for which the geometric dune-erosion model was formulated (Komar and others, 1999). Several of our studies on the Oregon coast have involved collection and analysis of beach profiles. Foremost is the study of Allan and Priest (2001) to establish hazard zones (or setback lines) along the dune and bluff backed shores of Tillamook County. Included in that study was the extensive use of light detection and ranging (LIDAR) survey data collected in April 1998 to measure beach and dune profiles, used to derive the beach slopes and beach-dune junction elevations required in application of the geometric dune-erosion model. That application was based primarily on "design" storm conditions that included processes acting in the long term, the rise in sea level expected during the next 50 to 100 years, increases in wave-swash runup elevations due to the documented increase in deep-water wave heights and periods off the Oregon coast, and even the potential for a subduction earthquake that could result in an abrupt 1- to 2-m subsidence of the coast. As a result, our assessed setbacks based on the geometric dune-erosion model are greater than the erosion and flooding zones of interest to FEMA, which include only the impacts of short-term processes, those associated with individual major storms or the cumulative impacts of a series of storms.

The objective and tasks of this study as related to tests of the FEMA methodology are met through reanalyses of the Tillamook County beach profile data. While part of the required data is already available from our earlier report (Allan and Priest, 2001), specifically values of beach slopes and beach-dune junction elevations derived from the 1998 LIDAR surveys, additional analyses will be undertaken to include comparisons with the LIDAR surveys of 1997 and 2002 in order to examine the morphologies of the beach profiles and the degree to which they are uniform in slope as assumed by the geometric model, the extent to which they vary along the coast, and ultimately to determine the condition of the "maximum eroded profile" to be employed in the FEMA methodology.

This report begins with a review of the setting and erosion processes experienced along the Oregon coast, particularly those related to the cycles of erosion and reformation of the foredunes. A brief summary is then presented describing the geometric dune-erosion model that is to be compared with the beach and dune profiles. The primary scope of this report involves a presentation of the results of our analyses, which includes a variety of comparisons between the survey data and the dune erosion model, directed toward the above list of tasks.

2.0 THE OREGON COAST: SETTING AND EROSION PROCESSES

There are advantages in undertaking the tests of the geometric dune-erosion model on the Oregon coast. It represents a high energy environment, with winter storms generating deep-water significant wave heights in the range of 10 to 14 meters. Furthermore, there is a considerable variation in the Oregon coast as it consists of a series of "pocket-beach" littoral cells where stretches of beach tens of kilometers in length are separated and largely isolated by large rocky headlands (Komar, 1997). Some cells having abundant sand, while others are sand starved with limited buffering of the backshore properties, so each littoral cell can serve as an individual test of the dune-erosion model.

Isolated from one another by headlands, the littoral cells along the Oregon coast have individual sediment budgets in terms of the quantities and grain sizes of sand supplied to the beaches. Nearly all cells contain stretches of shore where foredunes back the beaches, as well as areas of wave-eroded sea cliffs. The intensity of erosion varies from cell to cell, in large part due to the width and sand volume in the fronting beach, determined by the sand availability to that particular cell. The beaches range from fine sand to coarse sand (with some granules and pebbles), again depending on the sediment sources, with accompanying wide ranges of beach slopes and morphodynamics of the beaches in response to storms; the beaches demonstrate the full range from "dissipative" to "reflective" beach types in the morphodynamics classification of Wright and Short (1983). Within this range, most beaches have median grain sizes on the order of 0.2 mm, which under the high wave conditions of the Oregon coast results in low beach slopes typically on the order of 0.04 (1 in 25) with very wide surf zones, that is, they have fully dissipative morphodynamic conditions. A few littoral cells have sediment sources that include coarse sand, gravel, and even cobbles. Finally, there are different degrees of human developments in the several littoral cells, ranging from minimal alterations from the natural conditions to cells where jetties have been constructed on tidal inlets and homes have been built in foredunes. This range in the level of development has also determined the extent of use of shore protection structures, primarily riprap revetments.

Considerable erosion along the Oregon coast has occurred in recent years in response to the strong El Niños in 1982-83 and 1997-98 (Komar, 1986, 1998; Komar and others, 2000) and the winter of 1998-99, when there were four major storms having deep-water significant wave heights in excess of 10 meters, which as of 1996 had been projected to be the 100-year storm event; that extreme event is now projected to yield 15- to 16-m significant wave heights (Allan and Komar, 2001). Due to the unusual severity of these storms, the heights of their generated waves, and the extent of the resulting erosion impacts, we undertook detailed analyses of their characteristics (Allan and Komar, 2002). We then applied the model of Ruggiero and others (1996, 2001), diagrammed in Figure 1, to analyze the summation of the measured tides and calculated runup levels of the waves at the shore, to determine the total water levels that produced the erosion. The calculation of the runup (including setup) is based on the empirical relationship

$$R_{2\%} = 0.27(SH_\infty L_\infty)^{½} = 0.11g^{½}S^{½}H_\infty^{½}T \qquad (1)$$

where S is the beach slope, H_∞ is the deep-water significant wave height, and L_∞ is the deep-water wave length that depends on the wave period T. The calculated vertical component of the runup, $R_{2\%}$, represents the 2% exceedence elevation. This relationship was established by Ruggiero and others (2001) on the basis of runup measurements on the Oregon coast together with data collected by Holman and Sallenger (1985) at the Field Research Facility in Duck, North Carolina.

Examples of the analyses for the series of storms are presented in Figures 2 and 3, respectively for the most severe storm during the 1997-98 El Niño winter and the particularly extreme storm on March 2-3, 1999; analyses are included for both the Oregon and Washington coasts, since the results differ somewhat due to the tracks taken by the storms. Note that the elevations in Figures 2 and 3 are relative to

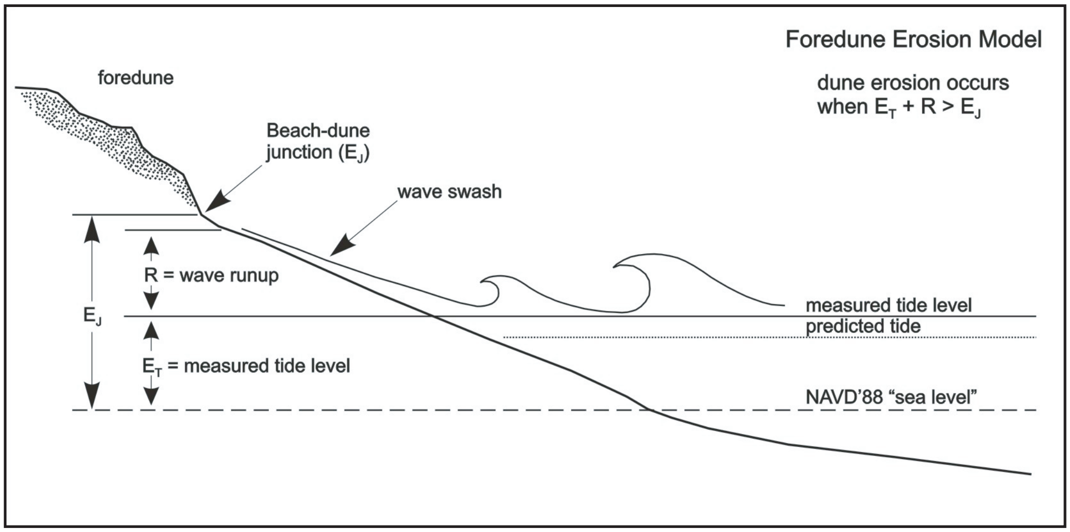

Figure 1. Assessment of the processes contributing to the total water level at the shore, the tides (E_T) plus the wave-swash runup ($R_{2\%}$), compared with the beach-dune junction elevation, E_j, that determines occurrences of dune erosion (after Ruggiero and others, 2001).

the National Geodetic Vertical Datum of 1929 (NGVD29) datum; to determine the North American Vertical Datum of 1988 (NAVD88) datum, add 1.0 meter to the values.

The analysis results for the five storms having deep-water significant wave heights greater than 10 meters during the 1997-98 and 1998-99 winters are summarized in Table 1 in terms of the wave breaker heights on the coasts calculated from the measured deep-water wave heights and period, the swash runup levels on the beach calculated from equation (1) for a beach slope $S = 0.04$, the increase in the measured tide above its predicted value. This enhanced level of the tide cannot strictly be equated to the storm surge since the monthly mean water elevations were already elevated independent of the storm occurrences. This was especially the case during the 1997-98 El Niño when the mean water level had been elevated by 0.40 meter along the Oregon coast at the time of the November 1997 storm due to warm water temperatures, etc., so the actual storm surge of that event was actually only 0.41 meter. In the most extreme storm, that on March 2-3, 1999, the storm surge measured on the Oregon coast by the Yaquina Bay tide gauge was 0.48 meter, while it reached 1.59 meters on the Washington coast (the Toke Point gauge in Willapa Bay) which was closer to the track of that storm (Allan and Komar, 2002).

Most important in Table 1 are the maximum total water elevations of the measured tide plus the runup as determined in analyses like those in Figures 2 and 3. This includes the predicted tide as well as the enhanced water levels that include the storm surge, and this addition of the tide makes the total water level relative to an elevation datum. Here we have used the NAVD88 datum, which will be employed throughout the remainder of this report. These total water levels are of special interest in that they are used in the geometric dune-erosion model to predict the potential extent of the resulting dune erosion during a storm. In that context, we have undertaken an extreme-value analysis of the total water levels, the measured tide plus the swash runup, with the results placing the El Niño storm of 19-20 November 1997 as representing only a 1- to 2-year event, while the major storm of the following winter on March 2-3, 1999 was somewhere in the range of having been a 25- to 50-year event.

While these extreme-value assessments are only very approximate, their relative values correspond to the degrees of dune erosion experienced along

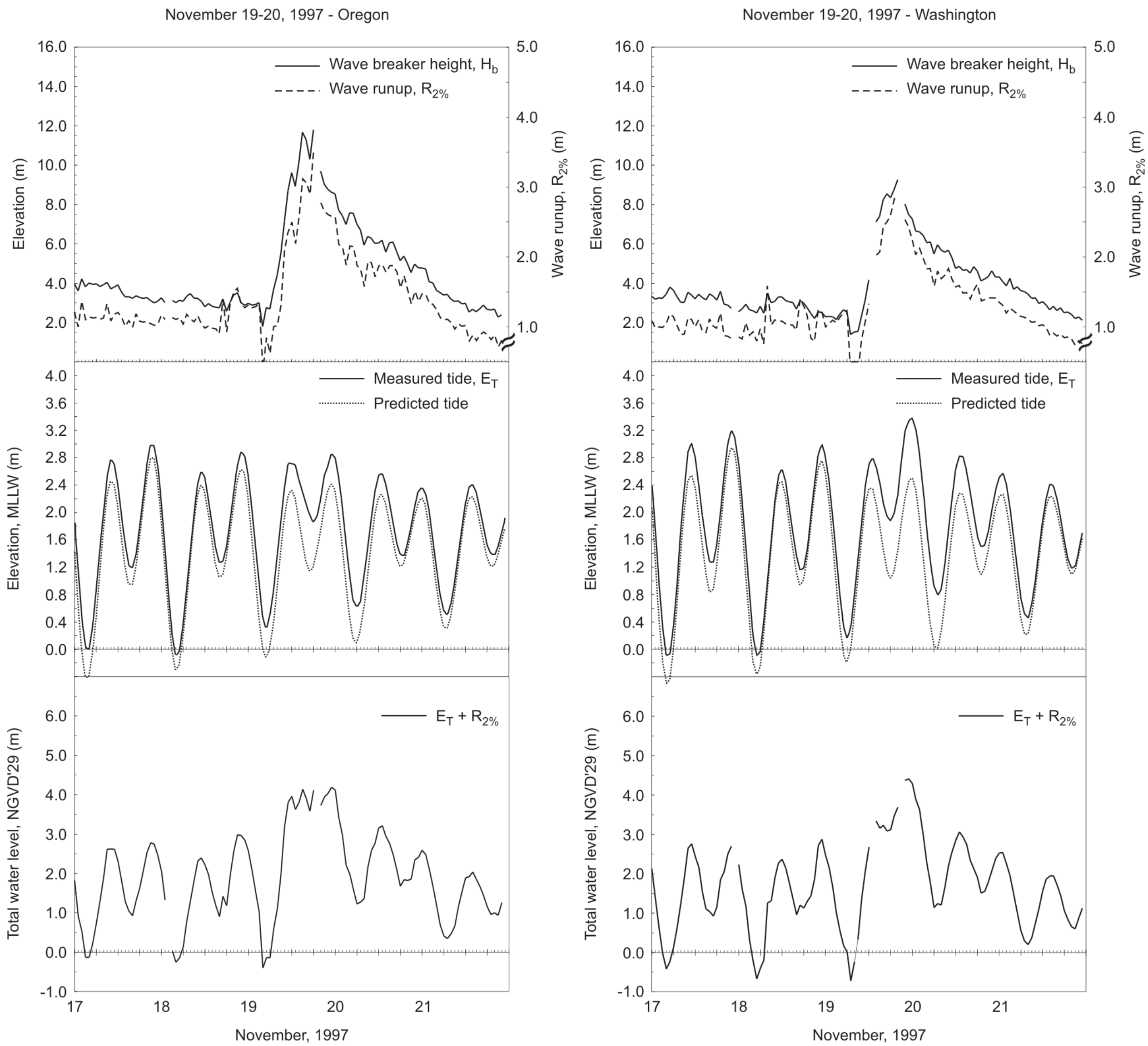

Figure 2. Analyses of the November 19-20, 1997 storm, the most severe of the 1997-98 El Niño winter (from Allan and Komar, 2002).

the Oregon and Washington coasts during those two winters. While there was some dune erosion along the coast during the 1997-98 El Niño winter that can be associated with the total water levels of the storm listed in Table 1, most of the dune losses occurred in hot-spot erosion sites north of headlands and jetties, produced by the northward movement of the beach sand within the littoral cells as a result of the southwest approach of the storm waves, this being typical of El Niño years (see the discussion of the El Niño-related processes in our separate report (Komar and Allan [2004]). With the total water levels achieved by the storms during the winter of 1998-99 having been significantly greater (Table 1), there was more extensive dune erosion along nearly the entire north Oregon and Washington coasts, not just in the hot-spot zones as occurred during the El Niño winter. Thus, the erosion of the dunes was cumulative under the "one-two punch" of the 1997-98 El Niño and the series of major storms during the winter of 1998-99 (a mild La Niña). Furthermore, the dune erosion culminated with the last storm in the series,

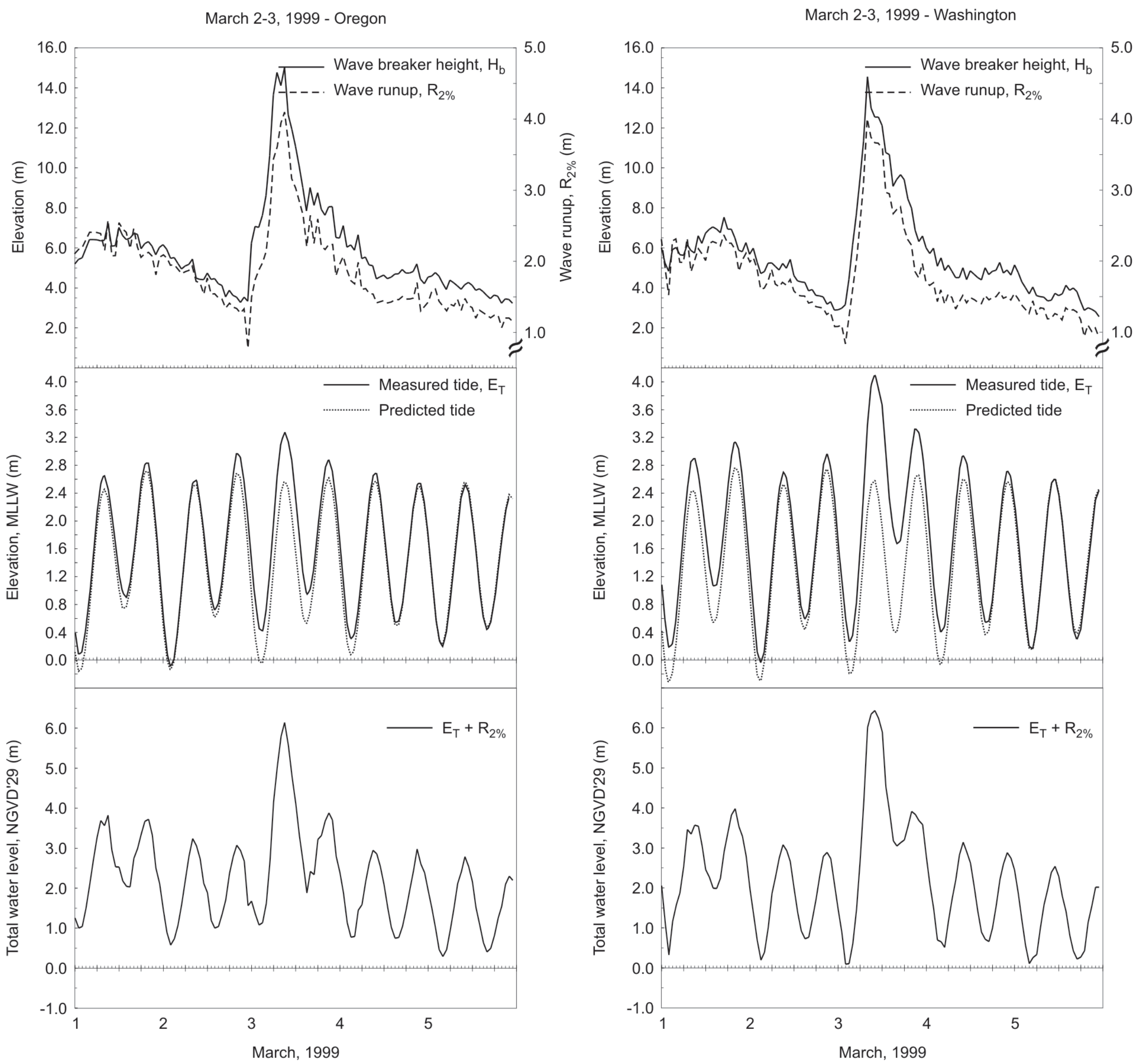

Figure 3. Analyses of the March 2-3, 1999 storm, the last and most extreme in the series of storms (from Allan and Komar, 2002).

that on March 2-3, 1999. This is the general pattern of dune erosion on the Pacific Northwest coast, where it is the product of multiple storms during one winter or spanning two to three years. Storms have their greatest impacts if they occur late in the winter season, after the beaches have reached their lowest elevations in their seasonal profile cycles. This was the case during the severe winter of 1998-99, when three of the four major storms occurred in February to early March (Table 1).

