# EVALUATION OF COASTAL CHANGE AND THE POTENTIAL FOR EROSION DURING EXTREME STORMS AT CRISSEY FIELD, SOUTHERN OREGON COAST:

## TECHNICAL REPORT TO THE OREGON PARKS AND RECREATION DEPARTMENT

By

Jonathan C. Allan

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Newport, OR 97365

Cover Photo — Northward looking view along Crissey Field beach. The dark line of vegetation on the right of the photo depicts the approximate position of the shoreline in 1967, while the lighter colored vegetation to the west of it reflects the region of shoreline progradation since 1967 and its subsequent stabilization by European beach grass (*Ammophila arenaria*). Photo taken in March 2005 by J. C. Allan.

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

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2005

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*Acknowledgements.* This study was supported by a research grant from the Oregon State Parks and Recreation Department, for which we are grateful. In particular, I acknowledge the assistance provided by Mr. Matt Reynolds (OPRD), who helped out with some of the fieldwork undertaken in the area.

# EXECUTIVE SUMMARY

The Oregon Parks and Recreation Department (OPRD) is proposing to develop a state recreation site at Crissey Field, located west of Highway 101, north of the Oregon/California border, and south of the town of Brookings. Due to the proximity of the proposed "Welcome Center" to the Pacific Ocean, the Oregon Department of Geology and Mineral Industries (DOGAMI) was commissioned to provide an assessment of the coastal geomorphology of the Crissey Field littoral system, to determine the susceptibility of the proposed "Welcome Center" site, located some 61 to 76 m (200 to 250 ft) from the beach, to a variety of coastal geologic and oceanographic hazards. The data and analyses undertaken as part of this study reveal a number of important findings that include:

- The Crissey Field littoral cell, bounded in the north by Brookings and Crissey Point in the south, forms a subcell within a much larger littoral system that extends all the way to Point St. George adjacent to Crescent City located in northern California. The total length of the littoral cell is approximately 34 km (21 mi). Although sediments derived from the erosion of coastal bluffs and dunes provide some of the sediment that feeds the littoral cell, the bulk of the sand input is likely derived from three predominant sources: the Chetco, Winchuck, and Smith Rivers. Of these, the Smith River probably supplies the largest volume of sand to the beach sediment budget. The exact quantities of sand from these various sources are unknown;

- Beach sand at Crissey Field is characterized by coarse sand with a mean grain size of 0.57 mm; grain sizes range from 0.31 to 0.99 mm. As a result, the slope of the beach at Crissey Field is steeper (~3.5° in the summer, increasing to ~5.1° to 5.7° in the winter) when compared with beaches on the central to northern Oregon coast. These beaches are classified as intermediate to reflective using the nomenclature of Wright and Short (1983) and are thus capable of responding extremely rapidly to large storm wave events;

- Estimates of the seasonal variability of the beach at Crissey Field indicate that it varies by some 7–20 m (23–66 ft). Thus, it can be expected that the beach will erode landward and rebuild seaward by this amount over the course of several normal seasons. During periods of heightened storm activity, however, it can be expected that the response will be significantly greater. Unfortunately, there is no quantitative information on how the beach responded to the most recent extreme storms that impacted much of the central to northern Oregon coast during the 1997-98 El Niño and 1998-99 winters. Nevertheless, the response was probably not the same. For example, although the extreme March 2-3, 1999 storm generated 14.1-m (47.6-ft) significant wave heights offshore from Newport, measurements made at the Eel River buoy (south of Crissey Field) indicated that the wave heights did not exceed 6.7 m (22 ft). As a result, the response of the beach for this event alone was likely much less when compared with beach responses on the northern Oregon coast. Certainly, there is no field evidence (e.g., erosion scarps) to indicate the effects of the 1997-98 and 1998-99 extreme winter storms. This contrasts with sites along the central to northern Oregon coast, which continue to be characterized by the effects of those two extreme winters;

- Analyses of the spatial variability of historical and contemporary shoreline positions derived from aerial photographs (effectively the wet-dry sand line in the imagery) indicate that the Crissey Field shoreline has prograded (advanced) seaward by some 70 m (230 ft) since 1967 (Figure 17). As a result, the area characterized by the 1967 statutory vegetation line is now depicted by an established backdune that has been stabilized by the growth of European beach grass, stands of Sitka spruce, and Salal. It is speculated in this study that this phase of shoreline progradation may be due to the passage of sand around Pyramid Point, adjacent to the mouth of the Smith River, where the sand is then redistributed to the north toward Crissey Field as well as south toward Crescent City. Periodically, these processes may be further enhanced by the occurrence of an El Niño, which can result in much larger volumes of sand being transported northward along the littoral cell. However, the effects of El Niños on the dynamics of the Crissey Field beach and its adjacent subcells remain unknown;

- Apart from a brief phase of erosion during the mid 1980s that may be due to the 1982-83 El Niño, the shoreline has continued to fluctuate about its present position (Figure 17), which remains some 30 to 40 m (100 to 130 ft) seaward of its position in 1967. During this latter period of change, the dune crest did not recede landward, although its crest elevation was lowered slightly, suggesting that the crest of the dune was overtopped;

- In March 2005, a beach profile monitoring network was established adjacent to the proposed Welcome Center site. This initial network consisted of four profile sites and was eventually expanded to include six additional sites in June 2005. Presently, the network covers the entire shore between Crissey Point and the Winchuck River. Information from these sites and from a Real-Time Kinematic Differential Global Positioning System (RTK-DGPS) survey of the beach-dune junction elevation (akin to the most current vegetation line) along the entire shore indicate that the beach in the north has a mean elevation of 5.1 m (16.7 ft), whereas the southern two thirds of the shore has a mean elevation of 6.02 m (19.8 ft).

Coastal erosion hazard estimates of the beach in response to an extreme event was undertaken using a geometric model developed by Komar and others (1999). The model requires knowledge of the offshore wave climate (specifically, the deepwater significant wave height and the peak spectral wave period) and the slope of the beach to calculate the runup of the waves at the shore. These data are combined with a tidal component to yield a total water level at the shore. Three scenarios that account for different combinations of wave and tidal statistics unique to the area were developed for modeling the extent of dune erosion. Scenario 1 includes the occurrence of a 50-yr storm wave ($H_S$ = 12 m [39.4 ft]) characterized by a 20-s peak spectral wave period occurring over the course of an average higher high tide (2.095 m [6.87 ft]), a monthly increase in mean sea level (MSL) of 0.173 m (0.57 ft), and 0.5 m (1.64 ft) storm surge component. Scenario 2 incorporates the same parameters as above, with the inclusion of an increase in MSL due to an El Niño, while the scenario 3 incorporates a larger wave height (14 m [47.3 ft]), a shorter wave period (17 s), and a larger storm surge component (1.0 m [3.3 ft]). Results from the geometric dune modeling reveal the following:

- A HIGH-risk erosion estimate (scenario 1) that ranges from 36 m (118 ft) at the south end of the Crissey Field subcell to as much as 93 m (305 ft) adjacent to the Winchuck River (Figures 25 and 26). The average maximum potential erosion distance estimated for this subcell is 47 m (154 ft). Immediately adjacent to the proposed Welcome Center site, the HIGH-risk erosion hazard zone (scenario 1) is approximately 54 m (178 ft) wide;

- The HIGH-risk scenario 2 estimate yields a hazard zone that is approximately 2.5 to 5.8 m (8.2 to 19 ft) wider than the scenario 1 estimate;

- The MODERATE-risk scenario 3 estimate yields a hazard zone that is marginally smaller than that predicted under scenario 1, despite the larger wave height used in the modeling. This result is due to the shorter wave periods used in the modeling (17 s as opposed to 20 s used in scenario 1);

- On the basis of these results, the proposed "Welcome Center" site lies approximately 18 and 15 m (59 and 49 ft) outside of the HIGH-risk scenario 1 and 2 estimated erosion distances, respectively. Given the amount of conservatism that has been incorporated into these calculations, it appears that the proposed "Welcome Center" site is safe from the effects of dune erosion that may be caused by an extreme storm event;

- Field visits to the site did, however, indicate that portions of the backshore located between the 1967 vegetation line and today's active dune remain subject to periodic wave overtopping, inundating the backshore with seawater and woody debris. Accordingly, this designated zone of storm wave penetration should be free of infrastructure due to the ongoing dynamic nature of this portion of the beach.

Finally, consideration should also be made of three other hazards that could impact the area. First, a large portion of the Crissey Field area falls within the 100-year Winchuck River flood boundary. Second, the mouth of the river can fluctuate by some 150 to 200 m (492 to 656 ft) — the river's southernmost position occurred in 2000, and its northernmost position occurred in 1928 (Figure 17). As a result, such fluctuations may locally exacerbate the erosion of the beach that could have an impact on infrastructure constructed near the river mouth. Nevertheless, there is no field evidence to indicate that the migration of the river mouth to the south has occurred to such an extent that it directly impacted the beach immediately in front of the proposed "Welcome Center" site. Third, the area is well within the Senate Bill 379 tsunami inundation line. Accordingly, consideration of these additional hazards should be incorporated into the design and siting of the Welcome Center building and its accompanying infrastructure. In addition, due to some level of uncertainty in the long-term response of this shore, we recommend adopting some additional safety measures. These include:

- Designing the structure so that the center is located at an elevation above the 100-year flood boundary level (e.g., on pilings);

- Possibly incorporating some design aspects that would allow the building to be pulled off its foundations and relocated to an alternate site should the need arise (e.g., accelerated erosion due to an increase in mean sea level associated with climate change);

- Placing the proposed building landward of a line drawn between the following points: 1192426.043E and 44253.819N, and 1192462.664E and 44152.159N. These points are in the Oregon State Plane Coordinate System (meters), southern zone;

- Incorporating suitable information on the risks of tsunamis, including installing appropriate tsunami evacuation signs; and,

- Commissioning the Oregon Department of Geology and Mineral Industries to undertake periodic updated surveys of the beach profile network established in the area. These surveys should be done at least once every 5 years, and/or after a major storm or storms in series, or a major El Niño winter.

# INTRODUCTION

The Oregon Parks and Recreation Department is proposing to develop a state recreation site at Crissey Field, located west of Highway 101, north of the Oregon-California border, and south of the town of Brookings (Figure 1). The area is characterized by an abandoned World War II air-strip, low rolling dunes, rare native vegetation, and wetlands (Oregon State Parks and Recreation Department, 2003). The fontal foredune is vegetated with European beach grass and stands of Sitka spruce. The site is currently undeveloped and has long been considered as an appropriate location for an Oregon Welcome Center due to its proximity to the California border. The purpose of this study is to assess the coastal geomorphology of the Crissey Field littoral system, in order to to determine the susceptibility of the proposed siting location for the Welcome Center on a foredune overlooking the ocean and located some estimated 200-250 ft from the beach.

The response of coastal shorelines in the form of erosion or accretion is exceedingly sensitive to a multitude of complex factors that include the beach sediment budget, wave energy, variations in water level, nearshore morphology, shoreline orientation, and the geology of the region. Because many shorelines including significant stretches of the Oregon coast, are composed of unconsolidated sediments, they are able to respond rapidly and are among the most dynamic and changeable of all landforms. It is this dynamism at the coast that makes beaches such an integral and important landform as they moderate the effects of wave energy. Beaches and dunes therefore provide an essential buffering mechanism, protecting properties and infrastructure from wave attack.

Increasingly, the natural response of coastal shorelines to erode has come into conflict with the "built" environment due to the rapid growth in population and increased urbanization of coastal margins. Such development is characteristic of much of the Oregon coast, including significant portions of the northern Oregon coast (e.g., Neskowin, Pacific City, and Rockaway in Tillamook County and Siltez and Alsea Spits in Lincoln County), and is the product of escalating property values and the desire to establish infrastructure as close as possible to the ocean's edge (Schlicker and others, 1972; Komar, 1997; Allan and Priest, 2001). Once the properties are established, the expectation is that the coast will remain where it is. Clearly, for sensible shoreline management to occur, sufficient technically sound information on the likelihood and magnitude of shoreline change must be provided to decision makers so they can make informed choices regarding shoreline management practices. That is the ultimate objective of this investigation.

The following tasks will be carried out to develop an understanding of the coastal geomorphology of the Crissey Field littoral cell and its susceptibility from coastal hazards (especially coastal erosion):

1. Undertake an initial reconnaissance trip to the site and establish any necessary survey transects along the Crissey Field shoreline;
2. Undertake a second trip to the site around mid May to carry out an updated survey of the beach, in order to assess the extent of beach rebuilding that has occurred since March 2005 (i.e., post-winter beach survey);
3. Obtain LIDAR data from the U.S. Geological Survey (USGS) and NOAA's Coastal Service Center for 2002 (there are earlier LIDAR flights, but these did not cover the southern Oregon coast) and process the data in a Geographical Information Management (GIS) system. These data will be used in conjunction with any updated surveys of the beach to assess the response of the beach to coastal processes (waves, currents, and tides);
4. Obtain any historical and contemporary aerial photographs of the beach that can be used to assess the interannual to long-term variability of the shoreline;
5. Undertake an assessment of the incidence of extreme storm waves and tidal variability based on adjacent wave buoys and tide gauges. These data will be used to assess the susceptibility of the beaches south of

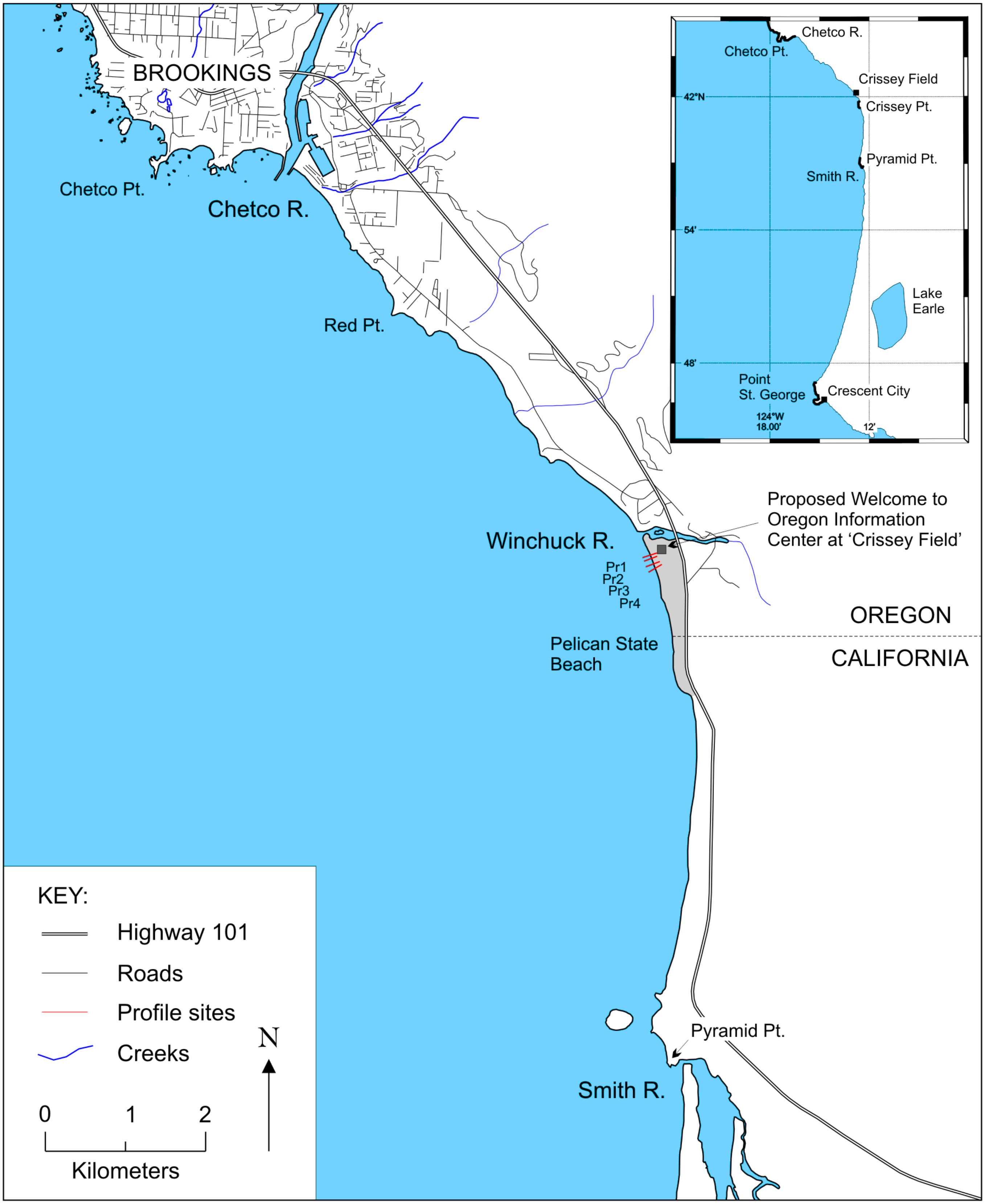


Figure 1. Location map of study area and beach monitoring network. The grey shaded area designates the main portion of shore covered in this study. Inset map shows the extent of the larger Smith River littoral cell, which includes Chrissey Field.