While the erosion experienced during those recent winters provides evidence for the potential dune retreat at the time of a 100-year event, the “design” condition, they fall short of that extreme. Our extreme-value analysis of the total water elevation predicts that the 100-year event would reach 7.9 meters NAVD88 for the Pacific Northwest. This is only marginally higher than the March 2-3, 1999 storm, which occurred at the time of a relatively moderate predicted tide. More realistically, we believe that the extreme “design” condition to

Table 1. Process-factors of the major storms during the 1997-98 El Niño and the winter of 1998-99, when four extreme storms occurred (from Allan and Komar, 2002).

Storm Date	Breaker Height (m)	Runup Level (m)	Elevated Tide (m)	Tdie + Runup, NAVD88 (m)
Oregon				
Nov. 19-20, 1997	11.8	3.5	0.81	5.2
Nov. 25-26, 1998	11.3	3.5	0.82	5.5
Feb. 6-7, 1999	10.8	3.0	0.66	5.3
Feb. 16-17, 1999	12.9	4.3	0.46	7.2
March 2-3, 1999	15.0	4.1	0.76	7.1
Washington				
Nov. 19-20, 1997	9.3	2.8	0.98	5.4
Nov. 25-26, 1998	10.8	3.1	1.15	5.5
Feb. 6-7, 1999	9.3	2.6	0.95	5.4
Feb. 16-17, 1999	12.7	4.2	0.82	6.6
March 2-3, 1999	14.6	4.0	1.76	7.4

assess a major occurrence of dune erosion should be represented by a still higher total water level. As reviewed by Komar and others (2002), we have developed various scenarios to represent the extreme erosion event, to be utilized in management applications. When we wrote that paper we were under the impression that the most extreme storms reaching the Pacific Northwest occur during non-El Niño years, their impacts assumed to be weakened during El Niños at these higher latitudes due to the more southerly tracks of the storms. Our more recent research has shown that El Niños actually increase wave heights along the coast of the Pacific Northwest in spite of the more southerly tracks of the storms (Allan and Komar, in press), although the increase is not as great as experienced in southern California. Our scenario 3 presented in Komar and others (2002) represented the "worst case" event when a major storm does occur during an El Niño winter, which we now recognize as having a higher probability of occurrence than thought at the time of that publication. The water level factors for that scenario are:

Predicted Tide	2.30 m NAVD88
Monthly Mean Water Level	0.50 m
Storm Surge	0.70 m
Wave Runup, $R_{2\%}$	5.11 m
TOTAL WATER LEVEL	8.61 m NAVD88

The total measured high tide comes to 3.50 meters NAVD88, which according to our analyses represents a 100-year extreme measured tide. In spite of its supposed low probability of occurrence, the tide-level factors selected in this Scenario seem reasonable in that the event represents a medium-high predicted tide occurring during an El Niño when the monthly averaged mean water level is increased by 0.50 meter as it was during the 1982-83 and 1997-98 events (Komar and Allan, 2004). The $R_{2\%}$ = 5.11 meters runup value is that for the 25-year storm event; the runup for the 100-year storm is calculated to be 5.58 meters. As discussed above, the storm surge during the March 2-3, 1999 storm reached 1.59 meters on the Washington coast, so the 0.7 meter value chosen in this Scenario is again modest, representing something on the order of a 25-year storm. In developing this Scenario we endeavored to adopt reasonable process components, maintaining the total close to a 100-year occurrence but without actually having undertaken a detailed joint probability analysis. It is seen that in this Scenario for the extreme design event, the total water level achieved by the tide plus the storm-wave runup is about 1 meter higher than that achieved during the March 2-3, 1999 storm (Table 1).

Since the major beach and dune erosion under the combined impacts of the 1997-98 El Niño and the series of storms in the winter of 1998-99, the subsequent winters have been relatively mild with smaller wave conditions that have resulted in generally little dune erosion. The beaches therefore began to achieve accreted profiles, and there has been some dune rebuilding as winds have blown sand from the beach into the backshore. This is an active process on the Oregon coast, where even during the few months following an episode of significant dune erosion the rebuilding begins. The sand in the vertical scarp of an eroded dune dries and slumps forward onto the beach, and the summer winds carry sand from the dry beach berm to the foot of the dune, quickly developing incipient dunes in front of the older, higher dune. From past experience it can be expected that the eroded dunes will eventually be restored by the natural processes, unless another winter of severe erosion interrupts the cycle.

In most areas of the Oregon coast there is minimal net long-term change in the beaches and dunes, in part because there are essentially no gains or losses of sand volumes within the littoral cells to produce progressive trends, and also due to the tectonic rise of the coast that to varying degrees offsets the erosion that would result from the global rise in sea level (Komar, 1997; Allan and others, 2003). With essentially fixed quantities of sand within the littoral cells, the dominant change is the cycle of sand movement between the beaches and dunes — dune erosion during a winter of major storms, followed by years to decades of dune reformation until they build out to their former extent. For this reason a primary focus of management on the Oregon coast has been to establish setback distances in the foredunes so that new homes are placed landward from the range in the cycle between dune retreat during major storms and the reformed dunes. Accordingly, we developed the geometric dune-erosion model having the objective of estimating the maximum potential extent of dune retreat in response to a series of storms that collectively would represent the 50 to 100-year occurrence.

3.0 THE DUNE EROSION MODEL

The geometric dune-erosion model was developed to place the establishment of hazard zones or setback lines in foredunes on a more rational basis in that it depends on the actual processes of dune erosion (Komar and others, 1999). As developed, its main application was intended for the Oregon coast, but was expected to be applicable with some modification to much of the U.S. West Coast. In Oregon the previously established setback lines were often arbitrary, at best based on the morphology and vegetation cover of the dunes, with no reference to the erosion processes, especially the extreme events that might occur only once in 50 to 100 years, representing the primary threat to developments in foredunes.

In searching for an improved methodology to assess the potential extent of maximum dune erosion, we explored the use of numerical beach and dune erosion models developed by coastal scientists and engineers. These included an early version of EBEACH (Kriebel and Dean, 1985), the SBEACH model of the U.S. Army Corps of Engineers (Larson and Kraus, 1989), and the COSMOS model developed in England (Nairn and Southgate, 1993), representative of the most sophisticated process-based models being developed in Europe and Japan. None of these models proved to be adequate in applications on the Oregon coast, as they significantly underpredicted beach profile responses and especially the extent of dune erosion during storms. This poor performance of the numerical models was attributed to their having been developed and tested under much different conditions than found on the high-energy Oregon coast with its low-sloping dissipative beaches. Even the most sophisticated model, COSMOS, did not include nearshore processes important on the U.S. West Coast, the foremost being the major component of infragravity energy, the energy at periods greater than the 20-s periods of the incident ocean waves. This infragravity energy dominates the inner surf zone of dissipative beaches along the West Coast, and is especially important to swash runup elevations and intensities, so without its inclusion in the numerical models it is not surprising that they under-evaluated the beach responses and extent of dune erosion.

Lacking a methodology to rationally establish setbacks in foredunes on the Oregon coast, we formulated the geometric dune-erosion model to estimate the potential extent of dune retreat that could threaten developments under extreme storm conditions (Komar and others, 1999). There are two stages in this methodology, the first to determine the "design" erosion event, the second applying the geometric model to evaluate the potential dune erosion during that event. The design event has been discussed above, developed in the form of a Scenario to project the potential extreme total water elevation having the 1% occurrence probability.

Having defined the design erosion event, the next step in our methodology to establish setback distances on the Oregon coast has been the application of the geometric dune-erosion model developed to conform with the erosion processes. Our model is conceptually similar to the Bruun geometric model that analyzes the beach erosion and shoreline retreat under the long-term rise in sea level, but is more closely similar to that of Edelman (1968, 1972) formulated to assess the potential dune retreat on the coast of the Netherlands due to elevated storm surges in the North Sea. Storm surges are much less important on the Oregon coast, and as seen in the "design" Scenario presented above, it is the combination of the tide plus wave runup that produces the erosion. Our methodology developed for application on the Oregon coast also differs from the present Dutch approach established by the later revisions of Vellinga (1982, 1983), which through laboratory tests empirically accounts for the movement of the eroded dune sand across the surf zone and the resulting delay in the dune erosion behind the causative processes. Without an inclusion of this erosion delay, it is apparent that the model analysis on the Oregon coast will represent the maximum potential erosion, which might be achieved only with a series of storms, any one storm not having sufficient duration to produce the projected maximum dune erosion derived from the geometric model.

The geometric dune-erosion model derived for application to the Oregon coast is depicted in Figure 4. With this specific application the conditions include (1) most beaches will be dissipative as defined in the classification of Wright and Short (1983) and

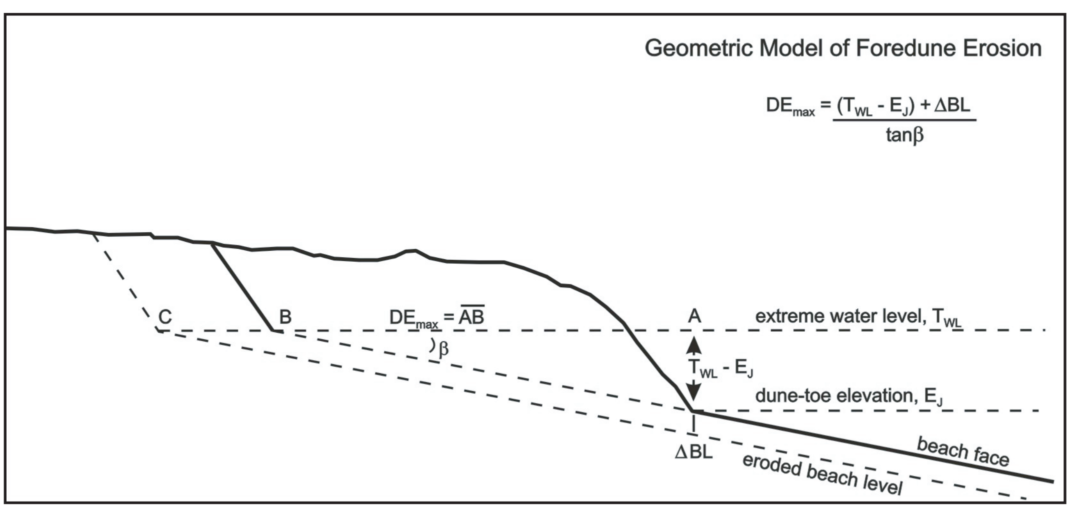

Figure 4. Geometric model used to assess the maximum potential dune erosion, DE_{max}, in response to a storm that produces an extreme total water level, T_{WL} (after Komar and others, 1999).

therefore do not experience marked changes in sand levels during a single storm event, although there will be a summer to winter cycle in beach elevations; (2) during major storms the surf zones are hundreds of meters wide and the waves and currents rapidly disperse the sand eroded from the dunes; and (3) the beach face within the swash zone at the base of the dunes has a nearly uniform slope (typically about 1 in 25), which is maintained and extended landward as the dunes are eroded. These observed conditions made possible the formulation of a simple geometric model (Komar and others, 1999). Like the Dutch models, it is accepted that the cut back of the dunes will occur at the level reached by the water, the total water level as analyzed by the Ruggiero and others (2001) process model in Figure 1 and given in the Scenario presented above. Unlike the Dutch models, our model is not concerned with the conservation of sand since the sand released by the dune erosion is assumed to rapidly disperse rather than raising the elevation of the beach in front of the dune. Quite the opposite, our geometric model includes a factor that accounts for the local lowering of the beach face (ΔBL in Figure 4) in that embayments eroded by rip currents have been observed to be important to the zones of maximum dune erosion, and therefore could be included in the analysis.

In that the level of a Pacific Northwest beach within the inner surf zone undergoes little change during the erosion event, the geometric analysis simply extends that slope landward as depicted in Figure 4, cutting away the dunes up to the total water-level elevation established by the design storm event. Accordingly, the derivation yields the simple relationship

$$DE_{max} = \frac{(T_{WL} - E_j) + \Delta \mathrm{BL}}{S} \tag{2}$$

for the horizontal distance of dune erosion, DE_{max}, where T_{WL} is the total water level achieved by the design event relative to the elevation of the toe of the dunes prior to the erosion, E_j, with ΔBL being a possible change in the beach face elevation produced by a rip-current embayment or general beach face erosion during the storm. The dune retreat DE_{max} forms the horizontal leg of a right triangle, while the other parameters combine to determine its vertical leg, so they are related by $S = \tan \beta$, the slope of the beach face within the swash zone fronting the dunes.

The application of equation (2) is sensitive to the value of the beach-dune junction, E_j, and the beach slope, S. These data have been evaluated based on surveyed beach and dune profiles derived from LIDAR data (Allan and Priest, 2001), and have been expanded to include the 1997 and 2002 LIDAR data sets for the purposes of this report. As will be demonstrated by the test results presented in section 5 of this report, this approach to establish E_j is difficult and often subjective. McDougal and MacArthur (2004) have proposed that this elevation instead be based on the annual total water levels evaluated with the Ruggiero and others (2001) model, Figure 1, such that E_j in equation (2) is replaced by the 1-year recurrence of the water level while T_{WL} is the 100-year recurrence level. This suggestion will be tested in section 5 for the littoral cells in Tillamook County. In that by coincidence the November 19-20, 1998 storm of the El Niño winter was a 1- to 2-year event, the 5.2- to 5.4-m NAVD88 total water levels (Table 1) of that storm should correspond to the beach-dune junction elevations, E_j, seen on the April 1998 LIDAR surveyed profiles analyzed in section 5.

Although based on direct observations of dune erosion experienced on the Oregon coast, the geometric model and the prediction of the dune retreat with equation (2) has undergone minimal previous testing. The absence of testing was due to the lack of funds — in the late 1990s, Oregon Sea Grant devoted all its research funds to fisheries; the timing was unfortunate, as the Oregon coast had just entered the period of greatest erosion impacts experienced in at least the past half century. The “double whammy” of the 1997-98 El Niño followed by the 1998-99 winter with its series of extreme storms would have provided a suitable test of the model. Without the funds to undertake the necessary extensive program of ground surveys for a satisfactory test of the model, profiles were collected at only a few sites and were limited to before and after the two winters, reflecting the cumulative erosion but not permitting detailed documentations storm by storm. We were able to confirm that the calculated total water level, T_{WL}, during the last and most extreme storm, that on March 2-3, 1999, showed reasonable agreement with the surveyed elevations of the eroded dune scarps. As well as providing confirmation of the methodology used by Ruggiero and others (1996, 2001) to determine the water level T_{WL}, this agreement also represented partial confirmation of the geometric dune-erosion model in that a basic assumption in its derivation was that the total water level controls the elevation at which the dunes are cut back, just as in the Dutch geometric models. However, as expected, it was found that the surveyed horizontal retreat of the dunes was less than the calculated DE_{max} from the model, but too few profiles were available for analysis to establish the degree of over-prediction.

In spite of the lack of sufficient testing, the geometric model has been used to establish hazard zones or setback lines on the Oregon coast. The reality is that at present there is no rational alternative available. An important advantage of the model has been its simplicity, easy to use in coastal management applications with minimal training required; its chief shortcoming is equally its simplicity, not accounting for important factors such as limited durations of the storms and the delayed response of the dune retreat behind the erosion processes. More extensive testing of the model is required, possibly leading to revisions that will improve its predictions of potential dune erosion during extreme events.

4.0 SURVEY METHODS AND PROFILE DATA

The tasks of the present study related to tests of the FEMA methodology are met primarily by analyses presented below of the Tillamook County beach profile data originally collected by Allan and Priest (2001) for the establishment of hazard zones/setback lines utilizing the geometric dune-erosion model. With the analyses being county wide and therefore including many kilometers of the coast, the only practical means to obtain beach profiles required in this application was to derive them from the LIDAR surveys undertaken jointly by the U.S. Geological Survey (USGS), National Aeronautics and Space Administration (NASA), and National Oceanographic and Atmospheric Administration (NOAA), with the data available on NOAA's Coastal Services Center web site (http://www.csc.noaa.gov/crs/tcm/index.html). The LIDAR data consist of *x*, *y*, and *z* values of the beach topography derived using a laser ranging system mounted on board a De Havilland Twin Otter aircraft which flies at an altitude of approximately 700 meters at a speed of about 60 m/sec. The flight path follows the shore, measuring a beach elevation at approximately every square meter of ground surface, within a swath that is about 350 meters wide. On the wide beaches typical of the Oregon coast, normally two flights are made in rapid succession, with a degree of overlap of the surveyed swaths. Taken together, the surveys include a portion of the inshore area of dunes and sea cliffs, as well as the dry beach. The LIDAR technology does not operate at wave lengths that penetrate into the water, so the flights are undertaken close to low tide to maximize the area of the beach survey. In most cases the survey data still need to be truncated in the offshore direction in order to avoid the mistaken inclusion of the varying water surface. Similar systems (e.g., SHOALS) can penetrate into the water to continue the offshore profiles to several meters water depth, but they require clear water devoid of air bubbles created by the surf, which would prohibit their use on the Oregon coast. In the onshore direction, the laser-measured elevations are affected by ground vegetation, and in the case of foredunes this might be expected to produce anomalous high elevations, on the order of 10–50 cm, the typical growth height of European dune grass which covers most of the Oregon dunes.

Several studies have been completed to verify the data collected by LIDAR surveys in terms of the accuracy of their horizontal positions and especially of the recorded elevations. The first of these were the studies of Krabill and others (1995, 1999) in connection with LIDAR surveys of the Greenland glaciers to determine whether they are melting due to global warming; they found a horizontal accuracy better than ±1.50 meter and vertical accuracy of ±0.15 meter. Sallenger and others (2003) undertook comparisons between LIDAR surveys of beaches and those obtained with modern ground-based measurement systems that included (1) a differential global positioning system (GPS) equipped all-terrain vehicle and (2) a GPS antenna mounted on a stadia rod. The comparisons were undertaken at the Field Research Facility in Duck, North Carolina. The results where much the same as found by Krabill and others (1995, 1999). The root-mean-square differences associated with the LIDAR compared with the ground survey measurements ranged from 0.13 to 0.19 meter, with 0.15 meter representing all of the intercomparisons. This root-mean-square error represents a total error for individual elevation estimates, including uncertainties associated with random and mean errors, the latter being the largest source of error that was attributed to drift in the differential GPS.

LIDAR survey data have also been compared with ground surveys on the beaches of the Pacific Northwest, specifically in the Columbia River Littoral Cell as part of the joint study of that cell by the USGS and Washington's Department of Ecology. This littoral cell has a total beach length of 165 km, with most of that length being north along the Washington coast to Point Grenville, extending for about 30 km south along the Oregon coast to Tillamook Head. This study included an extensive program of monitoring the beaches and dunes through quarterly ground surveys. Comparisons were made with the October 1997 and April 1998 LIDAR data from the USGS/NASA/NOAA survey flights to test the accuracy of the results. While these comparisons have not been published, Ruggiero (pers. comm., Aug. 2004) indicates that the agreement was very good; example comparisons can be viewed on the web site of NOAA's Coastal Service Center (http://www.csc.noaa.gov/beachmap/html/clammer.html).

Problems have been found with the LIDAR surveys in the analyses by Daniels (2001), undertaken as part of the Columbia River Littoral Cell study. He found that errors can be introduced when the WGS84 ellipsoid heights of the Earth's geoid initially utilized at the reference datum in the LIDAR surveys are transformed to a local survey datum such as NAVD 88, this conversion resulting in a systematic offset of the vertical elevations. In his specific application to the Columbia River Littoral Cell, he found a south-to-north trend in this error, 0.08 meter at the south end of the cell (at Seaside) to a maximum of 0.21 meter at the north end (Pacific Beach).

From this series of studies it appears that the uncertainties involved in the LIDAR surveys of beach and dune profiles should be viewed as being on the order of ±0.15 meter. This is acceptable in the tests of the geometric dune-erosion model using profile data from the LIDAR surveys, in view of the fact that the uncertainties in assessing the ocean processes are likely greater, specifically the values of the total water levels, T_{WL}, used in equation (2) for the geometric model.

LIDAR surveys were undertaken by the USGS/NOAA/NASA along much of the U.S. West Coast in September-October 1997, April 1998, and September 2002. The 1997 and 1998 pair of surveys were completed to bracket the El Niño winter of 1997-98, in order to document the beach responses to that major climate event. These October and April surveys respectively captured the beach morphologies and elevations at the end of the summer, just prior to the onset of winter storms, and then their morphologies at the end of the winter erosion period, the April 1998 surveys coming close to documenting the maximum extent of the El Niño induced erosion. It is unfortunate that additional LIDAR surveys were not flown in October 1998 and April 1999, at least in the Pacific Northwest, in that as related above that winter with four major storms proved to be more erosive coast wide, including the significant loss of foredunes. The third LIDAR survey in September 2002 was undertaken in anticipation of the occurrence of another major El Niño, but that event fizzled so a repeat survey was not completed the following spring. As noted above, the winters of 1999-2000 and 2000-2001 were fairly mild with few storms so there was minimal subsequent beach and dune erosion; therefore, to a degree the September 2002 LIDAR survey can document the extent of the dune erosion at the end of the highly erosive winter of 1998-99. But as will be seen in the analyses presented below, the primary morphologic change between the end of the erosion in 1999 and the next LIDAR survey in 2002 was some accretion of the beach and the initiation of dune reformation, with the accumulation of wind-blown sand in front of the wave-cut dune scarp formed during the 1997–1999 erosion period.

The LIDAR surveys have seen applications in studies that documented the impacts of the 1997-98 El Niño on West Coast beach morphologies, the intended objective of having undertaken those survey flights. Of particular interest has been a documentation of the northward shift of the beach sand within the littoral cells in response to the more southerly tracks of the El Niño storms. This northward displacement was first noticed on the Oregon coast during the major 1982-83 El Niño, such that beaches at the south ends of the littoral cells became depleted in sand, leading to "hot spot" erosion zones, with another zone of hot spot erosion located north of inlets due to their northward migrations in response to the strong wave arrival from the southwest (Komar, 1986).

The LIDAR surveys in September-October 1997 and April 1998, during the next major El Niño, with its ability to document the changes in beach elevations along the full lengths of the littoral cells, better demonstrated this northward displacement of the beach sand and resulting hot spot erosion. Such studies have been undertaken by Revell and others (2002) and Allan and others (2003) in the Netarts and Rockaway Littoral Cells on the northern Oregon coast, and by Sallenger and others (2002) on the central California coast south of San Francisco, accounting for the extreme bluff erosion at Pacifica. Revell and others undertook a detailed analysis of the beach elevation changes using the LIDAR data, to measure both the northward displacement of sand in that cell and the seasonal movement of sand from the dry berm to the offshore bars during that El Niño winter; they also documented the resulting hot spot erosion at the south end of the cell (at Cape Lookout State Park) and to the immediate north of the tidal inlet to Netarts Bay. Allan and others (2003) undertook additional analyses of the LIDAR data in the Netarts cell and demonstrated that the mean shoreline had eroded by some 20 m along the south end of the cell with the erosion progressively decreasing toward the north. In contrast, the north end of the cell showed accretion that ranged from 10 to 15 m. Allan and others (2003) also demonstrated the magnitude of the "hot spot" effect adjacent to the Tillamook and Nehalem jetties in the Rockaway littoral cell. Sallenger and others (2002) similarly found a northward displacement of sand on the beaches of central California, leading to lowered beach/bluff junction elevations in the hot spot zone at the south end of the littoral cell. They applied the model of Ruggiero and others (2001) to evaluate the frequency of wave attack of the bluff toe based on its elevation, and found a correlation with the LIDAR-measured distance of dune recession that winter. A more detailed review of these studies, and of El Niño processes in general, can be found in a separate report (Komar and Allan, 2004). In addition to theses applications of the LIDAR surveys in research examining the coastal impacts of a major El Niño, its extensive coverage along the West Coast has been important to studies undertaken to establish hazard zones or setback lines, with that of Allan and Priest (2001) in Tillamook County being a prime example.

5.0 ANALYSIS RESULTS — TILLAMOOK COUNTY

The tasks of this study related to testing the geometric dune-erosion model are being met by analyses of Tillamook County beach profile data derived from the LIDAR surveys. In our work for the County to assist them in establishing setback lines, the analyses were based entirely on the LIDAR survey of April 1998, with profiles extracted at 100-m intervals along the County's shore. In areas where the beach is backed by foredunes, we applied the geometric dune-erosion model, utilizing values of beach slopes and beach-dune junction elevations measured directly on those profiles (Allan and Priest, 2001). However, in the present study additional analyses are required, which includes profiles extracted from the October 1997 and September 2002 LIDAR surveys in order to make comparisons with the April 1998 surveyed profiles to document the extent of beach and dune erosion during the 1997-98 El Niño and in the winter of 1998-99. Of particular interest will be the distance of dune retreat and loss of dune-sand volumes that occurred between the April 1998 and September 2002 LIDAR surveys, reflecting the impacts of the major storms during the 1998-99 winter.

Our analyses also include examinations of the morphologies of beach profiles and the degrees to which they are uniform in slope as assumed by the geometric model, the elevations of the beach-dune junctions and how they compare with total water levels of storms listed in Table 1, and the extent to which these profile parameters used in equation (2) for the dune-erosion model vary along the shore. Ultimately of interest is the determination of the "maximum eroded winter profile," DE_{max}, to be employed in the geometric dune-erosion model as applied in the FEMA methodology.

The coast of Tillamook County contains four littoral cells, which from north to south are:

- Rockaway Littoral Cell (Cape Falcon to Cape Meares)
- Netarts Littoral Cell (Cape Meares to Cape Lookout)
- Sand Lake Littoral Cell (Cape Lookout to Cape Kiwanda)
- Neskowin Littoral Cell (Cape Kiwanda to Cascade Head)

The beach sand and beach-dune morphologies within these littoral cells are fairly typical of the Oregon coast, with the median grain size of the sand being approximately 0.2 mm (standard deviation = 0.037) (Peterson and others, 1994), resulting in very low beach slopes and wide surf zones, characteristic of "dissipative beaches" in the morphodynamics classification of Wright and Short (1983). In being the dominant beach type on the Oregon coast, as well as along the entire U.S. West Coast, this focus on the Tillamook beach and dune systems has strong relevance for establishing a FEMA methodology. Locally within these littoral cells the sand is coarser grained, for example in the community of Neskowin at the south end of the Neskowin Littoral Cell, where the beach is composed primarily of coarse sand to granules, with steeper beach slopes that places them in the "intermediate beach" category of the morphodynamics classification. Along some stretches of shore (e.g., south Netarts Spit) the sand beach is backed by a berm of gravel and cobbles — such beaches are not included in the analyses presented in this report. The longest stretches of shore where the beaches are backed by foredunes are found in the Rockaway and Neskowin Littoral Cells, so the primary focus of the analyses presented here is on the LIDAR surveys of those cells.

5.1 Examples of LIDAR Profiles and Documented Dune Erosion

The LIDAR surveys were used to construct beach and dune profiles at 100-m longshore increments, resulting in a very large number of profiles spanning the lengths of the four littoral cells in Tillamook County. Examples are shown in Figure 5 from the Rockaway Littoral Cell, with each site having profiles derived from the three LIDAR surveys. The Rockaway Cell can be considered as consisting of three sub-cells, separated by the jetties on the inlets to the Nehalem Estuary and Tillamook Bay. These jetties act as mini-headlands, so the three sub-cells have a degree of independence as observed in their beach-profile responses. From top to bottom in Figure 5, the three panels of profiles are from Nehalem Spit, Rockaway Beach, and Bayocean Spit.

As graphed in Figure 5, the profiles have a vertical exaggeration of 2.3, which increases the apparent slopes and heights of the foredunes. Even with this vertical exaggeration the beaches appear to be relatively flat, nearly uniform in their slopes, but with a small degree of concavity that would be accentuated by the vertical exaggeration. For each site it is seen that the series of three profiles from the LIDAR surveys document the progressive erosion of the foredunes. Between the October 1997 and April 1998 surveys, that is, during the El Niño winter, the primary erosion is seen to have occurred on the fronting beach, with relatively small losses having been experienced in the dunes. During that winter the beach elevations in these examples were lowered by 0.5 to 1.0 m, with about a 2.0-m lowering experienced in the 40 meters directly in front of the dunes on profile 190. Elevation decreases of 0.5 to 1.0 meter are typical of Oregon's dissipative beaches during the winter (Aguilar-Tuñon and Komar, 1978; Shih and Komar, 1994), so this extent of beach reduction can be considered as normal for the seasonal cycle. Some retreat of the dunes is seen to have occurred during that El Niño winter, creating near-vertical dune scarps up to 2-m height on profiles 80 and 190. This is also not unusual, especially in view of the fact that the October 1997 LIDAR survey appears to have recorded the beach and dunes in a very accreted condition, following several years of reduced storms. As discussed above, during such quite periods it is typical for sand to be blown landward from the beach and accumulate at the base of the older, more permanent dunes. This is reflected in the 1997 LIDAR profiles where it is difficult to establish where the dunes end and the beach begins; this is even the case when the sites are inspected in the field. The distinctions between the dunes and beaches are more readily apparent in the April 1998 LIDAR surveys at the end of the winter, after there had been some erosion including that produced by the major storm in November 1997 (Table 1). None of these profiles came from hot-spot zones of enhanced El Niño erosion, so do not reflect those localized more extreme impacted areas that are characteristic of El Niños (Komar and Allan, 2004).

It is apparent in the profiles in Figure 5 that a great deal more dune erosion occurred between the LIDAR surveyed profiles of April 1998 and September 2002. This erosion occurred during the winter of 1998-99 with its series of four major storms (Table 1). While the 2002 LIDAR survey documents the eroded positions of the foredunes, it is apparent that the fronting beaches are in the process of recovery from the storm induced erosion, having had three summers to acquire sand with the intervening winters having been relatively mild. On Nehalem and Bayocean Spits (profiles 80 and 250), the beach elevations have been raised to about their 1997 levels, and something of a berm had formed in front of the eroded dunes, having widths on the order of 25 to 50 meters. In that the wave-induced beach recovery would have been limited primarily to the lower beach, it may be that aeolian processes were again important to the formation of these berms, representing sand blown from the beach to the base of the dunes. On profile 190 from Rockaway, both the beach and dune for the 2002 survey are still in an eroded condition with low elevations. There is a definite change in the beach slope at about the 220-m cross-shore distance, so it is possible that the beach from that point to the base of the dunes represents the area of beach recovery, even though it is far from complete.

Profile series from three sites in the Neskowin Littoral Cell are shown in Figure 6. All three sites are located on Nestucca Spit toward the north end of the cell. The same trends of erosion are seen as those discussed above, with little loss of the dunes having occurred during the 1997-98 El Niño winter, but with significantly greater dune losses in the winter of 1998-99. Again, there is evidence for the ongoing recovery of the beach in the September 2002 survey.

There is a noticeable difference in the degree of dune erosion from site to site, seen in Figure 5 for the Rockaway Littoral Cell but especially in Figure 6 for the Neskowin Cell, with almost no erosion having occurred at profile 45 in contrast to that at profiles 40 and 50. We have not explored the cause of this variability as found in these LIDAR profiles, but past experience suggests that it is due to beach irregularities that are associated with the presence of rip currents and the embayments they cut into the beach. In particular, this has been an important control on the degree of erosion experienced on Nestucca Spit, the location of the profiles presented in Figure 6. There was a major occurrence of erosion on this spit by a storm in February 1978, and our investigation at that time found a considerable degree of alongshore variability in the extent of beach and dune erosion, and accompanying property losses, due to the presence of rip current embayments that accentuated the extent of the localized erosion (Komar, 1978). This likely also accounts for the variation from site to site seen in Figure 6 for Nestucca Spit and is a probable factor in the variability found at all sites along the Oregon coast (Komar, 1997).