Brookings (including Crissey Field) to erosion from episodic storm events;

6. Undertake empirical modeling of wave runup along the shore using the Ruggiero and others (2001) runup model, to assess the susceptibility of the shore to coastal erosion. The approach will include modeling erosion potential based on various event scenarios and is similar to methods developed by Allan and Priest (2001) for the Tillamook county shoreline;
7. Collate and synthesize any reports and publications pertinent to the coastal geology and geomorphology of the area;
8. Produce a report synthesizing the coastal geomorphology of the area and the susceptibility of the beaches to coastal erosion.

# BEACH PROCESSES ON THE OREGON COAST

## Introduction

The Oregon coast is approximately 360 miles long and can be broadly characterized as consisting of long stretches of sandy beaches that are bounded by resistant headlands. These types of systems are referred to as *littoral cells* (Komar, 1997) and include both a cross-shore (littoral zone, Figure 2) and a longshore extent. There are at least 18 major littoral cells identified on the Oregon coast, with the majority of the shoreline (72%) consisting of dune-backed sandy beaches, while the remaining shore (28%) comprises a mixture of bluff-backed beaches, rocky shores, and coarse-grained (gravel) beaches. Because the headlands extend into deep water, wave processes are generally regarded as unable to transport beach sediment around the ends of the headlands. As a result, the headlands essentially form a natural barrier for sediment transport, preventing sand exchange between adjacent littoral cells. Thus, a littoral cell is essentially a self-contained compartment, deriving all of its sediments from within that cell. Crissey Field likely belongs to the Smith River littoral cell, which extends from Chetco Point (adjacent to Brookings) in the north to Point St. George located northwest of Crescent City (Figure 1). The length of this cell is approximately 34 km (21 mi). However, the Smith River cell may be divided into at least three subcells, which include the region from Point St. George to Pyramid Point (adjacent to the mouth of the Smith River), from Pyramid Point to Crissey Point, and from Crissey Point to Chetco Point (Figure 1). Nevertheless, with the exception of Chetco Point and Point St. George, the subcells probably do not limit alongshore movement of sediment between the cells.

Beaches composed of loose sediments are among the most dynamic and changeable of all landform types, responding to a myriad of complex variables that reflect the interaction of the processes that drive coastal change (waves, currents, and tides) and the underlying geological and geomorphological characteristics of the beaches (e.g., sediment grain size, shoreline orientation, beach width, sand supply and losses, etc.). Coastal processes (waves, currents, and tides) have a threefold role in contributing to the morphology and position of the beach:

- Promoting the supply of sediments to the beach system for beach construction;
- Transferring sediments through the beach system, and;
- Ultimately, removing sediments elsewhere through the process of erosion.

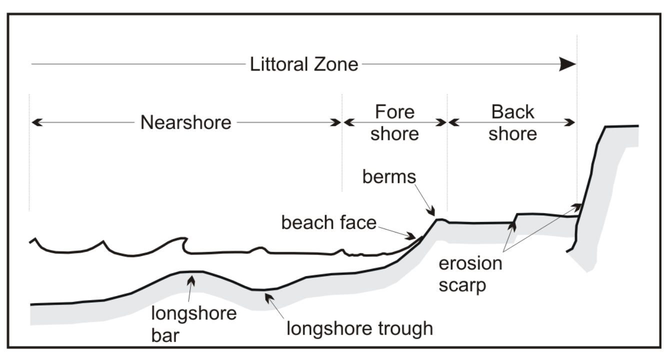


Figure 2. Terminology used to define aspects of the beach (Komar, 1998b).

Because beaches are composed of loose material, they are able to respond and adjust their morphology rapidly in intervals of time ranging on the order of seconds to several years, in response to storm events, enhanced periods of storm activity (e.g., the 1982-83 and 1997-98 El Niños), changes in beach material, and variations in water levels. Longer-term adjustments may also be perceived in the beaches and may be related to a change in sea level.

Integral to an understanding of coastal change along the Crissey Field beach is the concept of the *beach sediment budget*. This concept is analogous to an accounting system such that an assessment is made of the amount of sediment that is arriving at a beach (credits) with that which is removed (debits) and equating these to the net gain or loss (balance of sediments) for a given beach (Komar, 1998a). Thus, the balance of sediments should approximately equal the local beach erosion or accretion.

A clear distinction can be made between movements in the beach form (its height and width) over short time scales (in response to variations in waves and currents) versus longer-term changes, which are dependant on the state of balance or imbalance among the various elements of the sediment budget. From a shore management perspective it is important to distinguish clearly the shorter temporal beach changes from the longer-term adjustments as they have very different implications for land-use adjacent to any water body. In this way costly shoreline erosion and other hazards can be mitigated or avoided altogether, or at least anticipated and properly provided for. Unfortunately, for the purposes of this report, it is beyond the scope of this study to develop a detailed sediment budget for the Smith River littoral cell, because no study has been undertaken of the dynamics and volumes of sediment transport, inputs, and losses along the entire cell. However, within the cell, beach sand is probably derived from a variety of sources, including:

- Sediment from the Chetco, Winchuck, and Smith Rivers. Of these, the Smith River is likely to supply the largest volume of sediment to the coast, followed by the Chetco River adjacent to Brookings;

- Erosion of coastal bluffs located adjacent to Crissey Point, which likely contributes small amounts of sand and gravel to the beach system; and,

- Erosion of the dunes along the coast during times of major storms, which results in the sediment being redistributed along the shore.

Unfortunately, there is very little quantitative information on the response of the beach at Crissey Field to major storms, especially the extreme storms that struck the Pacific Northwest (PNW) during the 1997-98 El Niño and 1998-99 winters. However, a field visit to the site in March 2005 indicated that the site had not been impacted greatly by recent major storms. This contrasts with the central to northern Oregon coast, where similar beaches continue to be characterized by prominent erosion scarps. Furthermore, it is apparent from field visits to the site and from an assessment of 1967 aerial photographs of the area that the foredune at Crissey Field has both been aggrading (building) vertically as well as prograding (advancing) seaward. Vertical growth of the upper beach face and foredune has likely been aided by the proliferation of European beach grass (*Ammophila arenaria*) during the last 50 years.

Oregon's beaches can be broadly classified into two predominant types using the classification of Wright and Short (1983):

- Dissipative beaches are those that contain predominantly fine sands, are gently sloping (typical slopes range from 1.1° [1-on-50] to 2.9° [1-on-20]), and have wide surf zones that dissipate the wave energy as waves break and approach the shore.

- Intermediate to reflective beaches, which contain coarse sand and gravel, are steep sloping (3.2° [1-on-18] to 14° [1-on-4]), have narrow surf zones or in some circumstances a single breaker line so that wave breaking occurs very close to or directly on the beach face.

Measurements of the morphology of the beach at Crissey Field indicate that the slopes of the beach range from 3.5° (~1-on-16) to as much as 5.7° (~1-on-

10). Thus, they tend to fall under the latter category and are therefore intermediate to reflective in the classification of Wright and Short (1983). These types of beaches are exceedingly dynamic, responding rapidly to variations in the offshore wave energy. For example, data presented by Allan and others (2003) indicated that the mean position of the Agate Beach shoreline located north of the Port Orford Heads and adjacent to Garrison Lake varies by some 60 to 70 m (190 to 230 ft) between summer and winter, with the beach face eroding and rebuilding by this amount. (This variability is based on the shoreline defined as the location of the Mean Higher High Water [MHHW] contour elevation located at a height of 2.1 m [6.9 ft] [NAVD'88 based on the Port Orford tide gauge].) In contrast, the seasonal variability of the mean position of the beach at Crissey Field is lower, varying by some 7 to 20 m (23 to 66 ft) (calculated on the basis of comparisons between surveys undertaken in March and June 2005 [i.e., winter/early summer profiles] and 2002 Light Detection and Ranging [LIDAR[1]] topographic data). The driving force behind these variations is the seasonal change in the offshore wave climate. During the winter the wave energy (proportional to the square of the wave height) increases substantially and erodes the beaches, while during the summer the much lower wave energy enables the eroded sand to migrate back onshore, rebuilding the beach face.

Terminology used to describe the form of a beach is shown in Figure 2, while the specific zones within which important coastal processes are operating are presented in Figure 3. As indicated in both Figures 2 and 3, a typical beach cross-section comprises both a subaerial component (the beach foreshore and backshore) and an underwater component that includes the nearshore and offshore zones. Furthermore, the visible sandy foreshore comprises only a small portion of an onshore-offshore sand exchange system that extends well seaward. Thus, the cross-shore extent of the littoral zone extends from the backshore (which may encompass a dune field, beach ridge, sea-cliffs, etc.), seaward to some limiting depth where underwater bed changes tend to be minimal. The seaward limit of onshore-offshore sand exchange can be estimated empirically using formulas developed by coastal engineers on the basis of the offshore wave climate. These calculations suggest that the seaward limit of the littoral zone calculated for the Oregon coast extends out to a depth that ranges from 10 to14 m (33 to 46 ft).

## Longshore Sediment Transport

Within the littoral zone, a distinction can be made between sand movement that is directed in primarily onshore-offshore directions (cross-shore sediment transport) and the movement of sand parallel to the beach (longshore transport). The latter process can be especially significant and is dependent on the direction at which waves approach the shore. When waves approach the shore at some angle, longshore currents are formed. These currents are confined to a narrow zone landward of the breaker zone and can be responsible for the movement of substantial volumes of sand along the shore. Along the Oregon coast, the role of longshore currents is especially important due to a seasonal variation in the direction of wave approach between summer and winter (Figure 4A). During a "normal year," summer waves approach the coast from the northwest, driving sand toward the southern ends of Oregon's littoral cells. This process is further aided by strong north to northwesterly winds that develop throughout the summer and that are capable of transporting large volumes of dune sand toward the south and also landward to form dunes. In contrast, the arrival of large waves from

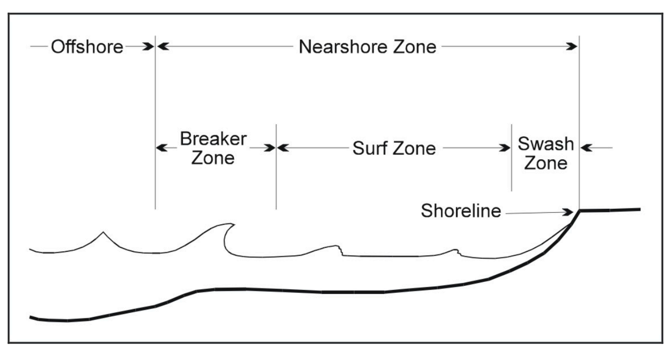


Figure 3. Terminology used to describe the various process zones in the nearshore (Komar, 1998b).

1. LIDAR is a remote sensing technology developed by the U.S. Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA) to collect topographic data (position and elevation) of the beach. Additional information on LIDAR and its application can be found at the NOAA Coastal Services Center website (http://www.csc.noaa.gov/crs/tcm/). Brock and others (2002) and Stockdon and others (2002) provide more information about the technology and its potential application.

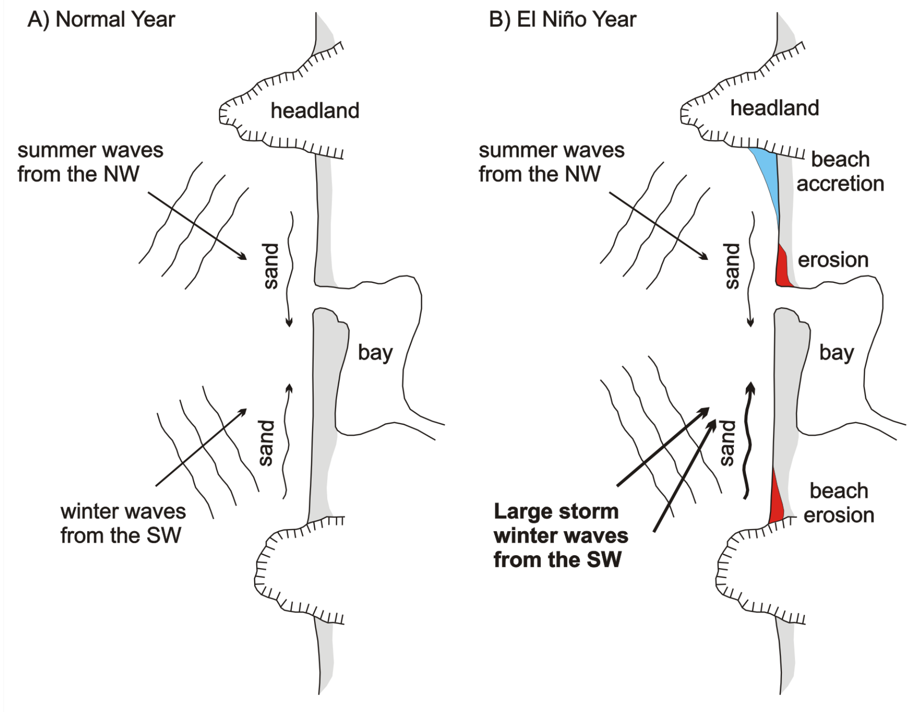


Figure 4. The alongshore seasonal movement of beach sediments on the Oregon coast for A) a typical year and B) an El Niño year (Komar, 1998a). El Niño storm waves cause "hotspot" erosion (red areas) and accumulation (blue areas).

the west to southwest during the winter results in a reversal in the net sand transport direction, which is now directed toward the north and can erode the beaches and dunes. Thus, over several normal years there is a net equilibrium balance so that the net sand transport is close to zero (i.e., there is no net long-term buildup [accretion] of sediment at either end of the littoral cells) (Komar, 1986).

Periodically, the volume and direction of sand transported along Oregon's littoral cells may be augmented due to the occurrence of an El Niño. El Niños typically occur at intervals of 5 to 6 years, but may recur on 2- to 7-year cycles. In the past two decades there have been seven El Niños, with the 1982-83 and 1997-98 events the strongest on record, while the period between 1990 and 1995 was characterized by persistent El Niño conditions, the longest on record (Trenberth, 1999). The 1982-83 and 1997-98 El Niños were particularly significant events, producing some of the most extreme erosion occurrences on the Oregon coast (Komar, 1986; Allan and Komar, 2002; Revell and others, 2002), including significant beach erosion at Garrison Lake at the south end of the Port Orford cell, Cape Lookout State Park, Neskowin, and Rockaway (Komar, 1998b; Allan and others, 2003, 2004).

El Niños impact Oregon's beaches in a variety of ways, most notably by elevating the mean water levels that cause the measured tides to be much higher than usual. Under normal conditions, the Oregon coast experiences a seasonal variation in its monthly mean water levels. During the summer water levels tend to be lowest, a result of coastal upwelling that produces cold, dense water, which depresses water levels along the coast. With the onset of winter, the upwelling process breaks down and ocean temperatures are much warmer; thermal expansion causes the level of the ocean to be elevated by some 0.2 m (0.6 ft), with the highest levels occurring in December and January (Allan and others, 2003). During an El Niño, however, ocean temperatures are further enhanced due to the release of a warm pool of ocean water that emanates from the tropics. The arrival of this warm pool along the Oregon coast during the winter elevates the ocean surface by an additional 0.3 m (1 ft). Thus, an El Niño may produce an increase in winter water levels by as much as 0.5 m (1.6 ft), greatly enhancing the capacity of waves to erode beaches and dunes during those months.

Aside from changes to mean water levels along the coast, during an El Niño there is also a southward displacement of the storm tracks so that they mainly cross the coast of central California (Seymour, 1996). As a result, storm waves reach the Oregon coast from a more southwesterly quadrant, creating an abnormally large northward transport of sand within Oregon's littoral cells. This creates "hotspot" erosion at the southern ends of the cells, north of the bounding headlands and also north of migrating inlets, shown conceptually in Figure 4B (red areas). The opposite response is found south of the headlands, where the northward displaced sand accumulates, causing the coast there to locally advance oceanward (Figure 4B, blue areas).

Detailed documentation of this northward sand displacement and hotspot erosion became possible during the 1997-98 El Niño by using LIDAR data gathered by the USGS and the National Aeronautics and Space Administration (NASA). For example, analyses by Revell and others (2002) used the fall-1997 versus spring-1998 LIDAR data to measure the vertical and volumetric changes in the beach that occurred during the El Niño winter along the length of the Netarts Littoral Cell in Tillamook County. They documented a clear pattern of northward sand transport in response to the southwest approach of El Niño storm waves. Allan and others (2003) undertook additional analyses of LIDAR data in the Netarts cell and quantified the "hotspot" erosion effect along the south end of the cell (Figure 5). Apparent in Figure 5 is the concentrated zone of erosion along the southern 3 km (1.9 mi) of shoreline, where negative values indicate erosion and positive values indicate accretion. The "hotspot" erosion effect is greatest along the southern 1–2 km (0.6–1.2 mi) of the coast where it reaches about -20 m (-65 ft) and progressively decreases northward along the spit. Figure 5 also demonstrates the northward transport of sediment along the cell, as conceptualized in Figure 4, with the shoreline having prograded seaward by some 10 m (33 ft) along the northern extent of the spit, and by several meters north of the mouth of Netarts Bay.

Unfortunately, the USGS and NASA did not undertake LIDAR measurements of the beach topography south of Coos Bay in 1997 (i.e., pre El Niño), and the 1998 LIDAR data did not extend south of Port Orford. As a result, it is not possible to demonstrate the hotspot erosion effect using pre

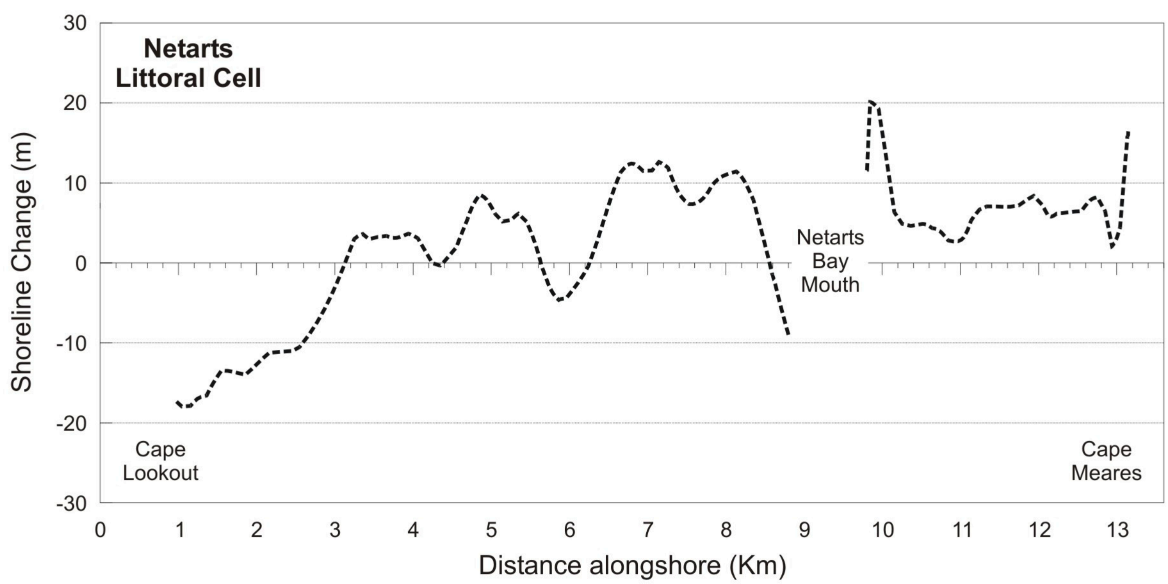


Figure 5. Example of the "hotspot" erosion effect identified in the Netarts littoral cell in Tillamook County (after Allan and others, 2003).

and post El Niño LIDAR data. However, given the location of Crissey Field at the north end of the Smith River littoral cell (and midway within its subcell), one can speculate that the beach adjacent to the proposed 'Welcome Center' may not have responded in such a dynamic fashion as has been observed at other beaches along the Oregon coast. As part of this study, a network of beach survey transects was established and measured using a Real-Time Kinematic Differential Global Positioning System (RTK-DGPS) in June 2005. This network extends from the Winchuck River south to Crissey Point and can be used in the future to quantify impacts on the beach system associated with an El Niño.

## Pacific Northwest Wave Climate

### *Introduction*

The wave climate offshore from the Oregon coast is one of the most extreme in the world, with winter storm waves regularly reaching heights in excess of several meters. This is because storm systems emanating from the North Pacific travel over fetches that are typically a few thousand miles in length and are also characterized by strong winds, the two factors that account for the development of large wave heights and long wave periods (Tillotson and Komar, 1997). These storm systems originate near Japan or off the Kamchatka Peninsula in Russia and typically travel in a southeasterly direction across the North Pacific toward the Gulf of Alaska, eventually crossing the coasts of Oregon and Washington or the shores of British Columbia in Canada (National Marine Consultants, 1961; Tillotson and Komar, 1997).

The degree to which North Pacific storms affect the Pacific Northwest (PNW) depends not only on the intensity of the storms but also on the intensity of the Pacific High and Aleutian Low atmospheric systems. During the summer months, the Pacific High moves northward so that only a few storms approach the PNW, and those that do tend to be weak. While storm waves during the summer months are relatively rare (i.e., locally generated wind waves predominate throughout the summer), long-period swell waves may still be experienced throughout the summer. These latter waves are likely generated by storms located in the far North Pacific (e.g., near the Aleutians) or from storm systems that develop in the Southern Hemisphere during their winter (e.g., winter storms that occur offshore from the New Zealand coast).

With the onset of winter, the Pacific High is displaced to the south, and the Aleutian Low atmospheric system deepens. The combined effect of these two systems and the location and strength of the jet stream contribute to the development of intense storms (termed *extratropical storms*) in the PNW. These storm systems develop in the form of rapidly moving intense frontal systems, or low pressure systems, and periodically as severe outbreaks, or extratropical "bombs" that develop rapidly and are characterized by a dramatic drop in atmospheric pressure (typically greater than 24 mb over a 24-hour period) (Sanders and Gyakum, 1980). Although North Pacific storms rarely acquire wind strengths comparable to hurricanes, their influence is often more widespread, affecting stretches of coast up to 1,500 km and producing extreme wave heights (significant wave heights of 10–14 m [33–46 ft]) on a fairly regular basis during the winter months.

### *Wave Climate Characteristics*

Wave statistics (heights and periods) and some meteorological information have been measured in the North Pacific using wave buoys and sensor arrays since the mid 1970s. These data have been collected by NOAA, which operates the National Data Buoy Center (NDBC), and by the Coastal Data Information Program (CDIP) of Scripps Institution of Oceanography. The buoys cover the region between the Gulf of Alaska and Southern California and are located in both deep and shallow water. The NDBC operates some 30 stations along the West Coast of North America, while CDIP has at various times carried out wave measurements at 80 stations. Presently, CDIP has only one buoy operating offshore from the Oregon coast, which is located near Coos Bay. In addition, the CDIP data sets tend to be characterized by short bursts of sampling (i.e., project specific) and long durations of no measurements so that records tend to have significant gaps. As a result, for the purposes of this report the CDIP data set has not been used. Wave measurements by NDBC are obtained hourly and are transmitted via satellite to the laboratory for analysis of wave energy spectra, significant wave heights, and peak spectral wave periods. These data can be obtained directly from the NDBC through their website (http://seaboard.ndbc.noaa.gov/Maps/Northwest.shtml).

Currently, three buoys are stationed within about 32–48 km (20–30 mi) from the Oregon coast (Figure 6); a fourth buoy was installed recently by NOAA approximately 112 km (70 mi) west of Tillamook. On the northern California coast, the closest NDBC and CDIP buoys to Crissey Field are located offshore from Humboldt Bay (Eureka) and Cape Mendocino (Figure 6). Table 1 describes the general characteristics of the wave buoys and includes their World Meteorological Organization station names, locations, water depths, periods of operation, and buoy type.

Previous analyses of significant wave heights along the central and southern Oregon coast have revealed little difference in measured wave heights between the Newport and Port Orford buoys (Allan, 2004); there is slight decrease in the wave height at the Columbia River buoy in the north (Allan and Komar, 2000a). In contrast, Allan and Komar (2000a) identified a significant decrease (~17%) in winter wave heights between NDBC buoy #46002 (not shown on the map) located offshore from the central Oregon coast and buoy #46013 located just north of San Francisco. This last buoy is located some 450 km (280 miles) south of Crissey Field. In contrast, analyses undertaken here of the wave statistics measured by the Newport (46050) and Eel River

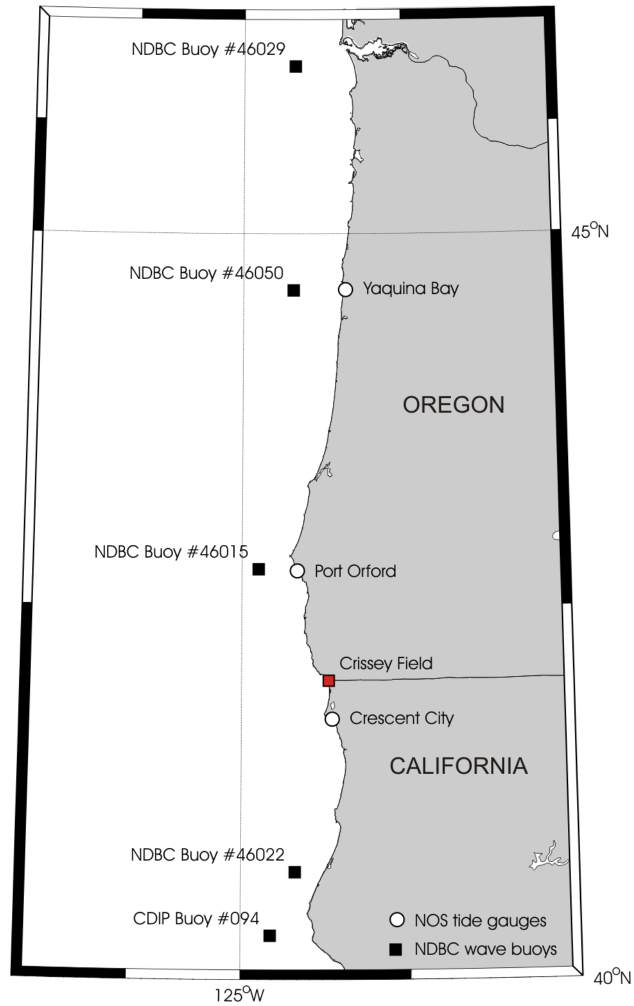


Figure 6. Locations of National Data Buoy Center (NDBC) and Coastal Data Information Program (CDIP) wave buoys and National Ocean Service (NOS) tide gauges.

Table 1. Wave buoy site characteristics.

| Station Name | Location | Water Depth (m) | Period of Operation | System |
|---|---|---|---|---|
| 46029 | Columbia River Bar<br>Lat. 46°07′00″N;<br>Long. 124°30′36″W | 128 | 1984 - present | 3-m discus buoy |
| 46089 | Tillamook<br>Lat. 45°52′53″N;<br>Long. 125°45′59″W | 2,230 | Nov 2004 - present | 3-m discus buoy |
| 46015 | Port Orford<br>Lat. 42°44′00″N;<br>Long. 124°50′30″W | 448 | 2002 - present | 3-m discus buoy |
| 46022 | Eel River<br>Lat. 40°46′53″N;<br>Long. 124°32′31″W | 448 | 1982 - present | 3-m discus buoy |

(46022) buoys indicate that the results are somewhat comparable (Figure 7).

There is a strong seasonality to the wave climate along the Oregon Coast, with the strongest storms and largest generated waves occurring in the winter months. This has been shown, for example, by Tillotson and Komar (1997) and by Allan and Komar (2000a). Figure 7A presents the monthly average deep-water significant wave heights ($H_S$) and peak spectral wave periods ($T_P$) for both the Newport (# 46050) and Eel River (#46022) buoys, while Figure 7B shows the maximum $H_S$ measured in each month and the monthly average maximum $H_S$. The graphs clearly show a prominent cycle in the mean monthly wave heights and peak wave periods. Waves are characteristically smallest (<2.0 m [6.6 ft]) between May and September, reaching a minimum in August (Figure 7A). During winter, average wave heights typically range from 2.8 to 3.5 m (9.2 to11.5 ft). However, during major winter storms, wave heights in excess of 7 m (23 ft) are not uncommon (Figure 7B), with the most extreme storms producing deep-water significant wave heights on the order of 14 to 15 m (45.9 to 49.2 ft). On average, wave heights tend to be slightly larger offshore from the central Oregon coast, especially during storms. The most significant difference identified between the two buoys is the larger maximum significant wave height measured by the Newport buoy (14.1 m [45.9 ft]) versus 12 m (39.4 ft) measured by the Eel River buoy offshore from Humboldt Bay (Figure 7B).