In summary, the LIDAR profiles document the progress of the erosion, beginning in October 1997 when the beaches were in their summer conditions, having elevated profiles and with no dune erosion having recently occurred. The surveys the following spring, obtained in April 1998, show the result of the erosion during the El Niño winter, which mainly affected the beaches with only minor dune erosion. This erosion was limited, as the largest El Niño storm in November 1997 was only a 1- to 2-year event, with profiles from the zones of greater El Niño hot-spot erosion not having been included. The extent of retreat of the dunes was significantly greater as recorded in the September 2002 LIDAR survey, with that erosion undoubtedly having occurred during the winter of 1998-99 with its series of unusually severe storms, the March 2-3, 1999 storm having been a 25- to 50-year event. While the LIDAR survey of 2002 still documents the extent of the 1998-99 dune erosion, the fronting beaches have again achieved accreted summer profiles, so will be less useful in establishing the maximum eroded winter profile needed in application of the geometric dune-erosion model.

5.2 Beach Slopes and Beach-Dune Junction Elevations

The primary beach-profile parameters in equation (2) for application of the geometric dune-erosion model are the beach slope, $S = \tan \beta$, and beach-dune junction elevation, E_j (Figure 4). Values for these parameters have been extracted from the LIDAR profiles in the Tillamook littoral cells, and the results will be presented here. Of interest is the correspondence between the elevations measured on the profiles and evaluated total water levels of the November 1997 storm during the El Niño winter and the March 2-3, 1999 storm the following winter; those storms can be expected to have been responsible for the greatest degrees of dune erosion and determined the E_j elevations respectively in the April 1998 and September 2002 LIDAR profiles. Tillamook County is on the northern Oregon coast, so is roughly midway between the water-level assessments in Table 1 for the mid-Oregon coast and Washington. On that basis, interpolating between the Oregon and Washington listings for those storms, the total water levels on the Tillamook beaches would have been on the order of:

November 19-20, 1975	3 meters NAVD88
March 2-3, 1999	7.3 meters NAVD88

These water levels will be compared with the measured E_j values derived from the LIDAR surveys, but it needs to be borne in mind that there are uncertainties in those evaluated water levels and also in the E_j elevations from the LIDAR surveys as reviewed earlier.

Even with the vertical exaggeration of the profiles in Figures 5 and 6, they still appear to be nearly uniform in their slopes, with the small degree of concavity being accentuated by the vertical exaggeration. For the most part this near-uniformity confirms the assumption made in formulating the geometric dune-erosion model, that the beaches have reasonably uniform slopes. From the few examples in Figures 5 and 6 it appears that the degree of concavity is greater in the 1997 profiles than in the 1998 profiles; this is likely due to the accreted state of the 1997 profiles with some wind-transported sand having been deposited at the back of the beach, while the April 1998 profiles represent the eroded condition where the incipient dunes have been removed. In these few examples there is also an indication that the average slope of the beach decreases as the dune erosion progresses, being noticeable lower in the slopes of the 2002 profiles at the end of the period of extensive dune retreat. Unfortunately, as discussed above, the September 2002 profiles were in the process of recovering from the erosion that had occurred in 1999, so most of the profiles are irregular with distinct changes in slopes, which complicates

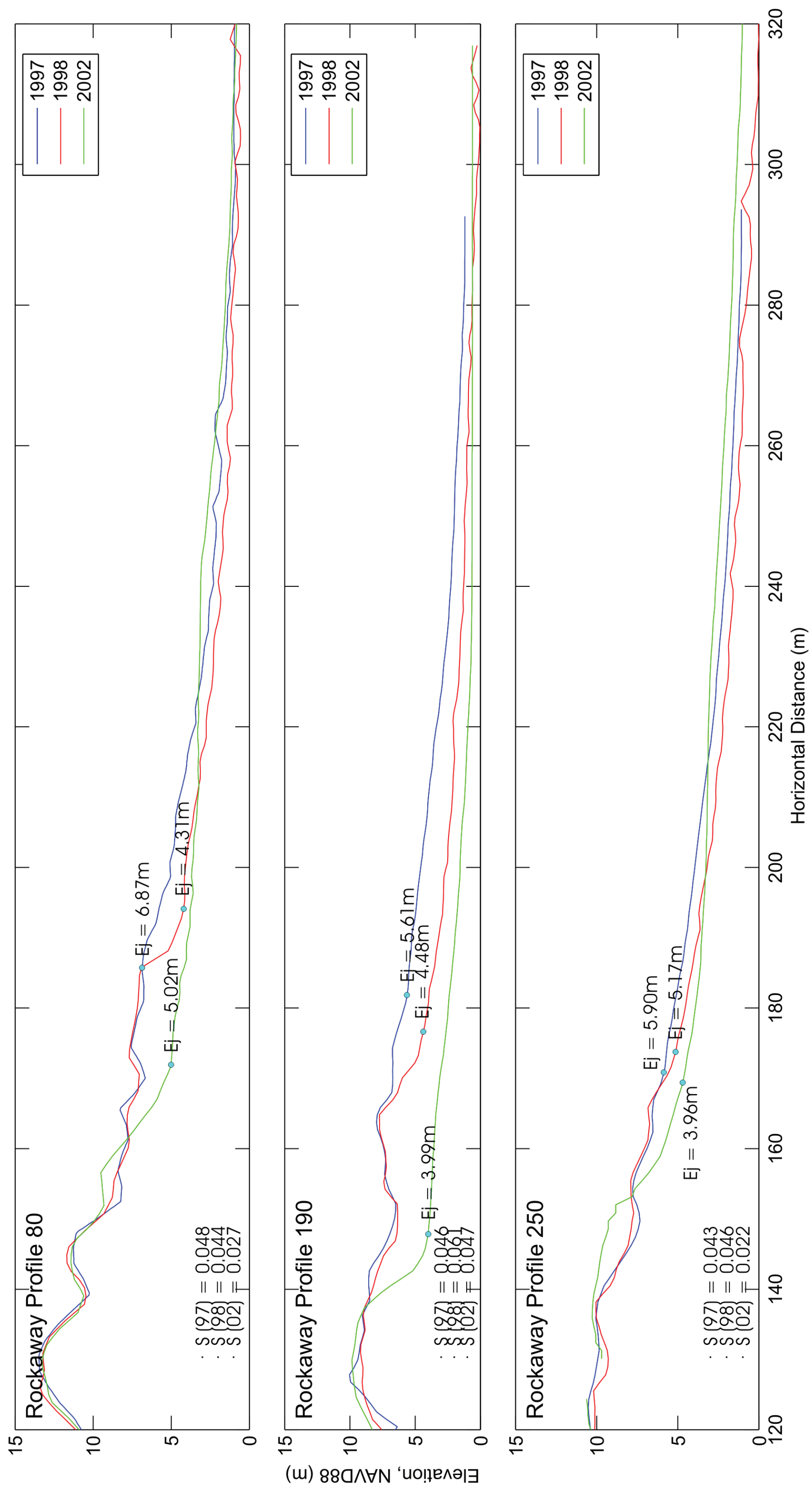

Figure 5. Beach and dune profiles from the Rockaway Littoral Cell, derived from the LIDAR surveys. The dots on the profiles are the identified beach-dune junction elevations, E_j. The vertical exaggeration of the profiles is 2.3.

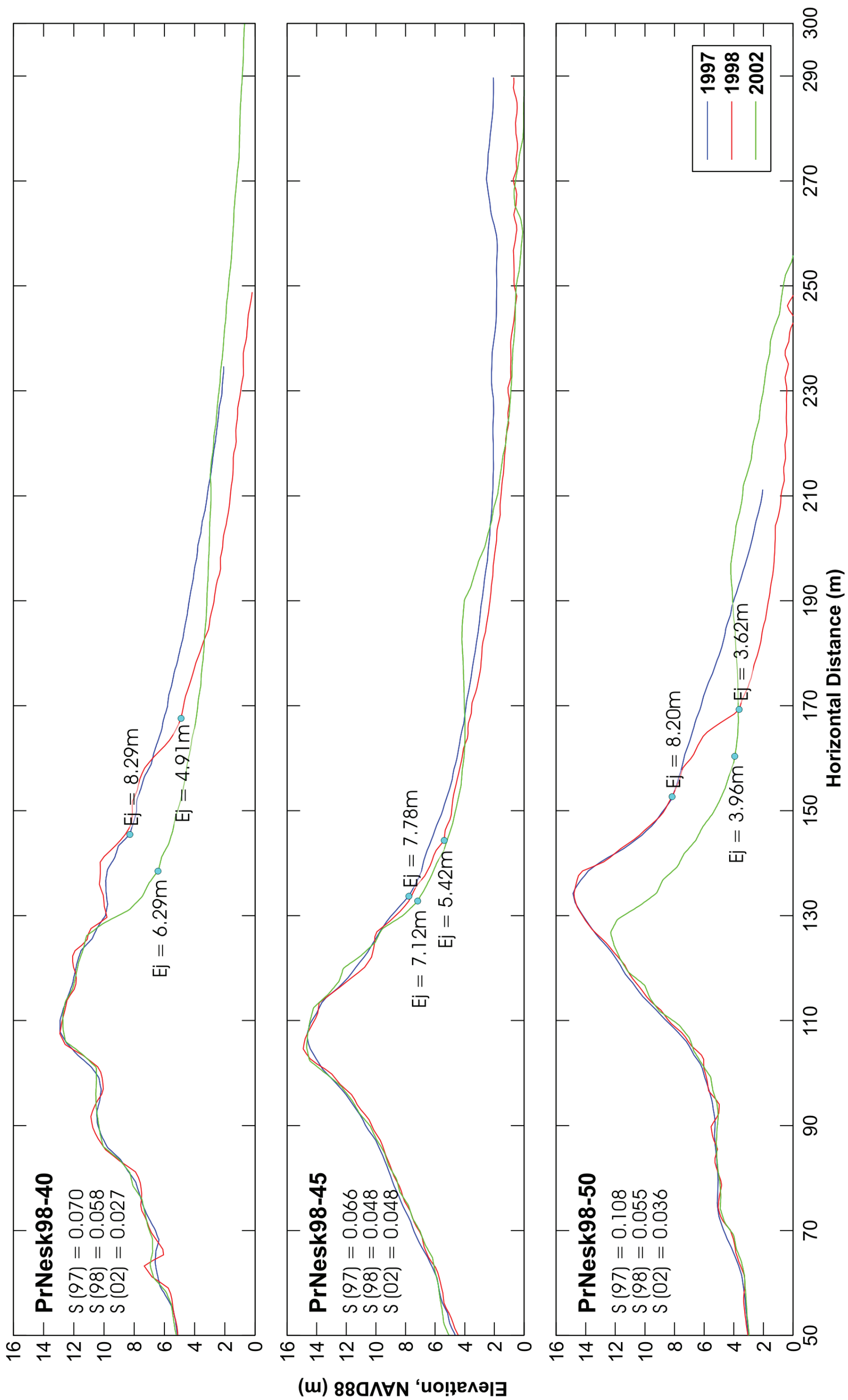

Figure 6. Beach and dune profiles along Nestucca Spit in the Neskowin Littoral Cell. Tthe dots are the identified beach-dune junction elevations, E_j. The vertical exaggeration of the profiles is 2.8.

their analyses. From these few observations of the profiles presented in Figures 5 and 6, it appears that the April 1998 LIDAR survey will be most applicable in establishing the "maximum eroded winter profile," which is not surprising in view that it is the only survey made near the end of the winter season when the normal seasonal cycle of erosion is greatest, and prior to the accretion of the summer months. However, the analyses need to establish whether the September 2002 profiles do indeed have lower slopes than those in April 1998, as this would imply that the beach slope decreases during the progress of dune erosion, rather than remaining constant as assumed in the derivation of the geometric dune-erosion model.

The determination of the beach-dune junction elevation, E_j, is relatively subjective in the LIDAR surveys. This is particularly true for the accreted October 1997 profiles as in most cases it is difficult to determine where the dune ends and the beach begins. The accumulation of wind-blown sand at the base of the higher, older dunes has produced a gradual change in slope from the high dunes to the beach berm, in most cases without a distinct break in slope. The identification of E_j is greatly improved in the April 1998 surveys, at least where some dune erosion had occurred during the winter of 1997-98 to create a scarp, the location of E_j being taken at the base of the scarp. This can be seen in the example profiles in Figures 5 and 6. The profiles from September 2002 present varying degrees of difficulty in that at some sites the eroded dune scarp from the 1999 storms is still apparent, whereas in other profiles the dry sand of the eroded scarp has slumped forward and there may also have been some accumulation of wind-blown sand derived from the beach during the intervening three summers subsequent to the 1999 erosion. Therefore, on average, the best determinations of E_j are for the April 1998 profiles, the results from the September 2002 survey are variable in quality, and the E_j values estimated for the accreted October 1997 profiles are most subjective and likely to have been affected by sand accretion rather than reflecting the total water levels of earlier storm events.

The vertical exaggeration used in Figures 5 and 6 helps in the selection of the E_j elevations in that this accentuates the change in slope expected at the toe of the eroded dune scarp. As illustrated in Figure 7 for one 1998 profile, the selection of E_j is even more evident when the profile is graphed having a 12.6 vertical exaggeration. In this example, E_j is at 4.3 meters NAVD88, about a meter below the maximum water level achieved by the November 1997 storm; as will be seen below, on average there is quite good agreement between the E_j junction elevations derived from the 1998 profiles and the water level of that storm. The vertical 12.6 exaggeration used in Figure 7 greatly accentuates the degree of concavity of the beach profile, and raises the issue of how a beach slope is to be determined for use in the geometric dune-erosion model. As illustrated in this diagram, if the lower portion of the profile is used where the beach is most uniform in slope, a value $S = 0.02$ is obtained, too low to represent the entire beach in calculations of the wave swash runup using equation (1), and as seen in Figure 7 implying that E_j should be tens of meters landward if erosion during the November 1997 storm had occurred with that 0.02 beach slope. An alternative choice illustrated in Figure 7 is to fit the beach slope to the steepest stretch of profile immediately in front of the dune, this approach having the advantage that it links the measured slope with the point selected for E_j (however, this does not always occur). In this example, the measured slope is $S = 0.05$, which is a reasonable value for an Oregon beach; however, again this is not always the case as the slopes so determined can be too high. Following such test analyses on a number of profiles, we decided to base the calculated profile slope on the full beach width, from the base of the dune (i.e., E_j) to the measured profile at the 1 meter NAVD88 elevation, which is close to the mean lower low water (MLLW) tidal datum. While we do not force the regression line to pass through the independently determined position for E_j, in practice they turn out to be close, at least in the 1998 profiles where both the beach slopes and beach-dune junction elevations are best established. In the example of Figure 7, the determined beach slope from linear regression across the full beach width is $S = 0.036$, which is reasonable for both the calculation of the swash runup and in obtaining a projected extent of dune retreat from the geometric model. Although it would appear from Figure 7 that a straight line fitted to the concave profile along its full length would result in a statistically poor match, this again is due to the extreme vertical exaggeration of that graph; in our analyses of the 1997 and 1998 profiles the R^2 goodness of fit values are typically on the order of 0.95 or greater, reduced to about 0.90 or greater for the more irregular profiles from the 2002 surveys.

The evaluated beach slopes and beach-dune junction elevations derived from the Rockaway Littoral Cell profiles are presented as histograms in Figure 8 for the three LIDAR surveys. The results for the three subcells were found to be closely similar, so have been combined in these histograms. Comparing the 1997 and 1998 survey results, it is seen that the distributions of the beach slopes are essentially identical, but the distributions of E_j differ significantly. For both surveys the modes and mean slopes are 0.04, which is typical of Oregon's dissipative beaches. This agreement in slopes between the accreted 1997 and eroded 1998 profiles results because of the near congruence of their profile shapes, evident in Figures 5 and 6, even though the 1998 profiles are shifted downward by about 1 meter in elevations from the 1997 profiles due to erosion during the winter of 1997-98. Our experience on Oregon's dissipative beaches is that while the profiles change in elevation by on the order of 1 meter between the summer and winter, the change has little effect on the average slope of the beach face, and this is reflected in the LIDAR profiles of 1997 and 1998, yielding the same mean slopes and very similar distributions (Figure 8).

In contrast to the measured beach slopes, the distributions of E_j are much different for the 1997 and 1998 profiles, Figure 8, with the mean of the former being about 1 meter higher. The mean for the 1998 profiles is 4.82 meters NAVD88, with the mode in the histogram being at 5.0 meters NAVD88. As presented above, the maximum total water level of the measured tide plus the wave-swash runup is estimated to have been 5.3 meters NAVD88 during the 19-20 November 1997 storm, the most severe of the El Niño winter storms, having occurred between the 1997 and 1998 LIDAR surveys. Therefore there is reasonable agreement between the estimated water level achieved by the maximum storm and the measured E_j values from the surveyed profiles, especially if one recognizes the uncertainties inherent in both. These surveyed E_j beach-dune junction elevations were employed in the analyses of Allan and Priest (2001) using the geometric dune-erosion model to establish setback lines for Tillamook County. McDougal and MacArthur (2004) have suggested that as an alternative approach, the total water level (tide plus runup) of the storm having a 1-year recurrence be used instead of the surveyed E_j values. The November 1997 storm is estimated to have had a 1- to 2-year recurrence, so the agreement between its water level and the mean value of E_j supports this recommendation by McDougal and MacArthur (2004).