A similar pattern can be seen for the peak spectral wave periods (Figure 7A), such that during the summer the periods are typically less than ~10 s, reaching a minimum of 8.5 s in July. Wave periods tend to be longest in December and January and range from 12 to 14 s on average and may reach as much as 25 s during major storms. In contrast to the wave heights, it is apparent that wave periods

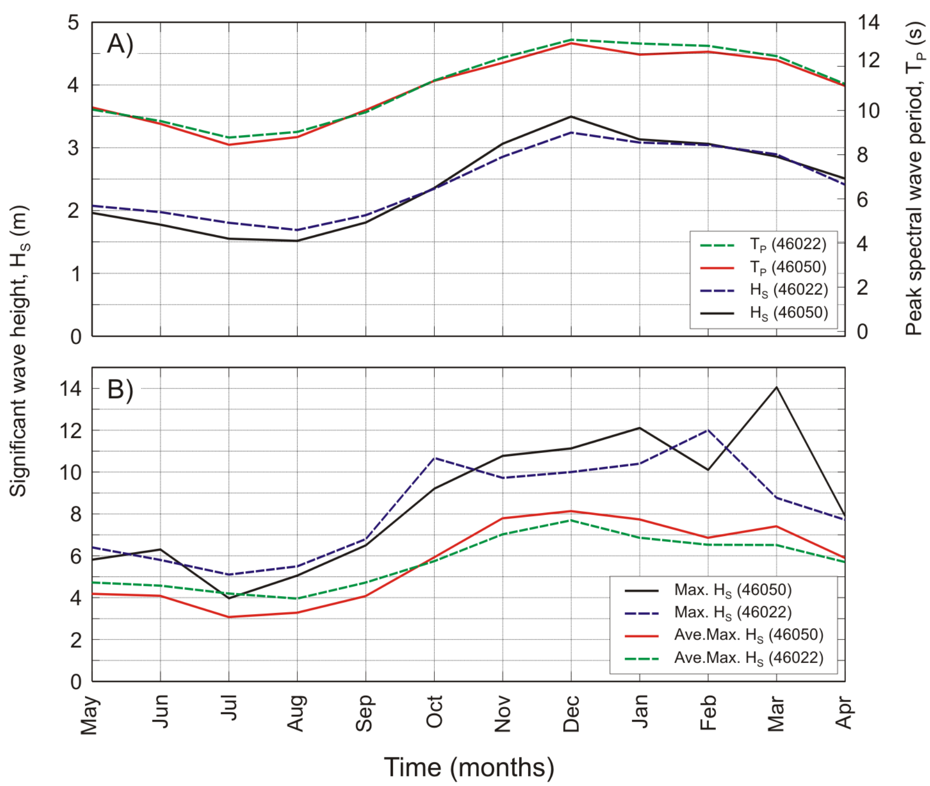


Figure 7. Monthly averages of A) significant wave height ($H_S$) and peak spectral wave periods ($T_P$), and B) average monthly maximum significant wave height (Ave. Max. $H_S$) and maximum significant wave height (Max. $H_S$) for the Eel River (#46022) and Newport (#46050) buoys.

measured offshore from Humboldt Bay tend to be characterized by slightly longer frequencies. This pattern is consistent with observations of wave periods along the entire U.S. West Coast, which indicates a general increase in the wave periods with progress into southern California. This response is largely due to an increase in the distances over which the waves travel (i.e., longer fetches) so that wave dispersion during travel across the wide expanse of the central North Pacific tends to enhance the development of long-period swells (Allan and Komar, 2000a).

Beginning with the 1997-98 winter, an El Niño, the Oregon coast experienced over 20 large storms when the deep-water significant wave heights exceeded 6 m (20 ft) for 9 hours or longer (Allan and Komar, 2000a); prior to the 1997-98 winter the maximum number of storms experienced using the above criteria was 10–12, which occurred in the early 1980s, highlighting the unusual nature of the 1997- 98 winter (Figure 8). These storms affected shipping and produced considerable beach and property erosion along the coasts of Oregon and Washington. On the basis of wave data through 1996, Ruggiero and others (1996) calculated the 100-year storm wave to be around 10 m (33 ft) for the Oregon coast. However, a storm on November 19-20, 1997, exceeded that projection. Wave conditions were far worse during the following 1998-99 La Niña winter (Figure 8), when 17–22 major storms occurred off the PNW coast; four storms generated deep-water significant wave heights equal to or greater than the 10-m (33 ft) projected 100-year occurrence. The largest storm developed on March 2–4, 1999, generating 14.1-m (46 ft) deep-water significant wave heights. Thus, the PNW received a ”one-two punch” from the successive El Niño and La Niña winters, with severe cumulative erosion of the coast (Allan and Komar, 2002). Nevertheless, it is important to appreciate that individual storms can produce quite different results along the coast due to the both intensity of the storm and its predominant storm track. For example, although the March 2-3, 1999, storm generated extremely large wave heights offshore from the central Oregon coast, wave heights measured by the

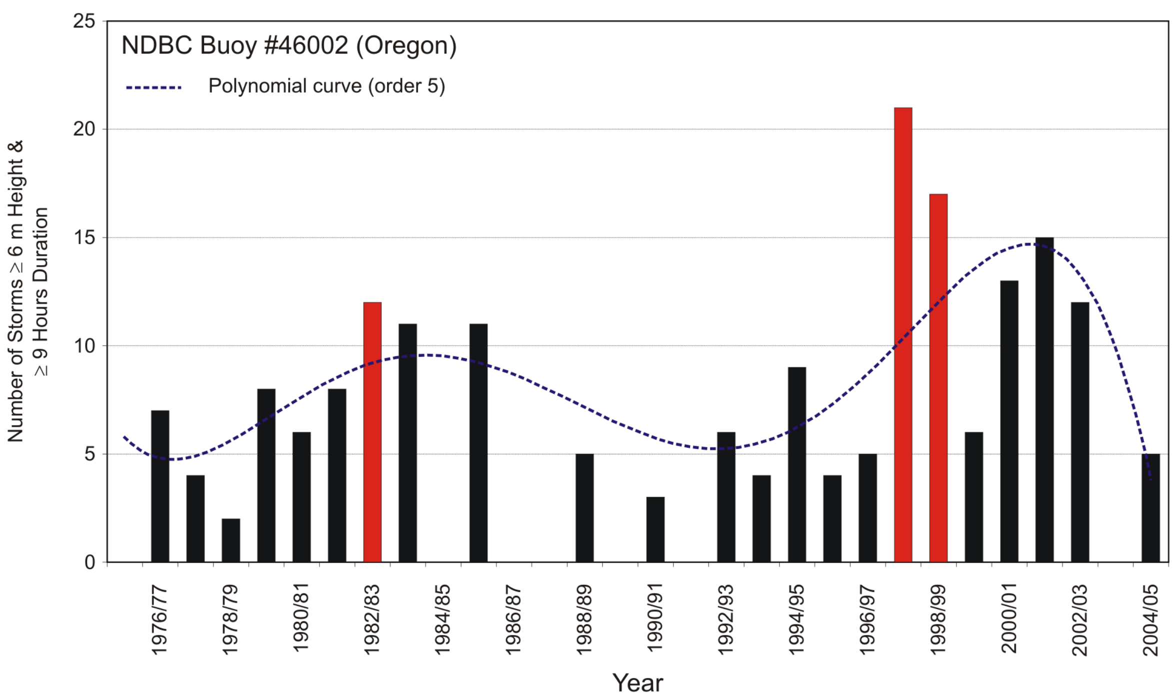


Figure 8. Incidence of storms between 1976 and 2005 that generated significant wave heights greater than 6 m for a duration of 9 hours or more (after Allan and Komar, 2000b). Data are based on the Oregon NDBC buoy (#46002). Note the unusually large number of storms that occurred during the late 1990s. Red shading denotes the major 1982-1983 and 1997-1998 El Niños and the extreme 1998-1999 winter. The blue dashed line is an order 5 polynomial regression that has been fit to the data to highlight longer cycles in storm periodicity.

Eel River buoy in northern California did not exceed 6.7 m (22 ft).

Between major storms, the reduced wave energies permit beach rebuilding, with the shoreline prograding (advancing) seaward and with foredunes rebuilding (Komar, 1997; Allan and Priest, 2001; Allan and others, 2003). This latter process, however, is much slower so that the foredunes may take several years to a few decades to rebuild.

Unfortunately, our confidence in wave direction information is less certain as there is much less information on wave direction offshore from Oregon, mainly because these data have only recently begun to be compiled and because of a dearth in instrumentation sites along the U.S. West Coast that have directional capabilities. Nevertheless, as a general rule it is understood that during the winter, waves typically arrive from the west or southwest, while in the summer the predominant wave direction is from the northwest, and is largely determined by the local wind regime (Komar 1997). This response is highlighted in Figure 9, which is based on an analysis of both summer and winter directional data measured by the Columbia River buoy (#46029, Figure 6). As indicated in Figure 9, the summer months are characterized by waves (83.7%) from predominantly the west to northwesterly quadrant, with fewer waves (14.6%) out of the southwest quadrant. The bulk of these reflect waves with amplitudes that are predominantly less than 3 m. In contrast, winter is dominated by much larger wave heights (up to 12 m) out of the southwest, which make up about 25% of the wave spectrum. Waves from the west are also important, increasing from about 20% in the summer to around 33% in the winter.

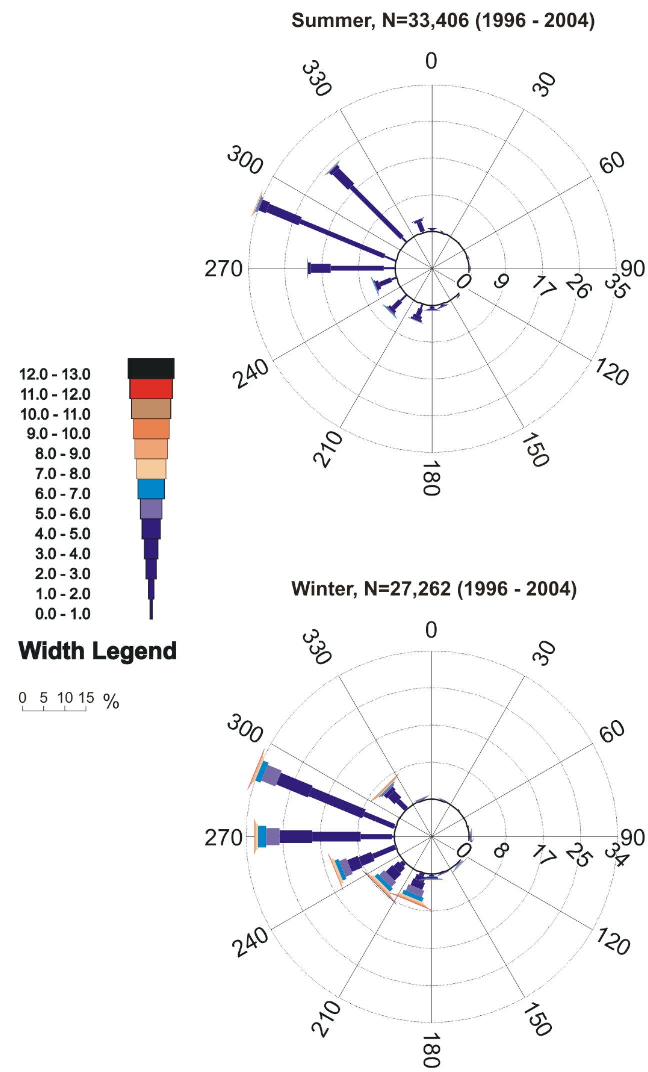


Figure 9. Wave directional information derived from the Columbia River (#46029) buoy for the period 1996–2004. *N* is the number of measurements.

## Tides

Measurements of tides on the Oregon coast are available from gauges located at four locations: the Columbia River (Astoria), Yaquina Bay (Newport), Charleston (Coos Bay) and Port Orford. The long-term record from Crescent City, California, is also useful in analyses of tides on the southern Oregon coast. Because of the proximity of Crissey Field to Crescent City, we have based our analyses of the tides on the Crescent City tide gauge. Tides along the Oregon coast are classified as moderate, with a maximum range of up to 4.3 m (14 ft) and an average range of about 1.8 m (6 ft) (Komar, 1997). There are two highs and two lows each day, with successive highs (or lows) usually having markedly different levels (Figure 10). Tidal elevations are given in reference to the mean of the lower low water levels (MLLW). As a result, most tidal elevations are positive numbers with only the most extreme lower lows having negative values. Figure 10 shows the daily tidal elevations derived from the Crescent City tide gauge (#9419750). Tides at Crescent City have a mean range[2] of 1.52 m (4.99 ft) and a diurnal range[3] of 2.09 m (6.87 ft). The highest tide measured at Crescent City reached 3.25 m (10.66 ft) and was recorded in January 1979 during the peak of the 1982-83 El Niño.

The actual level of the measured tide can be considerably higher than the predicted level provided in standard Tide Tables and is a function of a variety of atmospheric and oceanographic forces, which ultimately combine to raise the mean elevation of the sea. These latter processes also vary over a wide range of time scales and may have quite different effects on the coastal environment. For example, strong onshore winds coupled with the extreme low atmospheric pressures associated with a major storm can cause the water surface to be raised along the shore as a storm surge. However, during the summer months these processes can be essentially ignored due to the absence of major storms systems. El Niño climate phenomena may also super-elevate mean water levels for a period of a few months and are described below.

On the Oregon coast, tides tend to be enhanced during the winter months due to warmer water temperatures and the presence of northward flowing ocean currents that raise water levels along the shore. This effect can be seen in the monthly averaged water levels (Figure 11), derived from the Crescent City tide gauge, but where the averaging process has removed the water-level variations of the tides, yielding a mean water level for the entire month. Included in the figure are the results of similar analyses undertaken for the Port Orford tide gauge, located on the southern Oregon coast (Figure 6). Based on 73 years of data, the results in Figure 11 indicate that on average monthly-mean water levels during the winter are 0.17 m (0.57 ft) higher than in the summer; the Port Orford gauge indicates a seasonal increase in the mean monthly water levels by 0.23 m (0.74 ft) between summer and winter. Water levels are most extreme during El Niño events, due to an

2. The difference in height between mean high water and mean low water.
3. The difference in height between mean higher high water and mean lower low water.