The mean E_j for the 1997 surveyed profiles is 5.73 meters NAVD88, and the standard deviation is much greater than for the 1998 profiles (Figure 8). The higher E_j for the 1997 surveyed profiles undoubtedly reflects the accreted nature of those profiles, with sand having accumulated in front of the high dunes, blown landward from the beach. The values of E_j for the 1997 profiles therefore do not reflect a storm erosion event, as do the 1998 E_j values, but instead the extent of sand accumulation due in part to aeolian processes. The high standard deviation of the E_j distribution for 1997 reflects the natural variability of the amount of sand accumulation between profile sites, as well as the greater subjectivity in selecting the profile position to measure E_j in the 1997 surveys.

The distribution of the measured beach slopes from the September 2002 LIDAR profiles is noticeably shifted to lower values than the slopes for the 1997 and 1998 surveys (Figure 8). The mean slope for the 2002 profiles is 0.028 with equal numbers at 0.02 and 0.03 in the histogram. The indication is that there is a reduction in the mean slope of the beach in the swash zone at the time of a major storm leading to significant dune erosion. The E_j junction elevations measured in the 2002 survey are also lower than in the 1998 survey, the mean for 2002 being 4.38 meters NAVD88. This elevation for the measured E_j is substantially lower than the 7.3 meters NAVD88

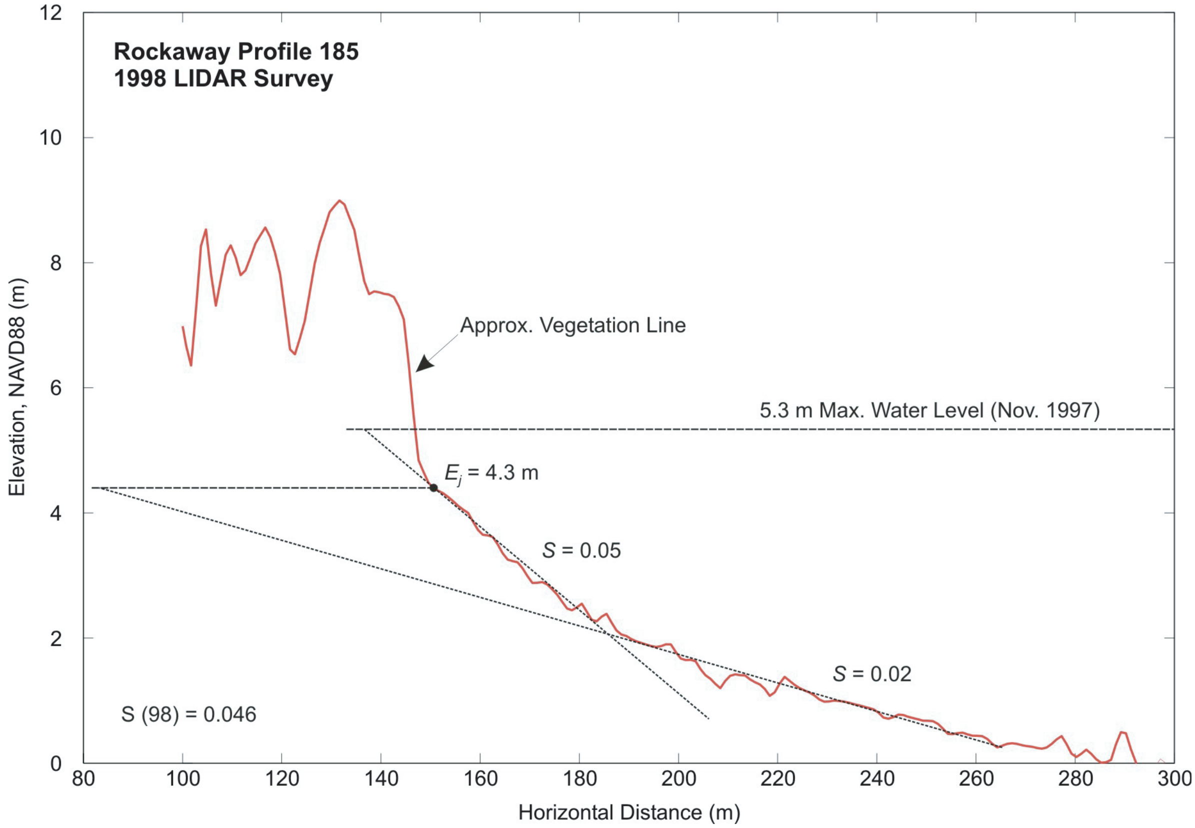

Figure 7. The analysis of a 1998 profile from the Rockaway Littoral Cell, graphed with a 12.6 vertical exaggeration, illustrating the selection of E_j and the beach slope, *S*.

maximum total water level achieved by the March 2-3, 1999 major storm, which is known to have been the primary cause of the dune erosion. As seen in Figure 8, the most elevated measured E_j values achieved only 6 meters NAVD88, still a meter short of the estimated total water level of the March 1999 storm. These differences are greater than can be attributed to uncertainties in the LIDAR surveyed elevations and in the evaluated total water level. Instead, the difference must be a reflection of the fact that the actual extent of dune erosion is significantly less than predicted by the dune-erosion model, also affected by the decrease in beach slope as the erosion progresses. This is illustrated schematically in Figure 9, with the post-storm E_j elevation being lower than the total water level of the storm, the extent of this difference reflecting the difference in the predicted versus measured extent of dune retreat. Also illustrated is the significance of the reduction in the beach slope during the erosion event, which potentially could enhance the degree of dune retreat so that becomes greater than predicted.

The measured beach slopes are plotted in Figure 10 versus the E_j junction elevations for the Rockaway Littoral Cell profiles. For the 1997 survey there is a clear trend of increasing slope with increasing E_j. According to equation (1) for the evaluation of the wave runup that depends on the beach slope, there might be an expectation that the steeper beach would produce higher runup levels, which in turn could be expected to yield more elevated E_j values for the eroded dunes. While this is clearly the case for coarser-grained beaches having steeper beach-face slopes, this is not the case for the low sloping dissipative beaches found in the Tillamook County littoral cells. Instead, the trend of increasing slopes with increasing E_j for the 1997 survey reflects the accreted conditions of the 1997 profiles with wind-blown sand accumulation at the back of the beach.

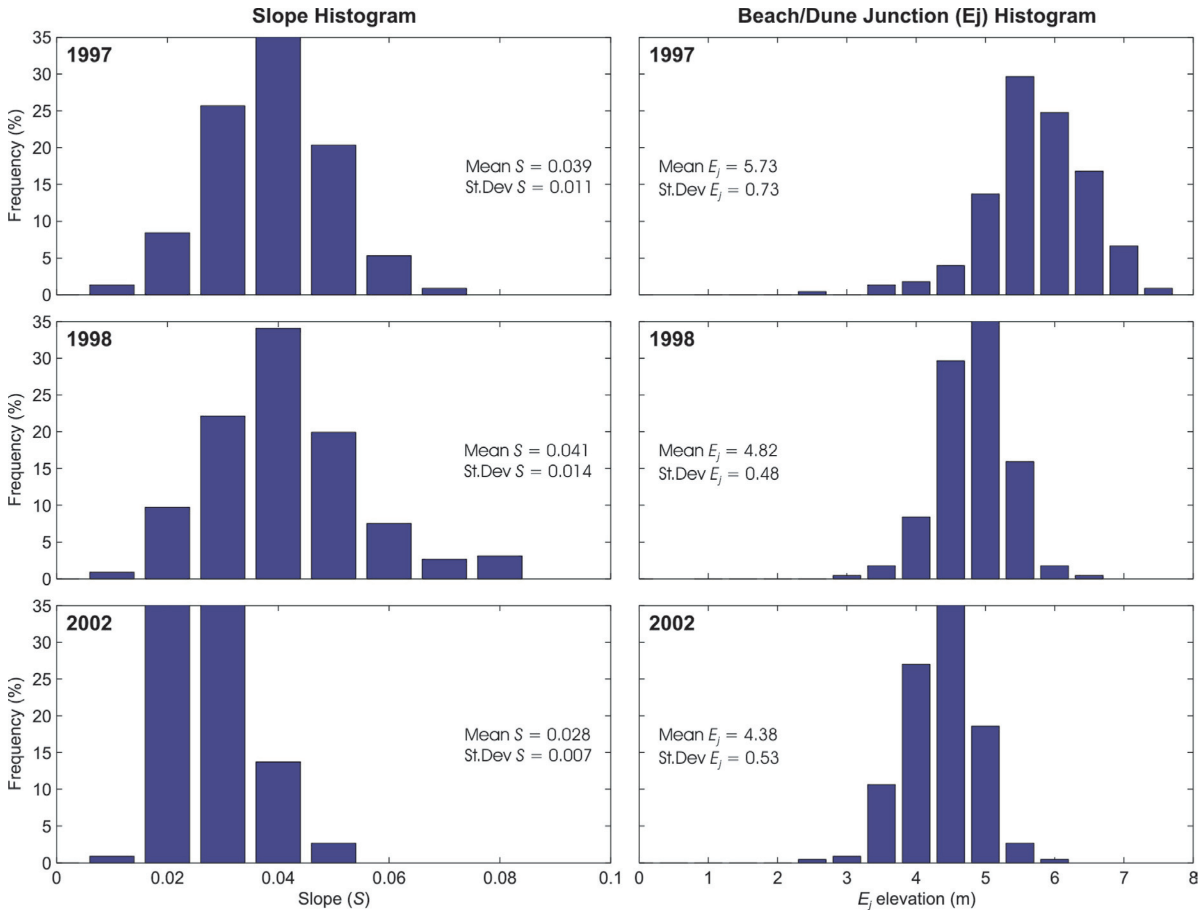

Figure 8. Histograms of beach slopes (S) and beach-dune junction (E_j) elevations measured from beach profiles in the Rockaway Littoral Cell, based on the 1997, 1998, and 2002 LIDAR surveys ($N = 226$).

There is no relationship between the beach slope and E_j in the 1998 profiles (Figure 10), which is expected where both parameters reflect an eroded beach and the runup level does not depend on the beach slope. The regression line for the 2002 surveys again shows a slight trend of increasing slope versus E_j, but much less so than the 1997 survey.

Similar analyses have been completed for LIDAR surveyed beach profiles in the Neskowin Littoral Cell, Tillamook County. Histograms of the measured beach slopes and E_j beach-dune junctions are given in Figure 11, with the results being much the same as found in the Rockaway Littoral Cell. In the 1997 surveys there is a bimodal distribution of beach slopes, with the largest mode centered on 0.03 to 0.04, slopes that are typical of dissipative beaches with sand of about 0.2 mm diameter. There is a second mode centered at a slope of 0.07 to 0.08, extending up to much higher values, 0.11 to 0.15. These steepest beach slopes are the same profiles that yielded the highest E_j junction elevations seen in the histogram for 1997 in Figure 11. These pairs all came from profiles on Nestucca Spit where high dunes back the beach, and it was found that in 1997 there was considerable backshore accumulation of wind-blown sand piled up against the older dunes, creating both the increased beach slopes and elevated E_j values.

The mean slope for the 1998 eroded profiles from the Neskowin Cell is 0.047 and the mean E_j is 5.19 meters NAVD88 (Figure 11); the slope is marginally greater than found in the Rockaway Littoral Cell, while the mean of E_j is slightly greater, in closer agreement with the 5.3 meters NAVD88 estimate for the maximum total water level of the February 1997 El Niño storm. The 2002 surveys again show a shift to lower beach slopes with a pronounced mode at 0.03, and a mean E_j of 5.18 meters NAVD88, which again is significantly lower than the 7.3 meters NAVD88 total water level of the March 1999 storm.

Graphs of beach slopes versus E_j junctions are presented in Figure 12 for the three LIDAR surveys in the Neskowin Cell. As with the Rockaway Littoral Cell, in the 1997 surveys there is a clear trend of increasing beach slope with increasing E_j elevations; as noted above, the scatter points at high slopes and E_j are where wind-blown sand has piled up against the older dunes along Nestucca Spit. This trend is again due in large part to the accreted condition of the 1997 profiles. This is further confirmed by the fact that all but one of those extreme data points disappear in the 1998 surveyed profiles following the winter erosion, there being only a slight tendency for the beach slope to increase with E_j (Figure 12). In 2002 the trend remains much the same as in 1998, but there is the beginning reappearance of higher slopes and E_j elevations as sand accretion against the eroded dunes has begun.

Analyses were also completed in the Sand Lake Littoral Cell of Tillamook County, but were limited due to problems with the 1997 LIDAR survey, the two survey flights not having overlapped so in most areas along this cell there is a gap in the data coverage. As a result, we were able to generate only 26 profiles. This was still sufficient to establish that the values of beach slopes and E_j beach-dune junctions are essentially the same as in the Rockaway and Neskowin Littoral Cells, and show the same variations between the three LIDAR surveys. The 1998 survey yielded a mean beach slope of 0.041 and mean E_j of 5.10 meters NAVD88; the latter value is again very close to the 5.3 meters NAVD88 maximum total water level of the November 1997 storm, clearly having been the erosion process that determined the E_j junctions in the profiles. The 2002 profiles again showed a decrease in beach slopes, reduced to a mean of 0.029, and a decrease in E_j to a mean of 4.96 meters NAVD88. Therefore, although there were problems with the 1997 LIDAR survey in the Sand Lake Littoral Cell, the results are still in full agreement with those from the other cells.

There are patterns of longshore variations in beach slopes and beach-dune junction elevations apparent in the Tillamook littoral cells. Graphs of the measured E_j elevations are given in Figures 13, 14, and 15, respectively for the Rockaway, Neskowin, and Netarts Littoral Cells. Overall they show the highest E_j values for the 1997 accreted profiles, intermediate for the 1998 eroded profiles, and slightly lower still for the 2002 profiles, agreeing with the histograms presented and discussed above. Of more interest here

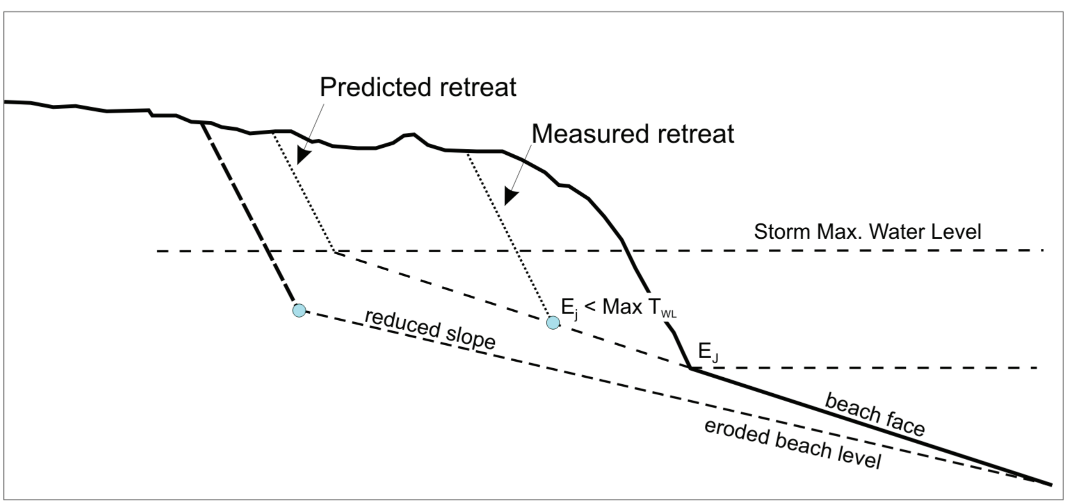

Figure 9. Schematic illustration of the relationship between the measured E_j beach-dune junction elevation after the dune erosion event and the total water level T_{WL} of the storm, depending on the difference between the dune retreat predicted by the dune-erosion model and that actually experienced.

are alongshore variations in the E_j values and how they might be affected by rip-current embayments and the northward displacement of the beach sand within the littoral cells that occur during El Niños due to the southwest approach directions of the storm waves (Komar, 1986; Revell and others, 2002; Allan and others, 2003; Komar and Allan, 2004). The pattern of variations in the Rockaway Littoral Cell, Figure 13, is dominated by a rhythmicity of about 500 meters in the longshore direction, which most likely is due to the presence of rip currents that eroded embayments leaving intervening shoreline cusps. Due to the presence of jetties on the Tillamook Bay and Nehalem Estuary inlets, acting as mini-headlands, the pattern of localized hot-spot erosion versus shoreline accretion resulting during the 1997-98 El Niño would be expected to create areas of erosion to the north of the jetties; at the scale of the analysis presented in Figure 12, this adds complication to the pattern but without clearly being distinguishable from the rip embayments. The results for the Neskowin Littoral Cell in Figure 14 are similar in apparently having been dominated by rip current embayments. The very high E_j values in the 1997 survey are seen to be grouped together in a series of profiles along Nestucca Spit, where wind-blown sand had been piled up against the older, high dunes that are characteristic of that spit. Those high E_j values are not present in the 1998 profiles, due to that sand accumulation at the back of the beach having been eroded during the 1997-98 El Niño winter.

The results in Figure 15 for the Netarts Littoral Cell are interesting in showing the effects on the E_j elevations due to the hot-spot erosion that occurred during the 1997-98 El Niño, reflected in the April 1998 LIDAR survey following that winter. As a result of the northward transport of sand during that El Niño, sand was lost from the beach at the south end of the littoral cell, this becoming the principal zone of hot-spot erosion, while sand accumulated at the north end of the cell. In addition to this northward

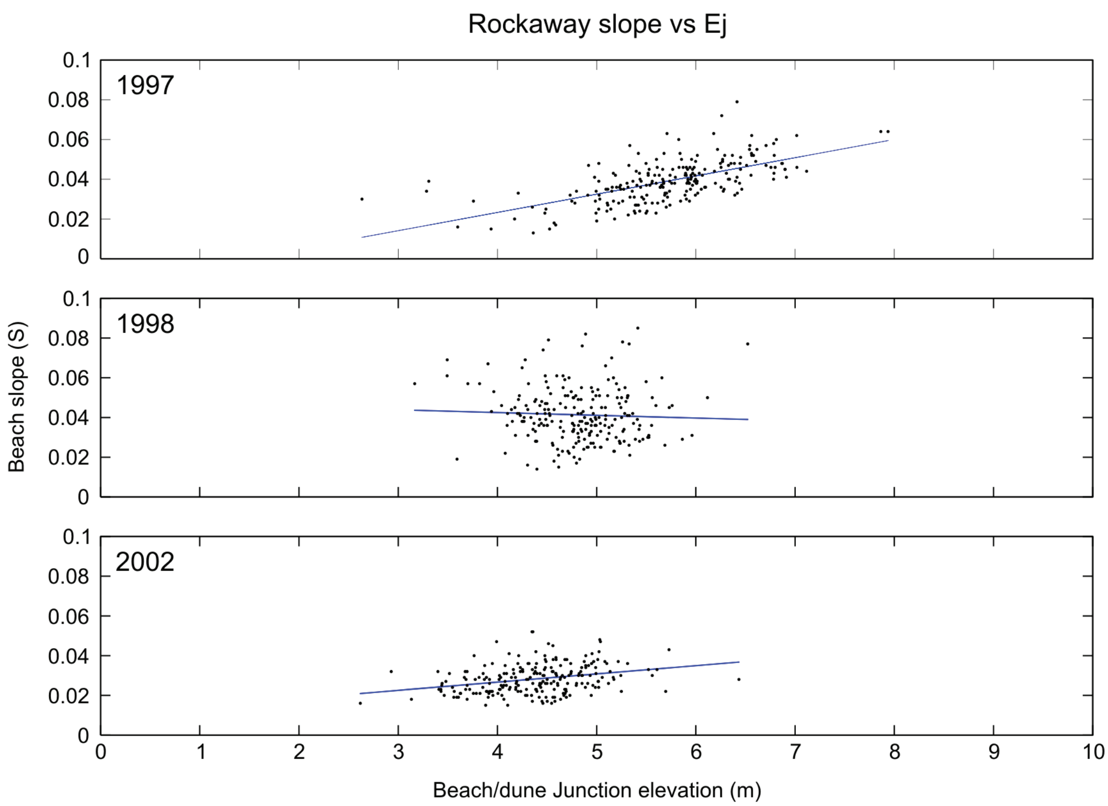

Figure 10. Trends of measured beach slopes versus E_j beach-dune junction elevations for profiles in the Rockaway Littoral Cell surveyed in 1997, 1998, and 2002 (N = 226).

displacement of sand, there was also a cross-shore movement as part of the normal summer to winter profile shift, so the change in elevation of the beach at any particular location is a combination of these two components of sand redistribution during the El Niño winter. This pattern was documented by Revell and others (2002) and Allan and others (2003) through analyses of the 1997 and 1998 LIDAR surveys, based on assessments of sand volumes and shoreline variability in the beach at 100-m increments along the shore. In Figure 15 the corresponding E_j elevations at 100-m increments for the 1998 survey show values on the order of 3.0 to 4.0 meters NAVD88 in the hot-spot zone at the south end of the cell, and 6.0 to 7.0 meters NAVD88 at the north end where the sand has accumulated. This simple pattern is again complicated by the rhythmicity caused by rip current embayments, including one adjacent to the headland at the north end of the cell where the value of E_j was lowered to 2.0 meters NAVD88. There is also a zone of lowered E_j junctions just north of the inlet to Netarts Bay, due to the combination of hot-spot erosion associated with the northward migration of the inlet and the presence of another rip embayment. There is seen to be little variation in the E_j values from about Profiles 60 to 100, this being along the length of Netarts Spit. The sand beach along the south part of the spit is backed by a steeply sloping cobble beach, which clearly restricts the variability of dune junction elevations and significantly reduced the extent of dune erosion during both the 1997-98 El Niño and the winter of 1998-99 with its series of several major storms (Allan and others, 2004). We have found that the 1998-99 storms resulted in more sand being shifted to the north in Oregon's littoral cells, and this likely accounts for the still higher E_j elevations in the 2002 survey at the bluff-backed north end of the Netarts Cell than in 1998, and with some dune erosion having occurred along the length of Netarts Spit that lowered the E_j elevations (Figure 15). The higher E_j elevations in the 2002 survey at the south end of the cell reflect in part the presence of a natural cobble berm along the south end of the spit and the presence of an artificial cobble berm/ dynamic revetment backed by an artificial dune that

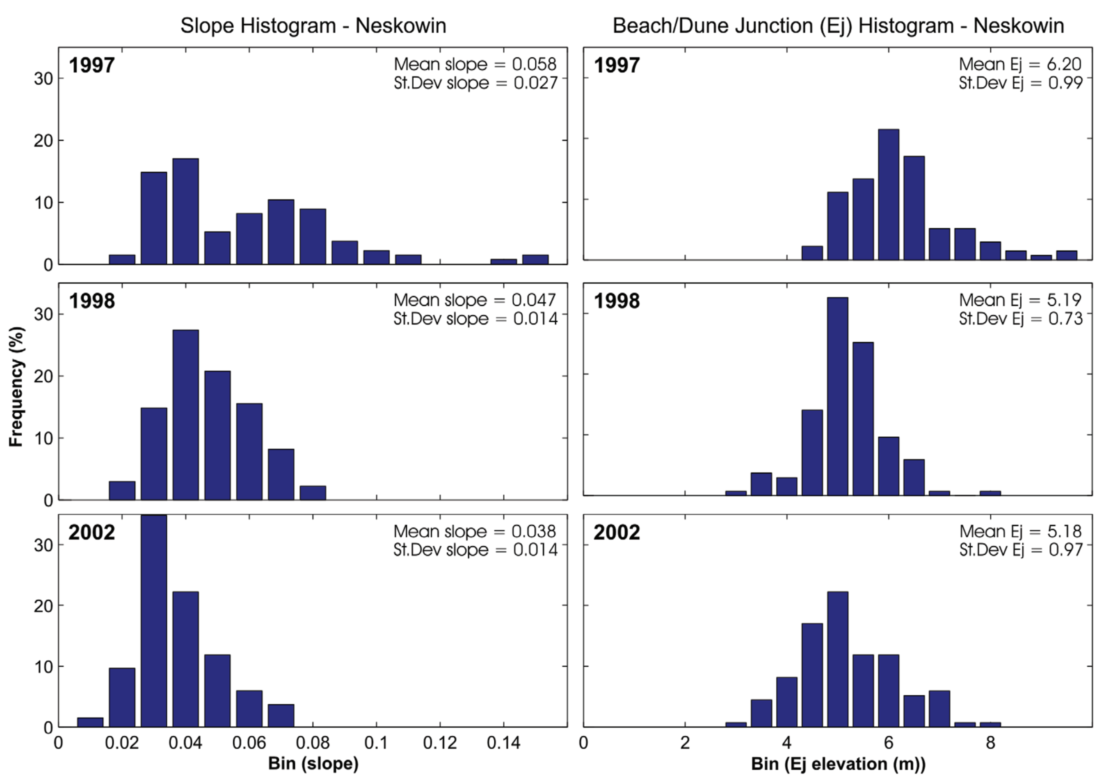

Figure 11. Histograms of beach slopes (S) and beach-dune junction (E_j) elevations measured from beach profiles in the Neskowin Littoral Cell (N = 125).

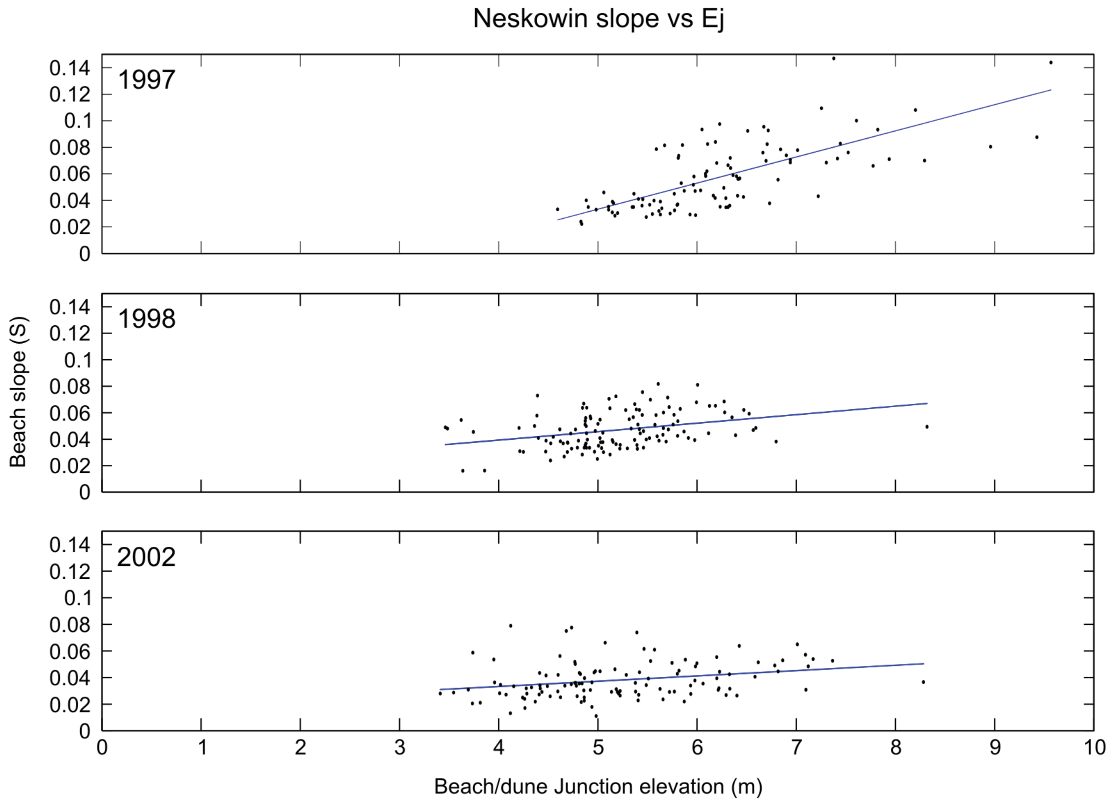

Figure 12. Measured beach slopes versus E_j elevations for profiles in the Neskowin Littoral Cell (N = 125).

was constructed to protect Cape Lookout State Park following the 1999 extreme dune erosion (Allan and Komar, 2004).

5.3 Dune Erosion Volumes

We have also initiated analyses of the volumes of sand eroded from the dunes backing the beaches of the Tillamook County littoral cells. Eroded volumes are of interest, to provide comparisons with the East and Gulf Coast FEMA methodology in which a dune volume of 540 ft^3 per foot of shoreline length (50 m^3/m) is viewed as being critical in providing sufficient protection to backshore properties from erosion and flooding by the 100-year (1%) erosion event, either a hurricane or major Northeaster. That criterion was derived in a report by Dewberry and Davis (1989) where measured dune volumes were correlated with recurrence intervals of storms assessed in terms of their storm surge elevations. Of interest will be whether the volumes of dune erosion on the Oregon coast support that critical 540 criterion used on the East and Gulf Coasts.

The geometric dune-erosion model does not directly include an assessment of the volume of sand in the eroding dunes. As the model is formulated, it predicts a maximum potential extent of dune retreat, irrespective of the dune height and volume. As a result, the higher the dune proportionally the greater the resulting volume of sand eroded for the predicted distance of retreat. One might expect, however, that the higher the dune and the greater the volume of sand that needs to be transported away as the dune is being eroded, the slower the progress of the erosion so that ultimately there is a smaller distance of dune retreat compared with that predicted by the geometric model.

While analyses have been initiated to determine the volumes of sand eroded from the dunes in Tillamook County in order to respond to these questions, both time and funding were insufficient to complete this work. We have completed calculations of dune erosion that occurred between the April 1998 and September 2002 LIDAR surveys at representative profile sites, the actual erosion having taken place

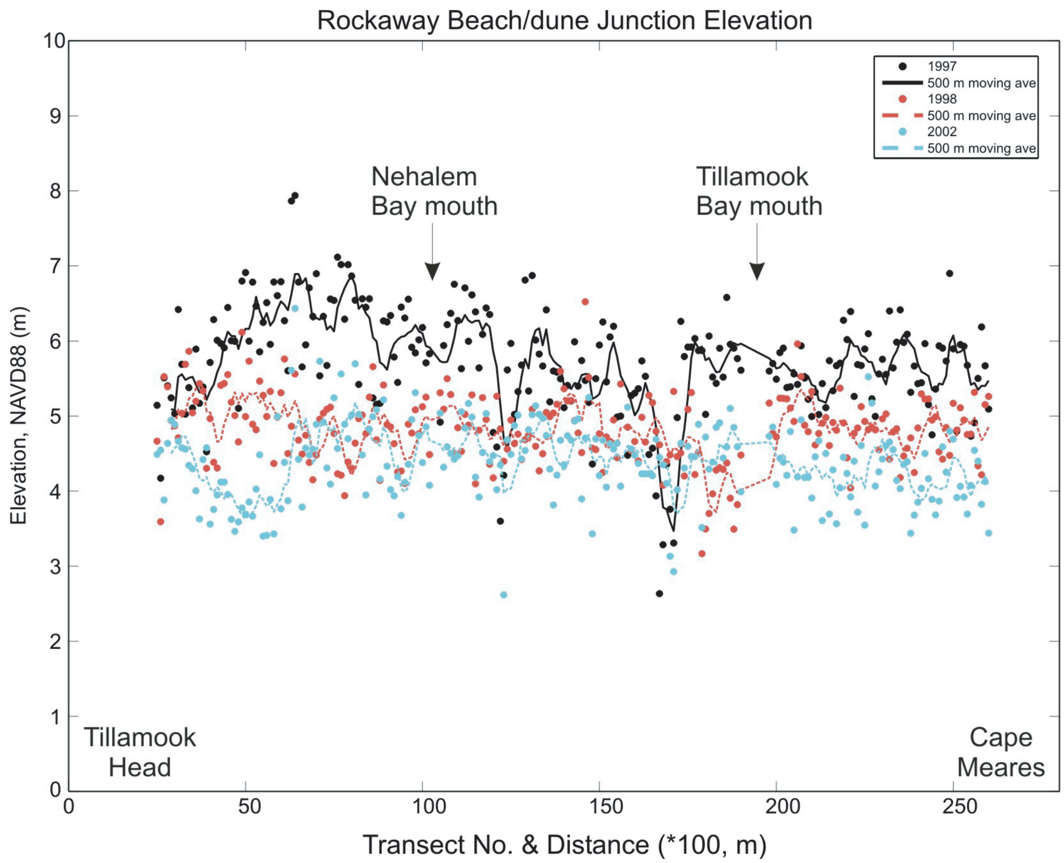

Figure 13. Longshore variations in E_j measured at 100-m increments along the shore of the Rockaway Littoral Cell. The fitted lines represent a 500-m moving average.

during the major storms of the 1998-99 winter. Those limited analyses focused on the Rockaway and Netarts Littoral Cells, the former being the area of extensive horizontal retreat of dunes having modest elevations, while the Netarts dunes are amongst the highest in Tillamook County.

Figure 16 is an example of a profile from the Rockaway Littoral Cell, where the dune elevation is approximately 9 meters NAVD88. The dune retreat between the 1998 and 2002 surveys was between 30 and 35 meters as measured at the E_j elevation of the 2002 profile. If one defines the dune erosion as having occurred above that elevation, the difference between the 1998 and 2002 surveyed profiles yields a dune erosion volume of 111 m^3 per meter of shoreline length (1194 ft^3 per foot of shoreline length). This volume of dune sand eroded is significantly greater than the critical 540 ft^3/ft volume used in the FEMA methodology on the East Coast for the 100-year event, even though the March 1999 storm that eroded the Oregon dunes has been assessed as only a 25 to 50-year event. One can argue that our estimate of the eroded dune volume is too low in that we should have included the volume of sand directly below the E_j elevation of the 1998 profile. The rotation of the beach to decrease its slope as the erosion progressed is well illustrated by this example in Figure 16, affecting the volume of dune loss at those lower elevations. If we include the volume of sand lost by beach erosion as well as dune erosion, the total comes to 155 m^3 per meter of shoreline length (1,670 ft^3 per foot of shoreline length).