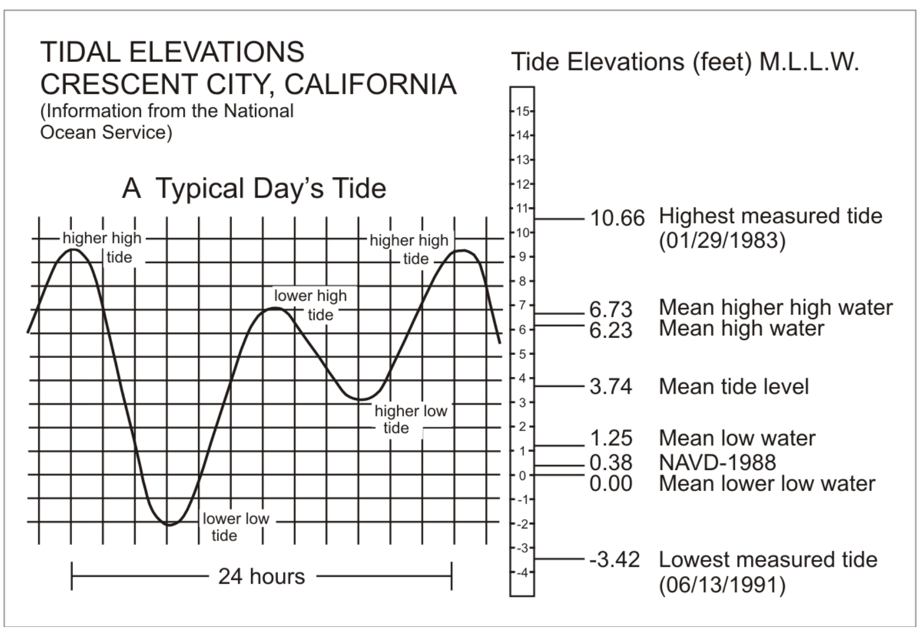


Figure 10. Daily tidal elevations measured in Crescent City on the northern California coast. M.L.L.W. is mean lower low water. Data from the National Ocean Service (http://www.co-ops.nos.noaa.gov/).

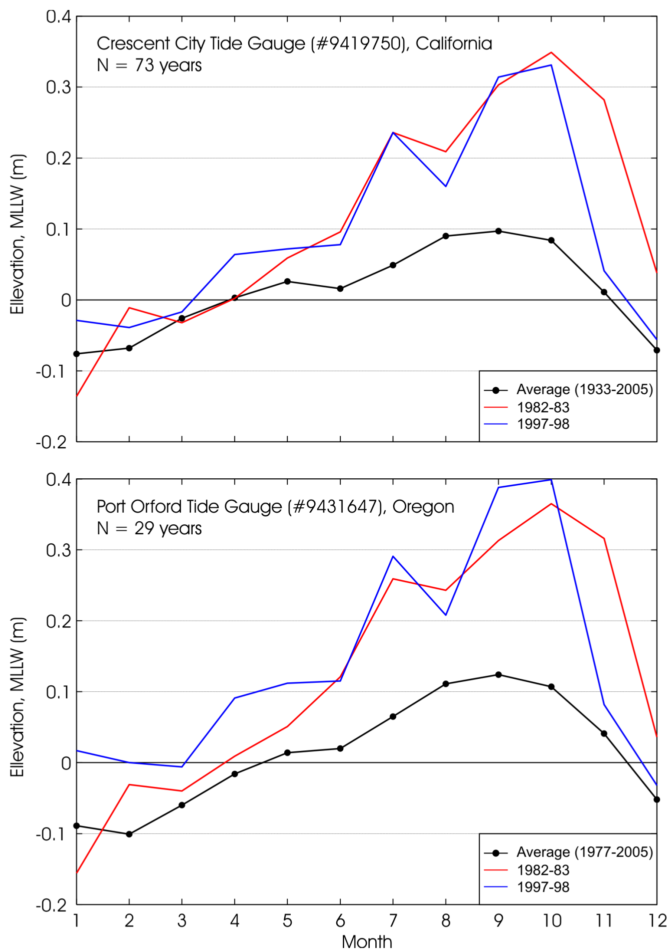


Figure 11. Mean monthly tides determined from the Crescent City tide gauge, California, expressed as a long-term average (1933–2005) and as monthly averages for the 1982-83 and 1997-98 El Niños. Included in the figure are similar analyses undertaken for the Port Orford tide gauge (1977–2005) located on the southern Oregon coast.

intensification of the processes, and are largely due to enhanced ocean surface temperatures offshore from the Oregon coast. This occurred particularly during the unusually strong 1982-83 and 1997-98 El Niños; as seen in Figure 11, water levels during those climate events were approximately 0.37 to 0.49 m (1.2 to 1.6 ft) higher in the winter than during the preceding summer at Crescent City. The importance of this is that all tides — low tides as well as high tides — would be elevated by that amount, enabling wave swash processes to reach much higher elevations on the beach. The patterns shown in Figure 11 are consistent with the findings of Huyer and others (1983), Komar (1986), and Allan and Komar (2002) derived from analyses of the Yaquina Bay (Newport) tide gauge, with the exception that the Yaquina Bay tide gauge yields mean water levels that are on average 0.1 m higher during an El Niño when compared with the gauge at Crescent City.

## SCALES OF COASTAL CHANGE

Coastal changes along the Pacific Northwest (PNW) span an extremely wide range of temporal and spatial scales, due to the diverse range of processes that influence the coastal environment (Shoreland Solutions, 1998). Most obvious and simplest to appreciate in the PNW are those beach changes that occur between summer and winter. For example, during the summer months beaches accumulate sediments due to the predominance of low wave heights and long periods, while in winter the same beaches erode rapidly in response to an increase in the wave energy and changes in the directions of wave approach. Periodically, these natural cycles of coastal change are further enhanced by the occurrence of infrequent high-magnitude storm events that can account for some 30 m (100 ft) of dune retreat along the coast (Komar and others, 1999). Ruggiero and Voigt (2000) presented measurements of beach change for six sites along the Clatsop Plains. They found that the Clatsop beaches eroded by as much as 38 m (125 ft) during the 1998-99 La Niña winter. Nevertheless, as noted by Komar and others (1999), the record of such occurrences is relatively short, limited to 30 years at best, so that the effects from extreme storm events, or from storms-in-series, remain largely qualitative.

This absence of high-quality field data was made particularly apparent after the extreme 1998-99 La Niña winter storm that occurred on March 2-3, 1999. That event is one of the most severe storms to hit the PNW Coast since the 1962 Columbus Day storm and resulted in widespread erosion along the Oregon coast (Allan and Komar, 2002). However, apart from a few problem sites such as at Cape Lookout State Park and several study sites on the Clatsop Plains, measured data of coastal recession rates associated with the storm are virtually nonexistent. This is especially true for much of the southern Oregon coast and, in particular, Crissey Field.

Recently, it has been recognized that the occurrence of severe storm events and the development of coastal hazards are related to major climate regime shifts such as the El Niño/La Niña Southern Oscillation (ENSO) phenomenon (Figure 12). El Niños exhibit dominant periods of 5-6 years (Ghil and Vautard, 1991) but may recur on 2- to 7-year cycles (Kleeman and others, 1996). Figure 12 shows a temporal plot of the occurrence of ENSO events since 1950 and is based on a multivariate ENSO index (MEI) developed by Wolter and Timlin (1993). Positive values of the MEI represent El Niño events, while negative values represent the La Niña phase. As can be seen from the graph, El Niños dominate the climate spectrum since about 1976, while La Niñas were more frequent prior to 1976.

ENSO events are superimposed on much longer climate cycles that periodically change on a 20- to 30-year basis. These latter climate shifts, known as the Pacific Decadal Oscillation (PDO), have occurred on at least four occasions during the past century (Mantua and others, 1997). Furthermore, warm phases of the PDO tend to be characterized by a greater incidence of El Niños, while the cold PDO phase is typified by a higher incidence of La Niñas. Since about 1977, the PDO has been in a predominantly warm phase characterized by a greater frequency of El Niños. Recently, scientists have been debating whether the PDO has “flipped” over into

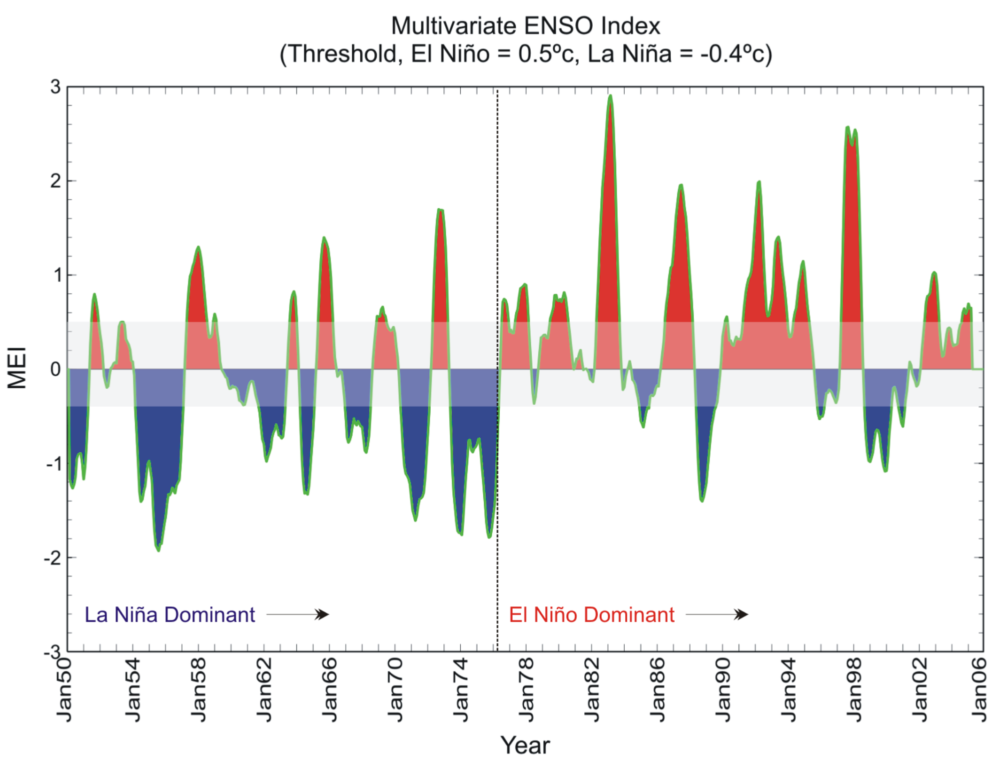


Figure 12. Multivariate El Niño/La Niña Southern Oscillation (ENSO) index (MEI) showing the incidence of El Niños and La Niñas since 1950 (data from Dr. K. Wolter, http://www.cdc.noaa.gov/people/klaus.wolter/MEI/). The shaded band indicates normal conditions.

its cold phase, which will likely be characterized by stormier/wetter conditions. It is thus possible that the rise in coastal erosion problems experienced along the Oregon coast during the past three decades may be related to the warm PDO phase, while the more recent period of severe erosion observed during the last few years, especially those associated with the 1998-99 La Niña winter storms, may be related to the beginnings of a cold PDO cycle.

Of further concern to coastal planners and managers are possible changes in the world's climate that may occur over the course of this century. It is likely that such climate changes will impact coastal systems, as variations in the incidence of storm frequency, storm tracks, or the heights of waves. For example, following efforts in the North Atlantic where long-term trends in the ocean wave heights have been identified (e.g., Carter and Draper, 1988; Bacon and Carter, 1991), Allan and Komar (2000a, 2000b, in press) have discovered similar upward long-term trends in the wave heights and periods (and therefore the wave energy) offshore from the PNW coast. This progressive increase in wave statistics is greatest offshore from the Washington coast, amounting to about 0.042 $m \cdot yr^{-1}$ for the annual averages of the winter waves, and represents a 1-m increase in the average wave heights during the 25-year record of measurements. Slightly smaller increases were found offshore from the Oregon and Northern California coasts. The exact cause of the rise in North Pacific wave heights was not determined. Recently, however, Graham and Diaz (2001) provided a comprehensive examination of the North Pacific storm climatology. Their results substantiate the findings of Allan and Komar (2000a; 2000b; in press). In particular, Graham and Diaz revealed that the frequency and magnitude of storms in the North Pacific have in fact been increasing since the early 1940s. Furthermore, they identified increasing sea surface temperatures in the western tropical Pacific as a plausible cause of the observed changes in North Pacific storm frequency and intensity.

It is apparent from the brief review presented here that atmospheric and oceanographic forces are far from constant in the PNW over short or even longer time scales. Furthermore, because coastal change tends to emulate the forcing mechanisms, namely climate, erosion of beaches is not necessarily a constant process. This makes it extremely difficult to project future patterns of coastal change. However, it is precisely this sort of projection that is required in this investigation. From a planning point of view, it is important to appreciate the wide range of temporal and spatial scales in which beaches can respond to atmospheric and oceanographic forces. Of particular importance is distinguishing movements in the beach form (its height and width) that occur over short time scales (in response to variations in the waves and currents) from longer-term changes that are dependent on the state of balance or imbalance among the various elements of the sediment budget. From a shore management perspective it is important to clearly distinguish the shorter temporal beach changes from the longer-term adjustments, as they have very different implications for land-use adjacent to any water body.

Unfortunately, few data are available along the Oregon coast to make concise statements about the long-term character of the coastal system. This absence of information makes it equally difficult to project future trends in shoreline positions. However, what is known about the coast is that the beaches mainly respond episodically (Komar and others, 1999; Peterson and others, 2000), due to the occurrence of large storms such as the March 2-3, 1999, or storms-in-series as occurred during the 1997-98 El Niño winter. This has led coastal scientists to develop models to account for such episodic erosion. In particular, Komar and others (1999) developed a geometric model to estimate the maximum potential erosion distance (MPED) on those beaches backed by dunes. In the absence of high-quality coastal data for the Crissey Field shore, this approach is used to establish coastal erosion hazard zones along the Crissey Field subcell shoreline.

# METHODS — MORPHOLOGY SURVEYS, LIDAR DATA, AND HISTORICAL SHORELINES

Several techniques have been used to provide documentation of the coastal geomorphology of the Crissey Field shoreline and to assess its susceptibility to extreme erosion. These include:

- Detailed analyses of the waves and tides that affect the morphology of the beaches (some of which were discussed previously);
- Analyses of a beach profile monitoring network established along the Crissey Field shoreline for the purposes of this study and from measurements of various coastal features along the subcell including the current beach-dune junction (akin to the vegetation line) line and shoreline position;
- Analyses of 2002 LIDAR beach topography data;
- Analyses of historical shoreline information; and,
- Analyses of the potential for beach and dune erosion under a range of extreme storm conditions.

## Beach Profile Surveys

In March 2005, the author and Mr. Matt Reynolds (OPRD) made an initial site visit to the beach at Crissey Field. The objective of the visit was to undertake a reconnaissance of the beach between the Winchuck River and Crissey Point to the south, and, in particular, the area adjacent to the proposed Welcome Center site. The reconnaissance also included a visual inspection of the beach to the south of Crissey Point down to the mouth of the Smith River (Figure 1). As part of this visit, a beach profile monitoring network was established along a 400-m section of the beach, immediately south of the Winchuck River (Figure 13) and adjacent to the proposed Welcome Center site. This network initially consisted of four profiles (cross-sections), spaced approximately 40 m apart. Such surveys provide a snapshot of the shape of the beach for that individual survey (e.g., height of the dune crest, beach slope, presence or absence of any erosion scarps, volume of sand, information on swash runup limits, etc.). Subsequent resurveys of the profiles provide insight into the spatial and temporal behavior of the beach as it responds to variations in waves, currents, and tides.