Two examples of such analyses of dune erosion on Netarts Spit in the Netarts Littoral Cell are shown in Figures 17 and 18. The dunes are seen to reach elevations of 13 and 28 meters NAVD88, respectively, at those two profile sites, the range of dune elevations on the Spit. The lower dune in Figure 17 retreated horizontally by about 15 meters, yielding an eroded dune sand volume of 103 m^3/m (1108 ft^3/ft). The

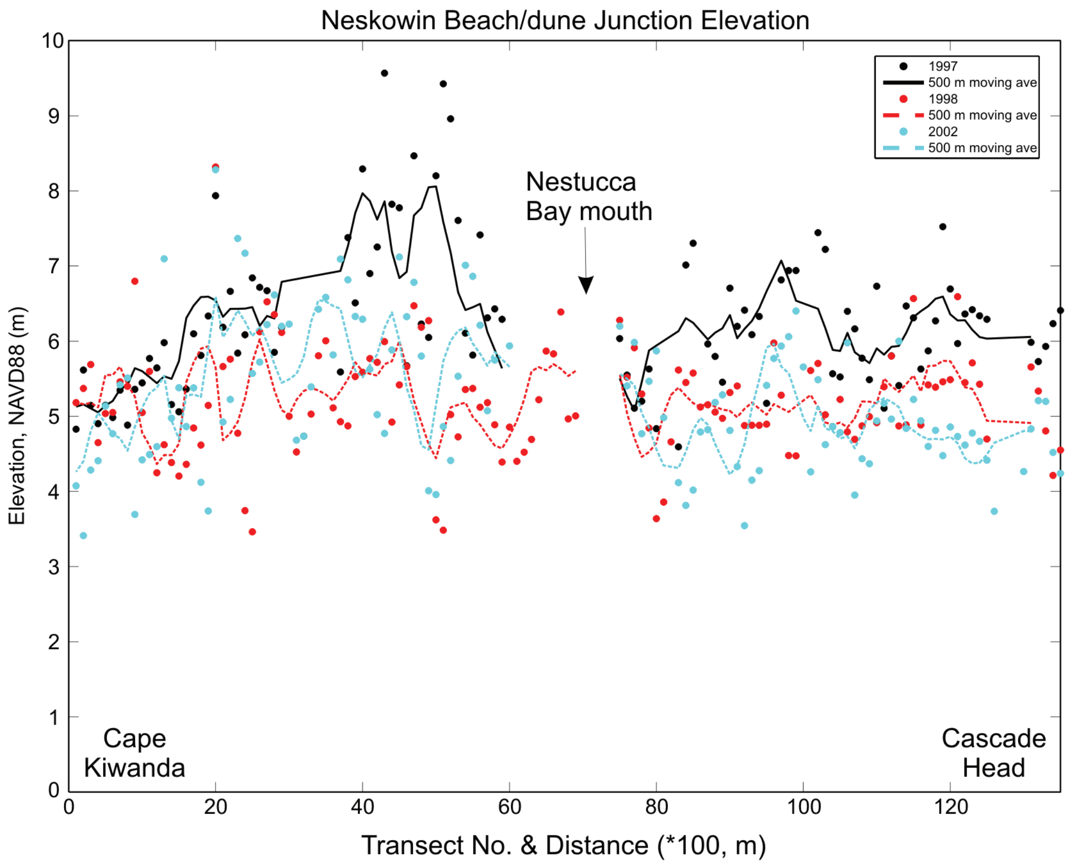

Figure 14. Longshore variations in E_j measured along the shore of the Neskowin Littoral Cell.

higher dune in Figure 18 retreated horizontally by less than 10 meters, but due to its considerable elevation the eroded volume was 193 m^3/m (2,077 ft^3/ft).

From these few examples (and others we have not presented), it is apparent that the dune erosion episodes on the Oregon coast can involve much greater volumes of dune sand than experienced on the East and Gulf Coasts where the 100-year event yielded the 50 m^3/m (540 ft^3/ft) critical volume used in the FEMA methodology. That East Coast volume is a mean value, and the maximum potential dune erosion is roughly estimated to be 6 times as great; this would yield 300 m^3/m (3,240 ft^3/ft) as a maximum, so the volumes found in our analyses of Oregon's eroded dunes are at least within the range found on the East Coast. It is apparent that a larger sample of eroded dune volumes from the Oregon coast is required in this comparison. However, the examples presented in Figures 16, 17, and 18 are fairly representative of the extent of dune erosion in the Tillamook littoral cells, so the volumes are not extremes, but instead are likely to be close to the means.

The three examples presented in Figures 16, 17, and 18 also suggest that higher dune elevations result in lower horizontal retreat distances, while the higher dunes still yield greater eroded volumes. Again, more analyses of this type need to be completed before they yield implications regarding the effects of the dune height on moderating the rate and distance of retreat, governed by the capacity of the waves to transport away the eroded sand volume.

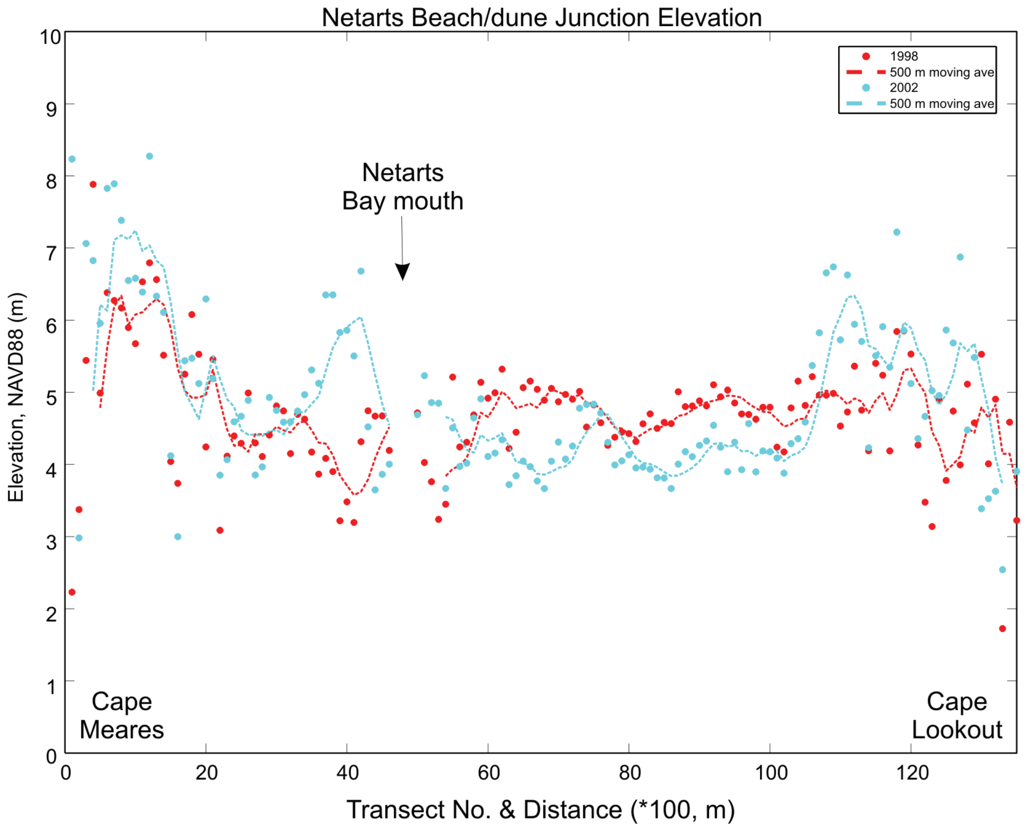

Figure 15. Longshore variations in E_j measured along the Netarts Littoral Cell, showing the lowered junction elevations due to the reduced level of the beach in the hot-spot erosion zone at the south end of the cell, and higher E_j values at the north end due to beach accretion.

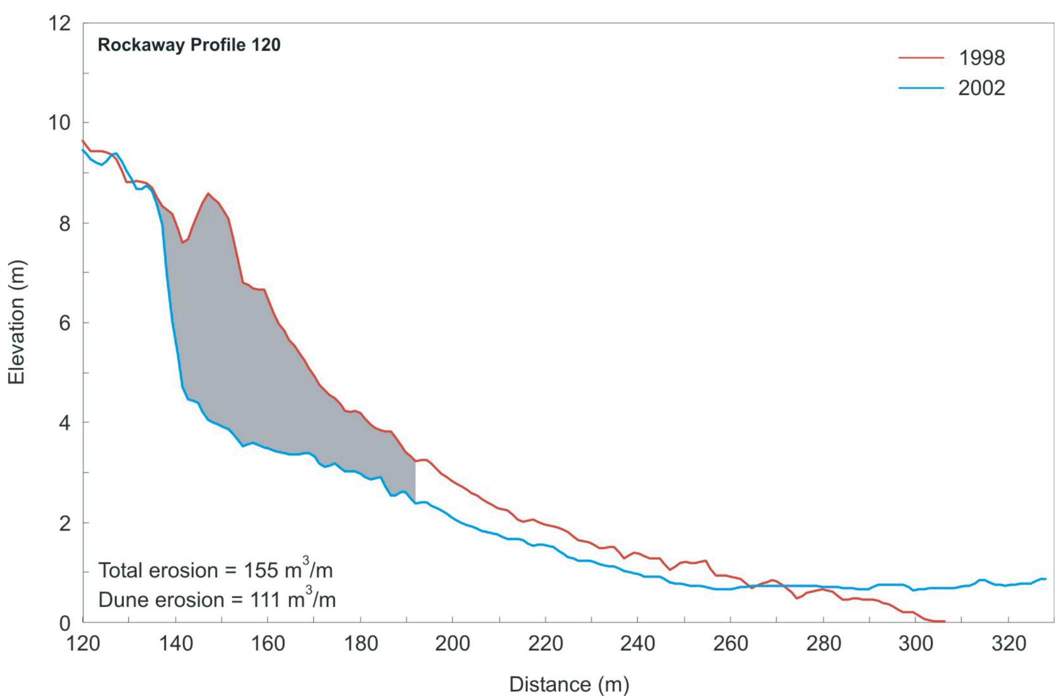

Figure 16. Analysis of the volume of dune erosion during the 1998-99 winter storms for a profile from the Rockaway Littoral Cell.

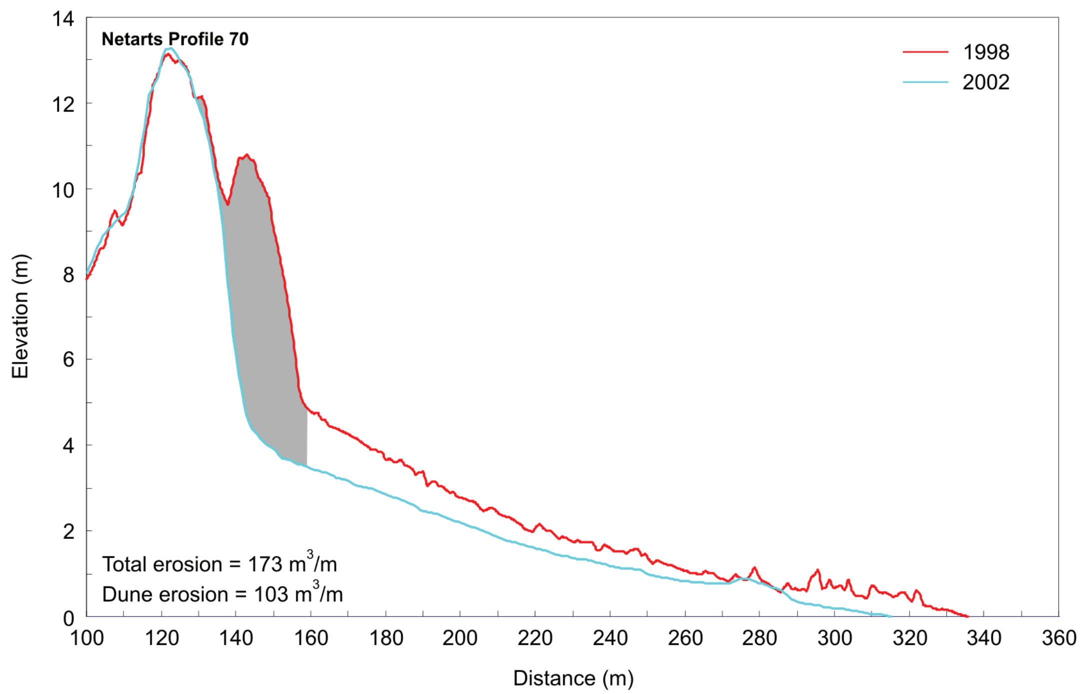

Figure 17. Volume of dune erosion for a profile from Netarts Spit where the dune reaches an elevation of 13 meters NAVD88.

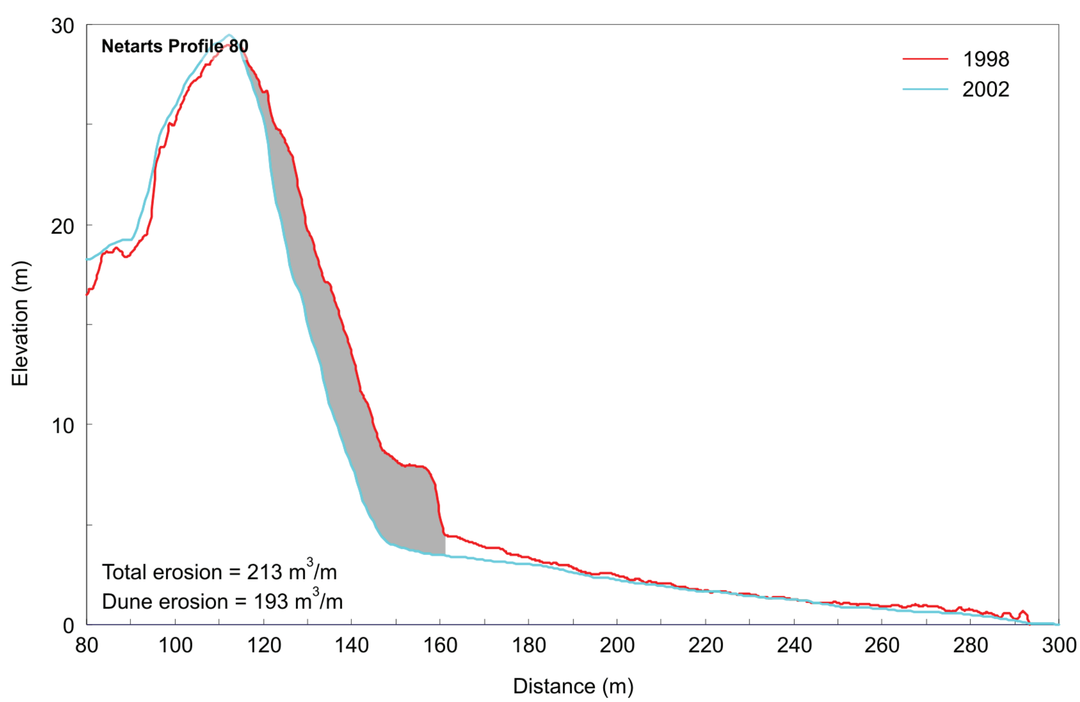

Figure 18. Volume of dune erosion for a profile from Netarts Spit where the dune elevation reaches 28 meters NAVD88.

6.0 CONCLUSIONS, DISCUSSION, AND RECOMMENDATIONS

The objective of this study has been to analyze beach survey data collected on the Oregon coast to test the geometric dune-erosion model under consideration by FEMA for its West Coast methodology to assess the susceptibilities of shore-front properties to erosion and flooding. The analyses undertaken in this report were based on LIDAR surveys of the beaches and dunes along the shore of Tillamook County on the northern Oregon coast, where there has been extensive beach and dune erosion in recent years under the combined impact of the 1997-98 El Niño and the winter of 1998-99, when the occurrence of four major storms resulted in significant dune retreat. Our analyses in particular focused on tests of the assumptions made in the derivation of the geometric dune-erosion model and on values of the parameters derived from surveyed profiles used in its predictions of the potential dune erosion, specifically the values of beach slopes and beach-dune junction elevations. The analyses presented in this report were based on beach and dune profiles extracted from the LIDAR surveys undertaken in October 1997, April 1998, and September 2002. The 1997 and 1998 surveys bracket the 1997-98 El Niño winter that initiated the erosion; although the 2002 survey came three years after the erosion during the winter of 1998-99, the 2002 profiles provide a record of the extent of dune retreat. The surveys therefore were able to serve as the basis for our analyses undertaken to test the geometric dune-erosion model.

6.1 Conclusions

The following conclusions were reached in this study, based on our analyses of the LIDAR surveys in four littoral cells on the coast of Tillamook County:

- The October 1997 surveyed profiles revealed accreted conditions on beaches and dunes, because the survey was undertaken at the end of the summer and also because there had been several years of relatively mild winters that permitted accumulation of wind-blown sand at the back of the beach, piled up against the older, higher dunes;

- The April 1998 survey demonstrated the occurrence of erosion subsequent to the October 1997 survey, with the levels of the beaches having been lowered by about 1 meter, which is typical of the beach cycle between summer and winter on the Oregon coast, and with some erosion of the dunes that created dune scarps 1 to 2 meters high;

- The September 2002 survey revealed the occurrence of significant dune erosion subsequent to the 1998 survey, attributed to the series of major storms that occurred during the winter of 1998-99;

- Measurements of a large number of beach slopes and beach-dune junction elevations, E_j, on the October 1997 profiles supported the conclusion that those profiles were in a highly accreted condition, producing E_j elevations related to the extent of accumulation of wind-blown sand at the back of the beach, not to the elevation of the total water level achieved by an earlier storm;

- Measurements of April 1998 profiles yielded beach slopes averaging about 0.04, which is typical of Oregon's dissipative beaches, and mean E_j elevations that ranged between the littoral cells from 4.82 meters and 5.19 meters NAVD88, close to the 5.3 meters NAVD88 estimate for the maximum total water level reached during the November 19-20, 1997 El Niño storm;

- The 2002 beach and dune profiles, following the extensive erosion by the 1998-99 winter storms, showed lowered beach slopes that were on the order of 0.02 to 0.03, indicating that while the dune erosion proceeds there is a progressive reduction in the slope from its pre-erosion value;

- The 2002 beach-dune junction elevations, E_j, were on the order of 5.3 meters NAVD88, significantly lower than the 7.3 meters NAVD88 total water level of the March 2-3, 1999 storm that caused most of the dune retreat, the difference reflecting the extent of reduction of the actual dune erosion below that predicted by the geometric dune-erosion model;

- Patterns of longshore variations in E_j elevations measured in the littoral cells demonstrate that they can be locally affected by rip-current embayments and by zones of hot-spot beach erosion during an El Niño, produced by the northward movement of sand within the littoral cells;

- While only limited analyses of eroded dune volumes were completed for the Tillamook littoral cells, the volumes ranged from about 111 to 193 m^3/m (1108 to 2,077 ft^3/ft), attributed mainly to the March 2-3, 1999 storm that had a 25- to 50-year recurrence interval, significantly greater than the 50 m^3/m (540 ft^3/ft) critical dune erosion volume used in the FEMA methodology on the East and Gulf Coasts for the 100-year event.

6.2 Discussion

The derivation of the geometric dune-erosion model was based on two simple assumptions: (1) the slope of the beach is maintained as the erosion progresses, and (2) the dune erosion potentially continues until the E_j junction elevation of the progressively retreating dune scarp reaches the elevation of the maximum total water, the tide plus the wave runup of the storm causing the erosion. The analyses derived from this study have demonstrated that neither of these assumptions is strictly correct.

As summarized above in the list of conclusions, the 1998 LIDAR profiles yielded a mean slope of about 0.04; the extensive dune retreat during the winter storms of 1998-99 lowered that slope to means of 0.02 to 0.03. Such a decrease in the slope could easily be included in applications of the geometric model by simply taking $S = 0.02$ or 0.03 in equation (2) for the model's prediction of the maximum potential dune erosion, DE_{max}, rather than using the pre-erosion value $S = 0.04$ as assumed in the derivation. This of course will increase the predicted dune retreat. If we take $T_{WL} = 7.2$ meters NAVD88 for the maximum total water level of the March 2-3, 1999 storm and $E_j = 5.2$ meters for the elevation of the beach-dune junction elevation at the inception of the dune erosion during the winter of 1998-99, equation (2) yields $DE_{max} = 50$ meters using $S = 0.04$, increased to 67 meters with $S = 0.03$, and 100 meters with $S = 0.02$. This demonstrates the sensitivity of the model calculation to the value of the beach slope, and that there is the potential for considerably more dune retreat due to this reduction in the beach slope as the erosion progresses.

It was recognized in the derivation of the geometric dune-erosion model that the actual extent of the dune retreat could be significantly less than the predicted value from equation (2), due to the low duration of most storms and especially of its water levels maintained close to its maximum total elevation, T_{WL}, used in the calculation. The assumption was made in the model derivation that the dune erosion could continue until the E_j junction of the progressively retreating dune scarp achieves the elevation of the maximum total water, T_{WL}, but it was recognized that this would not likely be achieved due to the limited storm duration. Accordingly, it was concluded in the present study that the low value of E_j following the 1998-99 erosion, on the order of 5.3 meters NAVD88, was significantly lower than the $T_{WL} = 7.3$ meters NAVD88 total water level of the March 2-3, 1999 storm due to the lag of the erosion so that it fell short of its potential maximum, that predicted by the geometric model. This conclusion is reinforced by the observation that the greatest horizontal retreat distances of the dunes during the 1998-99 winter amounted to about 35 meters, less than the predicted $DE_{max} = 50$ meters retreat based on equation (2) using $S = 0.04$, and much less than the calculated values of 67 to 100 meters obtained above based on the reduced slopes $S = 0.03$ and 0.02. It is apparent from these results that the DE_{max} estimates from the geometric model are inherently very conservative, with the disagreement between predicted and measured erosion distances increasing if an "improvement" is made in the basic model by accounting for the reduction in the beach slope that occurs during the dune retreat.

The variations in the E_j beach-dune junction elevations are also relevant to applications of the geometric model and its potential modifications. It was concluded that the elevations measured on the 1998 profiles corresponded closely to the T_{WL} maximum total water level of the November 1997 El Niño storm, while the E_j junctions in the 2002 profiles were a full 2 meters lower than the T_{WL} of the March 2-3, 1999 storm. These observations are explained by the contrasting degrees of erosion during the winters of 1997-98 and 1998-99. Except for the zones of hot-spot erosion during the 1997-98 El Niño erosion, the extent of dune retreat was minor and achieved the condition where the measured E_j elevations on the 1998 profile were essentially equal to the T_{WL} of the November 1997 storm that caused the erosion. This is of interest in that the T_{WL} = 5.3 meters NAVD88 level of that storm can be expected to occur on a 1- to 2-year basis, supporting the recommendation made by McDougal and MacArthur (2004) that an assessment of T_{WL} for the 1-year recurrence can be used for E_j in equation (2) for the prediction of $DE_{\max}$ by a major storm, that having a 100-year recurrence. The present study has demonstrated that the determination of E_j from the LIDAR profiles can be difficult and depends in part on the occurrence of a storm having an 1-year recurrence, which conveniently produces a minor degree of dune retreat with the formation of distinct dune scarps. Basing the evaluation of E_j for application in the geometric model on the water level of the 1-year recurrence would be simpler and would provide more dependable assessments.

6.3 Recommendations

The geometric dune-erosion model was formulated for the application of providing a rational assessment of long-term setback distances, reflecting the ocean processes that affect tides and wave runup during storms. The conservative nature of its predictions are appropriate for that application. However, this high degree of conservative predictions is less appropriate for the methodology needed by FEMA to assess the shorter-term hazards of erosion and flooding. Therefore, refinements of the model should be directed toward decreasing the difference between the predicted degrees of dune erosion compared with those actually experienced. To accomplish this, the following studies are recommended:

- Tests to explore the use of models like that of Kriebel and Dean (1993) to assess the time lag of dune erosion, also explored by McDougal and MacArthur (2004) in applications to West Coast beaches;
- More analyses of dune erosion volumes to determine whether the horizontal distance of dune retreat is related to the height of the dune and the volume of sand released, required to be transported away by the waves and therefore accounting in part for the delay in the dune retreat;
- Exploration of the adoption of a more moderate "design" storm condition that will yield a lower T_{WL} maximum total water level used in equation (2), for example by basing the assessment on a significant swash runup level rather than the more extreme $R_{2\%}$ runup, or accounting for the limited duration of the storm and dune erosion, perhaps by replacing the maximum total water level with its average spanning some period of time centered on the maximum.

Irrespective of any improvements in the geometric dune-erosion model such that its predictions of extreme erosion are closer to the measured dune retreat distances, it is recommended that the longer-term goal be the development of numerical, process-based models suitable for application on high-energy, low-sloping dissipative beaches characteristic of the U.S. West Coast. It is only with such models that we can account for the variable conditions of a major storm and deal with the fact that in most cases dune erosion on the West Coast is the result of a series of storms during the winter or even in successive winters, as occurred during the "double whammy" of the 1998-99 El Niño followed by the winter of 1998-99 with its series of extraordinary storms.

7.0 REFERENCES

Aguilar-Tuñon, N.A., and Komar, P.D., 1978, The annual cycle of profile changes of two Oregon beaches: Ore Bin, v. 40, p. 25–39.

Allan, J.C., and Komar, P.D., 2001, Wave climate change and coastal erosion in the US Pacific Northwest: WAVES2001, Proc. 4th International Symposium on Ocean Wave Measurement and Analysis, San Francisco, Amer. Soc. Civil Engrs., p. 680–689.

Allan, J.C., and Komar, P.D., 2002, Extreme storms on the Pacific Northwest Coast during the 1997-98 El Niño and 1998-99 La Niña: Journal of Coastal Research, v. 18, p. 175–193.

Allan, J.C., and Komar, P.D., 2004, Environmentally compatible cobble berm and artificial dune for shore protection: Shore & Beach, v. 72, no. 1, p. 9–18.

Allan, J.C., and Komar, P.D., in press, Climate controls on U.S. West Coast erosion processes: Journal of Coastal Research.

Allan, J.C., and Priest, G.R., 2001, Evaluation of coastal erosion hazard zones along dune and bluff backed shorelines in Tillamook County, Oregon: Technical report to Tillamook County, Portland, Oregon Department of Geology and Mineral Industries, 60 p.

Allan, J.C., Komar, P.D., and Priest, G.R., 2003, Shoreline variability on the high-energy Oregon coast and its usefulness in erosion-hazard assessments, *in* Byrnes, M.R., Crowell, M., and Fowler, C., eds., Shoreline mapping and change analysis: Technical considerations and management implications: Journal of Coastal Research, Special Issue no. 38, p. 83–105.

Allan, J.C., Komar, P.D., and Priest, G.R., 2004, Coast hazards and management issues on the Oregon coast: Coastal Workshop, Lincoln City, Oregon, Field Trip to the Oregon Coast, 29 April 2004, Oregon Department of Geology and Mineral Industries Open-File-Report O-04-18, 26 p.

Daniels, R.C., 2001, Datum conversion issues with LIDAR spot elevation data: Photogrammetric Engineering & Remote Sensing, v. 67, no. 6, p. 735–740.

Dewberry and Davis, 1989, Basis of Assessment Procedures for Dune Erosion in coastal Flood Insurance Studies: report to the Federal Emergency Management Agency, 70 p.

Edelman, T., 1968, Dune erosion during storm conditions: Proc. 11th Conference on Coastal Engineering, San Francisco, Amer. Soc. Civil Engrs., p. 719–722.

Edelman, T., 1972, Dune erosion during storm conditions: Proc. 13th Conference on Coastal Engineering, Amer. Soc. Civil Engrs., p. 1305–1312.

Holman, R.A., and Sallenger, A.H., 1985, Set-up and swash on a natural beach: Journal of Geophysical Research, v. 90(C1), p. 945–953.

Komar, P.D., 1978, Wave conditions on the Oregon coast during the winter of 1997-98 and the resulting erosion of Nestucca Spit: Shore & Beach, v. 44, p. 3–8.

Komar, P. D., 1986, The 1982-83 El Niño and erosion on the coast of Oregon: Shore & Beach, v. 54, no. 2, p. 3–12.

Komar, P.D., 1997, The Pacific Northwest Coast: Living with the Shores of Oregon and Washington: Durham, N.C., Duke University Press, 195 pp.

Komar, P. D., 1998, The 1997-98 El Niño and erosion on the Oregon coast: Shore & Beach, v. 66, no. 3, p. 33–41.

Komar, P.D., and Allan, J.C., 2004, El Niño Processes and Erosion of the U.S. West Coast: Technical memo to the Federal Emergency Management Agency, Aug. 9.

Komar, P.D., McDougal, W.G., Marra, J.J., and Ruggiero, P., 1999, The rational analysis of setback distances: Applications to the Oregon Coast: Shore & Beach, v. 67, no. 1, p. 41–49.

Komar, P. D., Allan, J.C., Diaz-Mendez, G.M., Marra, J.J., and Ruggiero, P., 2000, El Niño and La Niña—erosion processes and impacts: Proceedings of the 27th International Conference on Coastal Engineering, Sydney, Australia, p. 2414–2427.

Komar, P.D., Marra, J.J., and Allan, J.C., 2002, Coastal-erosion processes and assessments of setback distances, *in* Ewing, L. and Wallendorf, L., eds., Solutions to Coastal Disasters: Amer. Soc. Civil Engrs., p. 808–822.

Kriebel, D.L., and Dean, R.G., 1985, Numerical simulation of time-dependent beach and dune erosion: Coastal Engineering, v. 9, p. 221–245.

Kriebel, D.L., and Dean, R.G., 1993, Convolution method for time-dependent beach profile response: J. Waterway Port Coast. Ocean Eng., v. 119, no. 2, p. 204–226.

Krabill, W.B., Thomas, R.H., Martin, C.F., Swift, R.N., and Frederick, E.B., 1995, Accuracy of airborne laser altimetry over the Greenland Ice Sheet: International Journal of Remote Sensing, v. 16, p. 1211–1222.

Krabill, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W., and Yungel, J., 1999, Rapid thinning of parts of the southern Greenland ice sheet: Science, v. 283, no. 5407, p. 1522–1524.

Larson, M., and Kraus, N.C., 1989, SBEACH: Numerical model for simulating storm-induced beach change, Report 1: Empirical foundation and model development, U.S. Army Corps of Engineers Technical Report CERC-89-9.

McDougal, W.G., and MacArthur, R.C., 2004, Geometric model for foredune erosion, Technical Memo/Support Document for FEMA Guidelines, August 2, 2004, 28 p.

Nairn, R.B., and Southgate, H.N., 1993, Deterministic profile modelling of nearshore processes. Part 2, Sediment transport and beach profile development: Coastal Engineering, v. 19, p. 57– 96.

Peterson, C.D., Darienzo, M.E., Hamilton, D., Pettit, D.J., Yeager, R.K., Jackson, P.L., Rosenfeld, C.L. and Terich, T.A. 1994, Beach-shoreline database, Pacific Northwest Region, USA, Oregon Department of Geology and Mineral Industries Open File Report 0-94-2, 29 p.

Revell, D., Komar, P.D., and Sallenger, A.H., 2002, An application of LIDAR to analyses of El Niño erosion in the Netarts littoral cell, Oregon: Journal of Coastal Research, v. 18, p. 792–801.

Ruggiero, P., Komar, P.D., McDougal, W.G., and Beach, R.A., 1996, Extreme water levels, wave runup and coastal erosion. Proc. 25th International Conference on Coastal Engineering, Amer. Soc. Civil Engrs., p. 2793–2805.

Ruggiero, P., Komar, P.D., McDougal, W.G., Marra, J.J., and Beach, R.A., 2001, Wave runup, extreme water levels and the erosion of properties backing beaches. Journal of Coastal Research, v. 17, p. 407–419.

Sallenger, A.H., Krabill, W., Brock, J., Swift, R., Manizade, S., and Stockdon, H., 2002, Sea-cliff erosion as a function of beach changes and extreme wave runup during the 1997-1998 El Niño: Marine Geology, v. 187, p. 279–297.

Sallenger, Jr., A.H., Krabill, W.B., Swift, R.N., Brock, J., List, J., Hansen, M., Holman, R.A., Manizade, S., Sontag, J., Meredith, A., Morgan, K., Yunkel, J.K., Frederick, E.B., and Stockdon, H., 2003, Evaluation of airborne topographic Lidar for quantifying beach changes: Journal of Coastal Research, v. 19, p. 125–133.

Shih, S.-M., and Komar, P.D., 1994, Sediments, beach morphology and sea cliff erosion within an Oregon coast littoral cell: Journal of Coastal Research, v. 10, p. 144–157.

Wright, L.D., and Short, A.D., 1983, Morphodynamics of beaches and surf zones in Australia, *in* Komar, P.D., ed., Handbook of Coastal Processes and Erosion, Boca Raton, Fla., CRC Press, p. 35–64.

Vellinga, P., 1982, Beach and dune erosion during storms: Coastal Engineering, v. 6, p. 361–387.

Vellinga, P., 1983, Predictive computational model for beach and dune erosion during storm surges: Proc. Conference on Coastal Engineering, Amer. Soc. Civil Engrs., p. 806–819.