In a supplemental site visit undertaken in June 2005, the beach monitoring network was expanded to include six additional sites, providing coverage of the shore between the mouth of the Winchuck River and Crissey Point (Figure 13). Thus, two surveys of the beach have been undertaken and provide some

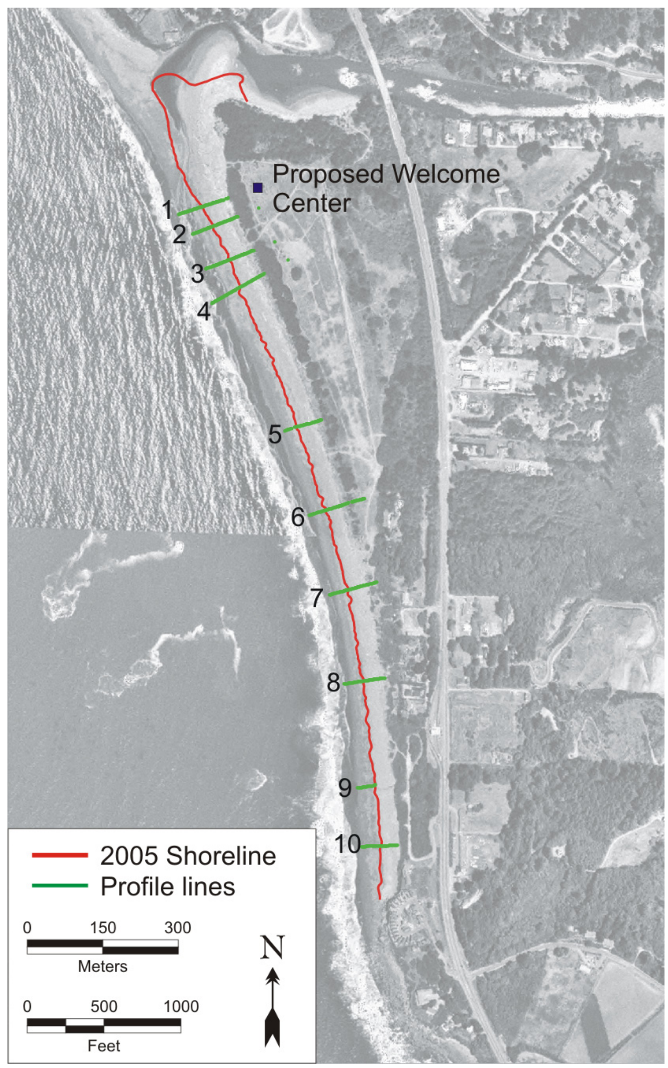


Figure 13. Locations of the Crissey Field beach monitoring network established in March and June 2005.

measure of the response of the beach between March and June 2005 (i.e., post winter and mid summer surveys). However, the most ideal scenario is for several additional surveys to be undertaken in the middle of winter and/or after major storms so that a more complete assessment of the response of the beach to storms could be made.

Surveying the beach profiles was accomplished using a state-of-the-art Trimble Real-Time Kinematic Differential Global Positioning System (RTK-DGPS), which includes a 5700 Base Station and 5800 Rover. At the time of the survey, precise coordinates of the location of the base station were unknown. However, these were subsequently established using the Online Positioning User Service (OPUS) of the National Geodetic Survey (NGS), which allows users to submit Global Positioning System (GPS) data files to the NGS, where the data are then post-processed against three Continuously Operating Reference Stations (CORS) using NGS computers and software to determine the position of the GPS unit. Additional error checking was undertaken in the field in June 2005 by performing a field site calibration to verify the NGS solution. This involved undertaking three 3-min site occupations of known NGS or Oregon Department of Transportation (ODOT) benchmarks. Benchmarks used included FISH (horizontal control), located adjacent to the U.S. Coast Guard Station on the banks of the Chetco River in Brookings, and two ODOT benchmarks (Q759 and M 759) for vertical control. Analyses of these data indicated that the greatest error between the NGS solution and the on-site field calibration was in the vertical control (the NGS solution underestimated the ground elevation by 0.11 m [ 0.36 ft]), which was adjusted accordingly to reflect the known vertical control points.

Having established a local coordinate system for the area, a topographic survey of the beach was undertaken both in March and in June 2005. The March survey focused on establishing the four initial beach profiles as well as mapping various morphological features including the position and elevation of the dune crest, the beach-dune junction line (akin to the vegetation line), areas subject to wave overtopping and hence characterized by a risk from ocean flooding, and the current location of the Winchuck River channel. Additional survey work undertaken in June 2005 was concerned with providing updated surveys of the four beach profile sites established in March 2005, expanding the profile network south to Crissey Point, surveying the (MHHW) shoreline (akin to the rack/strandline), and establishing the beach-dune junction line for the entire subcell.

## Light Detection and Ranging (LIDAR) Data

Additional information on the spatial and temporal variability of the Crissey Field beach was undertaken from an analysis of 2002 LIDAR topographic beach data measured by USGS and NASA. LIDAR is a remote sensing approach consisting of $x$, $y$, and $z$ values of land topography that are derived using a laser ranging system mounted onboard a De Havilland Twin Otter aircraft. The LIDAR data were obtained from the NOAA's Coastal Service Center (CSC), operated in tandem with the USGS and NASA. The LIDAR data have a vertical accuracy of approximately 0.1 m (0.3 ft), while the horizontal accuracy of these measurements is about 1.4 m (4.6 ft). All LIDAR data obtained from the CSC are in the 1983 Oregon State Plane Coordinate system, while the elevations are relative to the North American Vertical Datum of 1988 (NAVD' 88).

The LIDAR data were analyzed using a Nearest Neighbor grid interpolation technique to generate a grid data set. This process was accomplished using Vertical Mapper™ (contour modeling and display software), which operates within the Geographical Information System (GIS) software by MapInfo®. Additional cross-sections of the beach morphology were then constructed at 100-m intervals along the shore. These transects were used to extract various beach and dune morphological features (e.g., dune crest and beach slopes).

LIDAR was also used to derive a mean shoreline position along the Smith River littoral cell. Technically, the shoreline is the line of intersection defined by land, sea, and air, and its position in space is a function of the interaction between wave and current processes, sea level variability, sediment supply, coastal geology and geomorphology, and human intervention (Anders and Byrnes, 1991).

To identify the location of the shoreline from the LIDAR data, the data were first reduced to a tidal datum, in this case the Mean Lower Low Water (MLLW) tidal datum determined from the Crescent City tide gauge (Figure 6). To derive a tidal-based datum shoreline position, the elevation data were contoured and the MHHW contour level located at an elevation of 2.095 m above MLLW was identified as a representative shoreline position for the Crissey Field Beach. We have relied on the MHHW tidal-based shoreline, as opposed to a mean high-water (MHW) shoreline position, as recent studies (e.g., Ruggiero and others, 2003) indicate that the MHHW shoreline most closely approximates the high-water line (or rack line) used by NOAA's early National Ocean Service (NOS) surveyors.

## Aerial Photography and Historical Maps

Contemporary digital orthophoto quadrangles (DOQs) flown in 2000-01 along the Oregon coast were obtained from the Oregon Geospatial Enterprise Office (http://www.oregon.gov/DAS/IRMD/GEO/). The orthophotos provide the base information on which other data information layers (e.g., historical shorelines, LIDAR data, and profile locations, etc.) have been overlaid using the MapInfo GIS software.

Historical and contemporary information on the position of shorelines may be derived from a variety of sources including National Ocean Service (NOS) topographic "T-sheets," aerial photographs, GPS, or, most recently, LIDAR data (Moore, 2000; Zhang and others, 2002). T-sheets are detailed records of surveys that were undertaken to provide information on the location of shorelines for use on navigation charts issued by the NOS (formerly the U.S. Coast and Geodetic Survey). NOS surveyors used planetable-based ground surveys to derive a Mean High Water Line (MHWL) that was essentially based on the location of an everyday high-tide rack line. When viewed together, these data provide a first-order understanding of historical shoreline variability that supplement the estimates of coastal change determined by the geometric model. For example, variations in the position of the shore, typically identified as the Mean High Water Line (MHWL) on the NOS T-sheets, can reveal details of:

- Long-term and short-term advance or retreat of the shore,
- Longshore movement of beach sediment,
- Impact of storms, including spit breaches, overwash, and changes in inlet mouth position, and
- Human impacts caused by construction (e.g., jetties) or dredging.

Historical shoreline information has been derived from a 1928 NOS T-sheet that was surveyed along the shore. These data have been supplemented with beach and shoreline information derived from both land-based and aerial surveys of the Crissey Field beach undertaken in 1967 by the Oregon State Highway Department (now ODOT) to establish the State's "statutory vegetation line," the beach-zone boundary used to differentiate between upland properties and the state-owned or regulated beach. As surveyed in 1967, the statutory vegetation line generally corresponded with the line of vegetation where beaches were backed by dunes or extended along the toe of coastal bluffs (Komar and others, 2001).

In the absence of GPS ground control points, rectification of the 1967 images was accomplished using MapInfo's photo registration module, which allows aerial photos to be "rubber-sheeted" to a particular coordinate system based on identified map control points (MCPs; e.g., buildings, road junctions, and water tanks). The MCP data are used by the GIS software to calculate the transformations necessary to change a map's projection and scale. For the purposes of this study, the 1967 aerials were registered using the statutory vegetation line survey control points established by the Oregon State Highway Department surveyors (described in Oregon Revised Statute ORS 390.770) in 1967. Having registered the aerials, it is then possible to interpolate the morphology of the spit based on the 2-ft contours delineated on the aerial photographs. The accuracy of registering the 1967 aerial photographs was determined from comparing various features on the registered images with similar features that could be identified on the 2000-01 digital orthophotos and from a GPS survey undertaken in June 2005. This process revealed that the 1967 aerials typically landed to within approximately 3 m (9.8 ft) of similar features on the more recent 2000-01 photographs.

Finally, supplemental shoreline information has been derived by digitizing shorelines (in GIS) identified on digital orthophotos flown by the USGS in 1994, 2000/01 orthophotos flown by the State of Oregon, and from 1985/86 USGS digital raster graphics (DRGs).

## RESULTS

The Crissey field subcell makes up the northern portion of the larger Smith River littoral cell (Figure 14). The beach is bounded in the north by the Winchuck River and in the south by Crissey Point (Figure 1). Although the south end of this beach system is characterized by a small headland that may curtail the alongshore movement of beach sand, it is extremely unlikely that this in fact occurs, as sand may be transported just offshore of the headland, where the water is not too deep, enabling the sand to be freely exchanged both to the north and south of this boundary.

The beach at Crissey Field is characterized by coarse sand with a mean grain size of 0.57 mm, while the grain size may range from 0.31 to 0.99 mm (Peterson and others, 1994). Accordingly, the slopes of the beaches tend to be steeper when compared with the fine sand beaches that make up much of the central to northern Oregon coast. Analyses of the profile sites established for this study and from the 2002 LIDAR data indicate that the mean slope (*S*) for the summer beach profile is approximately 3.5° (1-on-16.5), increasing to ~5.1° (1-on-11.2) in the winter months, although slopes as high as ~5.7° (1-on-10) are not uncommon along the shore.

The beach system is backed by a well-vegetated foredune covered with European beach grass (*Ammophila arenaria*, Figure 14). Over the course of the last 50 years, this species of grass has become endemic along many of Oregon's beaches and is contributing to a rapidly changing coastal foredune system. European beach grass is a prolific grower and is extremely effective at trapping sand that is transported inland by aeolian processes. As sand piles up around the roots of the plants, the grass is capable of matching the rate of sand aggradation due to its extensive root system, which ultimately causes the dunes to build up higher.

To the extreme south end of the cell and just north of Crissey Point the foredune rises rapidly and abuts against a terrace (Figure 14). The terrace is composed of a fine gravel basal layer located immediately above the beach crest and is overlaid by coarse sand, with an additional gravel layer on top of the sand. Erosion of this feature likely contributes some material to the beach sediment budget, although it is probably negligible in comparison to the volume of sand presently being supplied by the Smith River to the south. This gravel terrace continues south of Crissey Point all the way to Pyramid Point, where it is bounded against the mouth of the Smith River. However, this latter terrace is presently not experiencing any erosion, as is evident by the well-vegetated terrace cliff face and the aggradation of sand in front of the terrace (Figure 15).

Figures 16 and 17 show the results from an analysis of historical and contemporary shoreline positions for the stretch of shore between Crissey Point and the Winchuck River. These data have been overlayed on a 2000/01 orthophoto and include shoreline position information derived from a 1928 NOS T-sheet, 1967 aerial photographs, 1985/86 USGS DRGs, 1994 digital orthophotos, 2000/01 digital orthophotos, 2002 LIDAR data, and 2005 GPS data.

As can be seen in Figure 16, the overall configuration of the shore did not appear to change greatly between 1928 and 1967, a period of some 39 years, with both shorelines having followed very similar tracts along the entire length of this beach. However, of

Figure 14. View looking south toward Crissey Point and the sand/gravel terrace located at the south end of the subcell (March 2005).

Figure 15. View looking south from Crissey Point toward the mouth of the Smith River. Note the well-vegetated gravel bluff face and the accumulation of vegetated low dune in front of the terrace (March 2005).

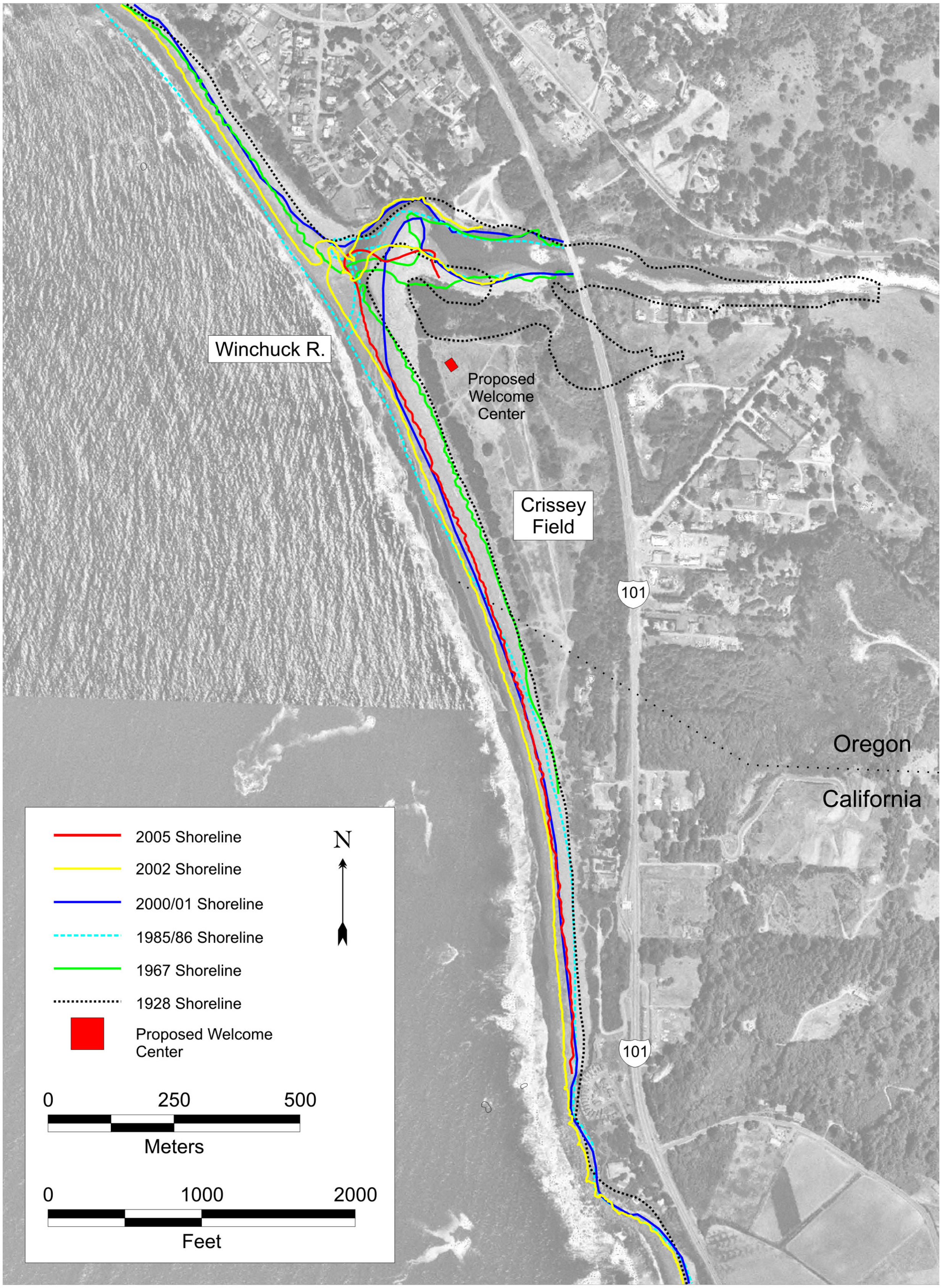


Figure 16. Historical and contemporary shoreline changes identified at Crissey Field and overlaid on a 2000/01 digital orthophoto.

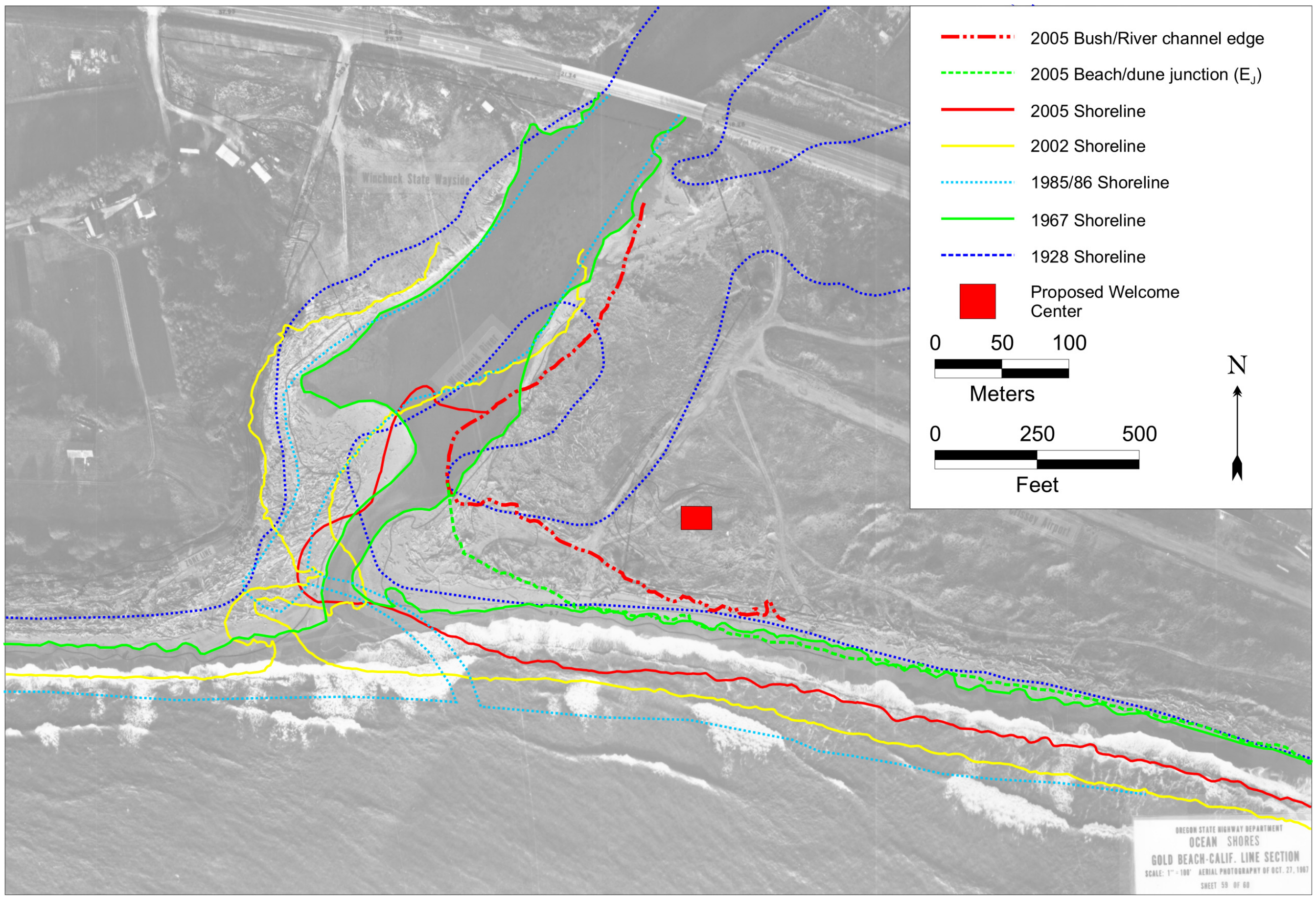


Figure 17. Detailed perspective of historical and contemporary shoreline changes identified at Crissey Field and adjacent to the proposed Welcome Center. These data have been overlaid on a 1967 digital orthophoto. Note the significant changes that occurred in the beach and foredune between 1967 and 2000/01.

interest in the north is the southward inflexion of the Winchuck River channel in 1928, placing the channel in close proximity (i.e., to the immediate north) to the proposed Welcome Center site. This region has likely remained susceptible to periodic river flooding. For example, it is apparent in Figure 17 that there is evidence of considerable accumulation of woody debris along the banks of the river, which extends southward to approximately the location of an old four-wheel drive track. Furthermore, portions of this area adjacent to the river continue to exist as a wetland, emphasizing its low-lying nature and its close association to the Winchuck River. According to the Oregon State Parks and Recreation Department (2003), approximately 90% of Crissey Field is located in the 100-year flood boundary. Although the OPRD observe that this does not preclude development, it would, however, require that the finished floor elevation of the Center be at least 7.6 m (25 ft) above sea level, which would likely require an elevated building.

Between 1967 and 1985-86, the beach foredune prograded seaward by some 70 m (230 ft). This response may be associated with the earlier 1982-83 El Niño, which could have resulted in “hotspot” erosion at the south end of the subcell and movement of the eroded sediments to the north, causing the shore to advance seaward. It may also reflect the movement of sand around Crissey Point. However, the 1985/86 shoreline position needs to be treated with some care due to uncertainty in how these shoreline data were derived by the USGS. Although not included in Figures 16 and 17, the beach did erode slightly in the north between 1985/86 and the early 1990s but by 2002 had again prograded seaward. Since 2002, the entire shoreline has eroded landward by approximately 20 m (65 ft) to its present configuration as measured by the June 2005 GPS survey.

The response of this beach over the past two decades highlights the dynamic nature of such beaches as they respond to variations in the incident wave energy and nearshore currents. However, of interest is the period of beach advance between 1967 and the early 1980s, suggesting either an extended period of relatively quiet wave conditions (i.e., lower wave energy levels) in which the waves were arriving out of the southwest, creating a northward transport of sand along the coast, and/or above average sediment supply to the beach system from the Smith River to the south. This latter view is certainly likely given the accumulation of sand to the south of Crissey Point (Figure 15), which has resulted in the development of a well-vegetated backshore and dune system in front of a terrace that previously must have been subject to wave erosion.

At Crissey Field, much of the foredune that was originally active (i.e., subject to wave erosion) in 1967 has since been stabilized by both European beach grass (Figure 18) and low stands of Sitka spruce (dashed red line in Figure 17). Under today's wave climate regime, the original 1967 shoreline is now characterized by the location of the beach-dune junction (dashed green line in Figure 17). Without a more comprehensive study of the dynamics of the larger littoral cell beach system (i.e., the entire Smith River littoral cell), it is not possible to say exactly why the beach prograded so much over the past 38 years or, more importantly, whether the beach could gradually revert back to its "original" state (as reflected in the 1967 aerial photographs) should the supply of sand decrease.

Figure 18. View looking north along the beach. Landward of the beach is a region dominated by European beach grass (*Ammophila arenaria*), while to the far right of the photo the presence of Salal (*Gaultheria shallon*) bushes and Sitka spruce mark the approximate location of the 1967 beach-dune junction.

## Erosion Hazard Zone Parameters

### *The Geometric Model*

For property erosion to occur on sandy beaches, the total water level produced by the combined effect of wave runup ($R$) plus the tidal elevation ($E_T$), must exceed some critical elevation of the fronting beach, typically the elevation of the beach-dune junction ($E_J$). This basic concept is depicted in Figure 19A. Clearly, the more extreme the total water level elevation, the greater the resulting erosion that occurs along both dunes and bluffs (Komar and others, 1999).

As can be seen from Figure 19, estimating the maximum amount of dune erosion ($DE_{max}$) is dependant on identifying the total water level elevation, $T_{WL}$, which includes the combined effects of extreme high tides plus storm surge plus wave runup, relative to the elevation of the beach-dune junction ($E_J$). Therefore, when $T_{WL} > E_J$, the beach retreats landward by some distance until a new beach-dune junction with an elevation approximately equal to the extreme water level is established (Figure 19B). As beaches along the high-energy Oregon coast are typically wide and have a nearly uniform slope (tan ß), the model assumes that this slope is maintained and that the dunes are eroded landward until the dune face reaches point B in Figure 19B. As a result, the model is geometric in that it assumes an upward and landward shift of a triangle, one side of which corresponds to the elevated water levels,

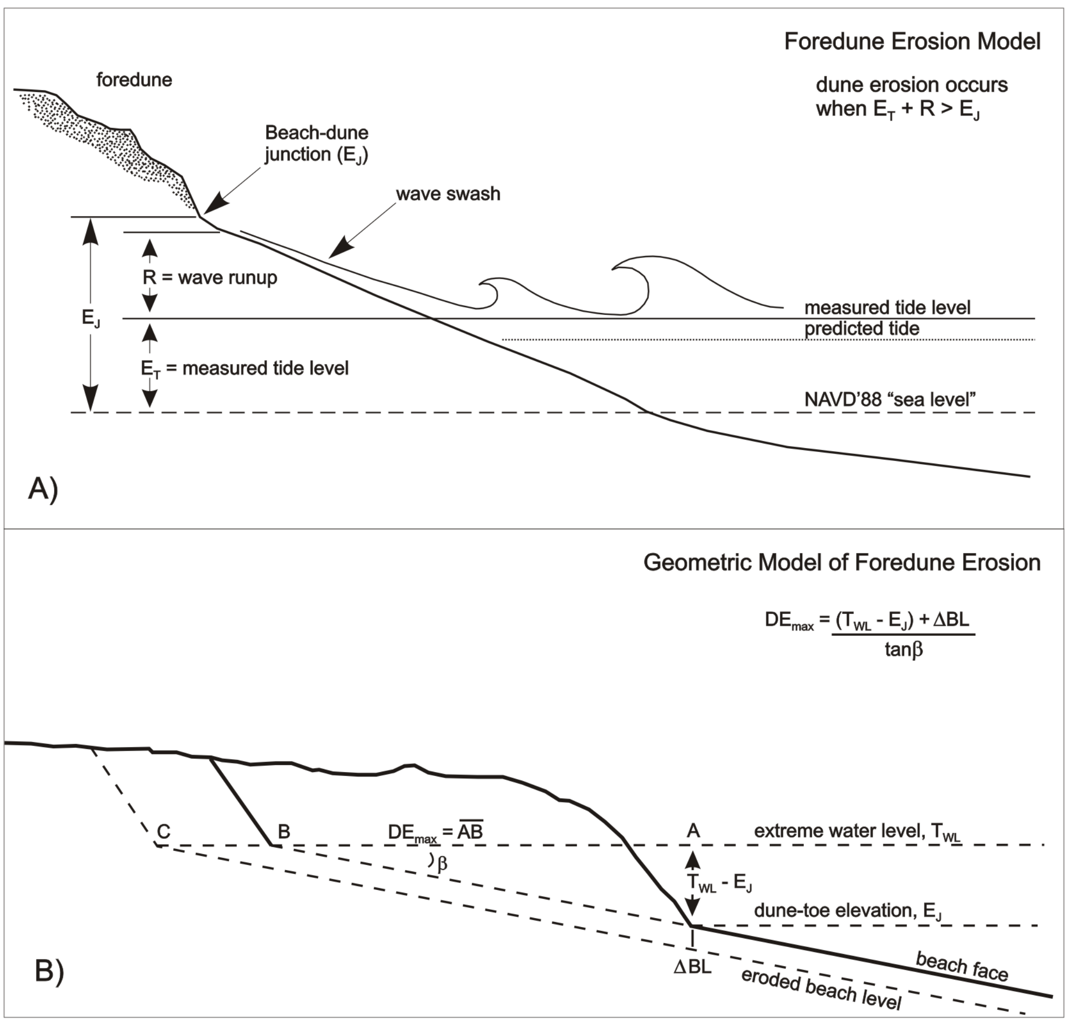


Figure 19. A) The foredune erosion model and B) the geometric model used to assess the maximum potential beach erosion in response to an extreme storm (after Komar and others, 1999).

and then the upward and landward translation of that triangle and beach profile to account for the total possible retreat of the dune (Komar and others, 1999). An additional feature of the geometric model is its ability to accommodate further lowering of the beach face due to the presence of a rip current. This feature of the model is represented by the beach-level change $\Delta BL$ shown in Figure 19B, which causes the dune to retreat some additional distance landward until it reaches point C. As can be seen from Figure 19B, the distance from point A to point C depicts the total retreat, $DE_{max}$, expected during a particular event that includes the localized effect of a rip current. Critical, then, in applying the model to evaluate the susceptibility of coastal properties to erosion is an evaluation of the occurrence of extreme tides ($E_T$), the runup of waves ($R$), and the joint probabilities of these processes along the coast (Ruggiero and others, 2001).

### *Wave Runup*

Detailed studies of wave runup along the Oregon Coast, under a range of wave conditions and beach slopes (Ruggiero and others, 1996; Ruggiero and others, 2001), have yielded the following relationship

$$R_{2\%} = 0.27(SH_{SO}L_O)^{1/2} \quad (1)$$

for estimating the 2% exceedence runup ($R$) elevation, where $S$ is the beach slope (tan ß), $H_{SO}$ is the deep-water significant wave height, $L_O$ is the deep-water wave length given by $L_O = (g/2\pi)T^2$, where $T$ is the wave period, and $g$ is acceleration due to gravity ($9.81\ m{\cdot}s^{-1}$). Therefore, estimates of the wave runup elevation depend on knowledge of the deepwater wave heights and peak spectral wave periods. As a major objective of this investigation is to estimate the maximum potential erosion ($DE_{max}$) that may occur in response to sustained periods of wave attack during extreme storm events (Figure 19), it is important to examine the probabilities of extreme wave occurrence offshore from the PNW coast.

### *Wave Statistics*

As observed previously, wave statistics (wave heights and periods) have been measured in the North Pacific using wave buoys and sensor arrays for almost 30 years. Previous analyses of these data up through 1996 indicated that the projected 100-year extreme storm for the Oregon coast would generate a deep-water significant wave height on the order of 10 m (33 ft) (Ruggiero and others, 1996). However, during the 1997-98 and 1998-99 winters, the PNW was affected by the equivalent of five 100-year storms. Since those two winters we have experienced four more 100-year storms. In response to these events, the wave climate of the eastern North Pacific was re-examined to determine the probabilities of extreme wave occurrence offshore from the PNW coast (Komar and Allan, 2000; Allan and Komar, in press). Using standard techniques of extreme value analysis, the 10- through 100-year extreme values for the deep-water significant wave heights were determined for several wave buoys located along the West Coast of the United States. These analyses yield 100-year storm wave heights that range from 15 to 16 m (46 to 55.1 ft), and were derived for four wave buoys offshore from the PNW coast. Apart from highlighting the extreme nature of the wave climate in the eastern North Pacific, these results also emphasize the variability of the wave climate along the coasts of Washington and Oregon due to deviations in the predominant storm tracks.

Because Crissey Field is located at the extreme south end of the Oregon coast and is in a zone of wave climate transition (i.e., higher wave heights offshore from Oregon versus lower wave heights offshore from northern California), analyses have been undertaken of the extreme wave heights and peak spectral periods based on the Eel River (#46022) and Newport NDBC buoys (#46050). Wave data from the Port Orford buoy were ignored here due to its short record of measurements (~3 years). Analyses were undertaken using the Automated Coastal Engineering System (ACES) package of coastal engineering and design analysis programs originally developed by the U.S. Army Corps of Engineers. This program includes several theoretical extreme-value equations, the objective being to find the curve that best fits the data. The data entered into the analyses are the monthly maximum wave heights greater than 6 m (19.7 ft). The resulting graphs and the derived values for the 2- through 100-year projected extreme deep-water significant wave heights are given in Figure 20.

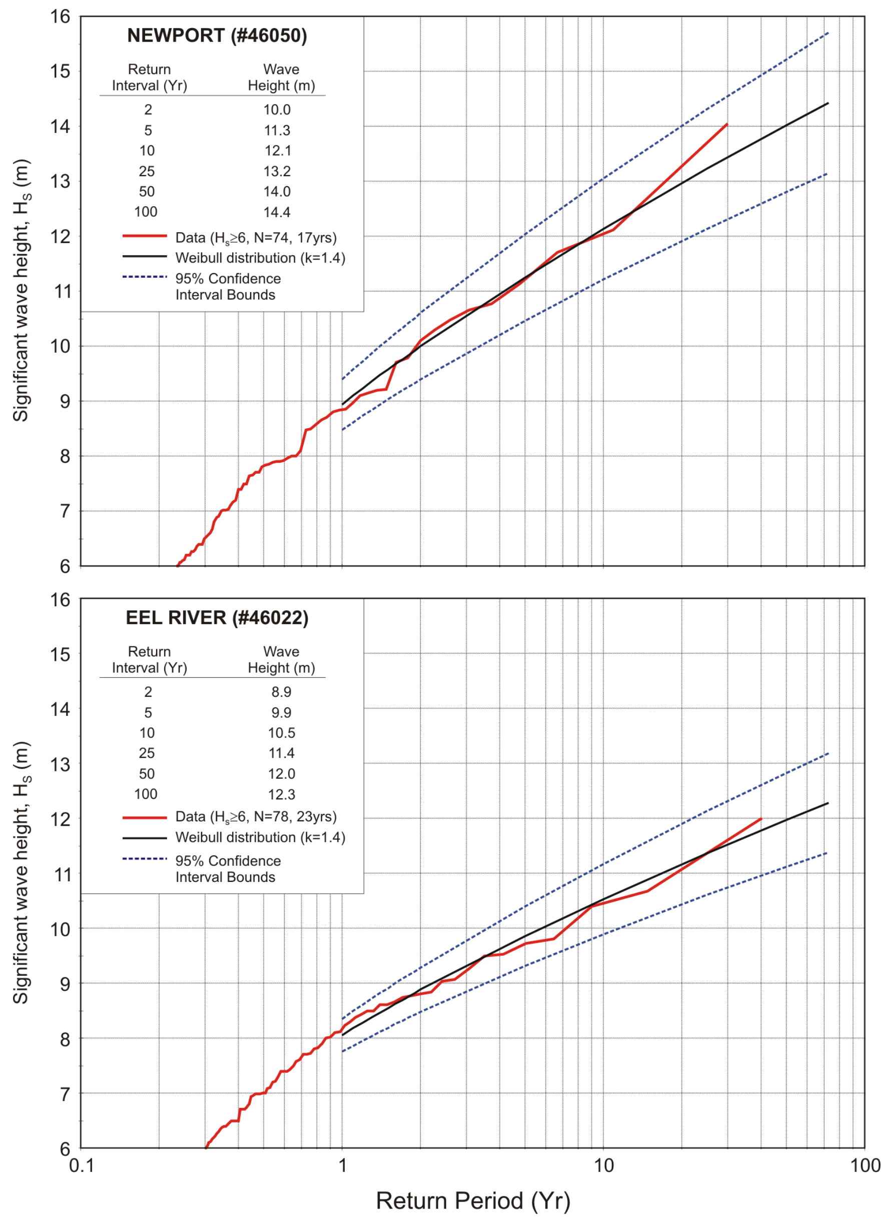


Figure 20. Extreme-value distributions fitted to monthly measurements of the largest (> 6 m) storm-wave heights measured by the Newport and Eel River buoys.

As can be seen in Figure 20, the estimated 50- through 100-year storm wave ranges from 12 to 12.3 m (39.4 to 40.4 ft) based on the Eel River buoy, and 14.0 to 14.4 m (45.9 to 47.2 ft) based on the Newport buoy. However, for such a projection to be statistically valid, it generally is considered that the measured record must be at least one third the time span of the projected extreme value; for example, to project the 100-year storm-wave conditions, it is necessary to have at least 33 years of wave measurements. The two NDBC buoys relied upon in the present analysis have been in operation since only 1982 (Eel River) and 1987 (Newport), which means that predictions greater than 69 and 51 years, respectively, are not statistically valid. This makes the 100-year projections somewhat uncertain. Nevertheless, because the wave runup model introduced above is more dependent on the peak spectral wave period (i.e., $T_P^2$), small differences in wave height do not greatly effect calculated wave runup or, ultimately, the predicted amount of dune erosion. In other words, a difference of 1-2 m (3.3–6.6 ft) between the Newport 100-year estimate of significant wave height and the estimate of 15-16 m (49.2–52.5 ft) calculated for the PNW (where the results are statistically valid) does not greatly affect the estimated amount of dune erosion predicted by the geometric model.

Integral to calculating wave runup on beaches and hence their potential for erosion is knowledge of peak spectral wave periods as well as wave heights. Tillotson and Komar (1997) developed joint-frequency graphs of significant wave heights versus spectral-peak periods for data derived from the CDIP-Bandon buoy and for the NDBC buoy located over the continental shelf offshore from Newport. Figure 21 shows the joint-frequency graphs developed in the present study, based on the Eel River and Newport wave buoys, located offshore from Humboldt Bay in northern California and offshore from Newport on the central Oregon coast, respectively. As can be seen for the Newport buoy, the largest wave heights are centered mainly at a period of about 14-15 s but may reach periods of about 20 s (Figure 21). For example, the February 16, 1999, storm was characterized by a maximum significant wave height of 10 m, while the peak spectral periods reached 20 s. In contrast, the largest wave heights are centered mainly at a period of about 16–20 s at the Eel River buoy. As noted previously, this reflects the longer fetches and greater dispersion times for waves traveling across the North Pacific and down into northern California. Figure 21 also shows that occasionally waves have periods up to 25 s, but they are typically associated with lower wave heights, less than 5 m at the Newport buoy and less than 8 m at the Eel River buoy, apparently representing long-period swell from a distant source rather than generation by local storms. Accordingly, because Equation 1 is especially sensitive to the magnitude of the wave period, and because we wish to build a degree of conservatism into the dune erosion modeling, we have focused on the longer-period wave events in our modeling of wave runup elevations.

### *Tides*

The elevation of the ocean, in part controlled by the astronomical tide, is extremely important for the occurrence of beach and property erosion along the Oregon coast (Komar, 1986). This process is particularly enhanced when large waves are superimposed on elevated water levels, so that wave processes are able to reach much higher elevations on the shore. It is the combined effect of these processes that invariably leads to toe erosion on coastal dunes and bluffs and, eventually, coastal recession.

Figure 19 indicates that the measured tides ($E_T$) and the wave runup levels ($R$) calculated from Equation 1 are combined to yield a total water level ($WL$) elevation, which is then input into the geometric model. When $WL$ exceeds the elevation of the beach-dune toe, erosion occurs and the dune retreats landward until a new beach-dune toe is established, which approximately equals the total water elevation caused by the storm. However, the addition of measured tides and wave runup components together, e.g., the 50-year runup level combined with the 50-year tide, is not as straightforward as it seems, due to the fact that these processes have been found to operate independently from each other (Komar and others, 1999; Ruggiero and others, 2001). In other words, the occurrence of an extreme storm does not necessarily mean that it will occur concurrently with an extreme tide. As a result, because both variables occur independently, it is necessary to consider their joint probabilities of occurrence, which is the product of the two individual probabilities. Thus, a 50-year runup level combined with a 50-year tide would yield a joint return period of about 2,500 years ($50 \times 50 = 2500$ years). To some degree, one can get around this problem by applying various combinations of extreme tides plus wave runup elevations. For example, a 50-year storm runup event may be combined with a 2-year extreme tide to yield a 100-year total water level. One approach might be to evaluate the total water levels associated with particular storms, the combined mean-water level (tides + surge + El Niño effects), and the wave runup, and then analyze the probabilities of these levels together (Komar and others, 1999). However,

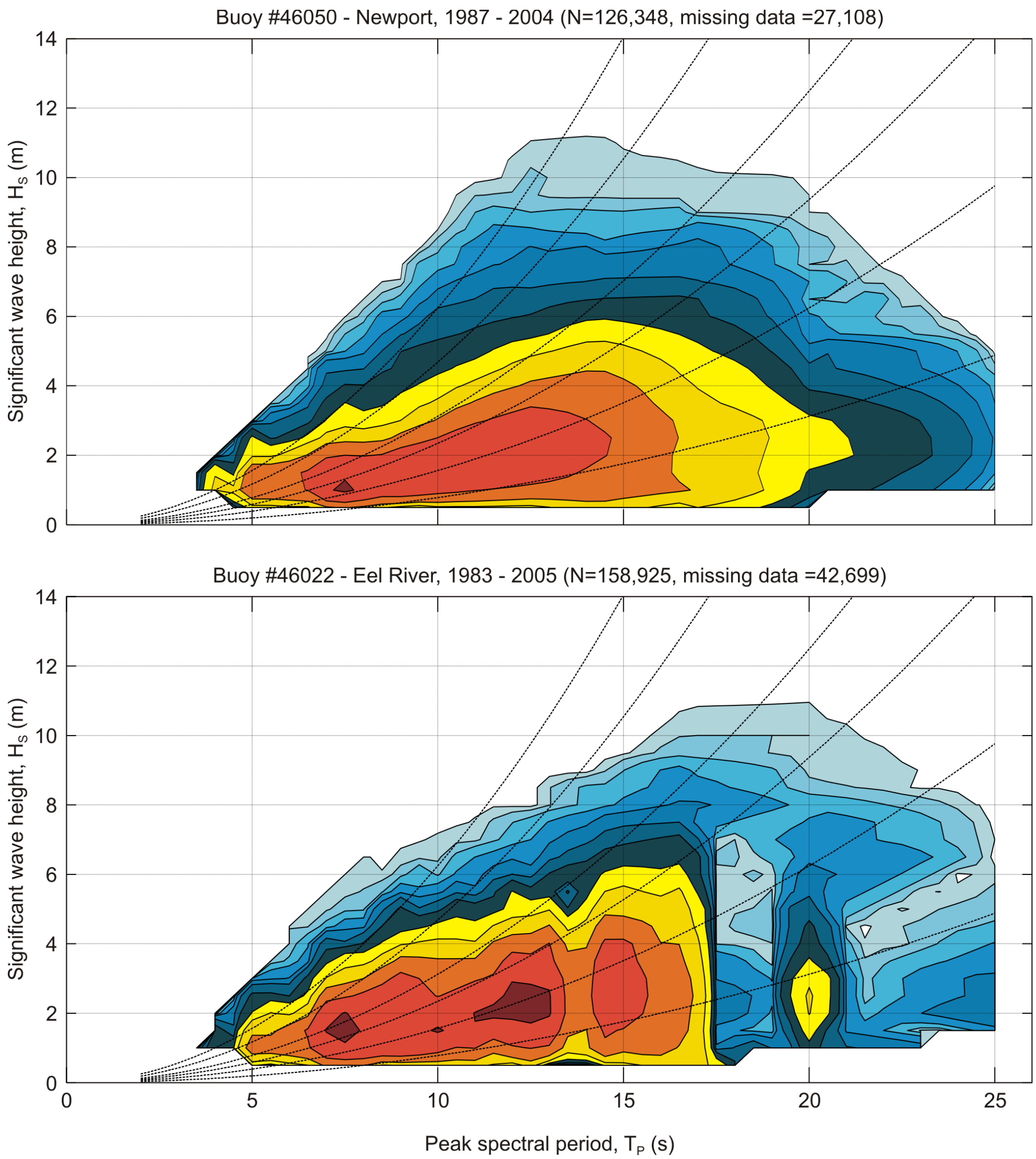


Figure 21. Joint-frequency graph of significant wave heights versus peak spectral wave periods, based on data from NDBC buoy #46050 (Newport) and #46022 (Eel River) positioned offshore from Newport, Oregon and Humboldt Bay, California (see Figure 1).

such analyses have yielded values that closely approximate those derived using the approach that sums the individual values (the approach adopted here), suggesting that either technique is useful. With that in mind, the scenarios described below assume that a major storm occurs over the course of an above average high tide. This is consistent with the approach taken by Komar and Allan (2000) and Allan and Priest (2001) in developing their scenarios of high waves and water levels along the central Oregon coast. At Crissey Field, the Mean Higher High Tide averages about 2.095 m (6.87 ft) relative to Mean Lower Low Water. When converted to the NAVD'88 datum, this amounts to an elevation of 1.98 m (6.5 ft). Thus, when other variables are added to this, all elevations will be relative to the NAVD'88 datum.

The actual level of the measured tide can be considerably higher than the predicted level provided in most standard Tide Tables and is a function of a variety of atmospheric and oceanographic forces that ultimately combine to raise the mean elevation of the sea. These latter processes also vary over a wide range of time scales and may have quite different effects on the coastal environment. For example, strong onshore winds coupled with the extreme low atmospheric pressures associated with a major storm can cause the water surface to be raised along the shore as a storm surge. Along the PNW coast, the role of storm surges in coastal hazard applications has for the most part been ignored, largely because the storm surge elevations were thought to be quite small. For example, analyses of daily mean water levels up through 1996 at Newport, Oregon, revealed that the surges are typically on the order of 0.09 to 0.15 m (0.3 to 0.5 ft) (Ruggiero and others, 1996). However, recent analyses of storm surges that occurred during the 1997-98 El Niño and 1998-99 La Niña winters revealed surges that were on the order of 0.40 to 0.61 m (1.3 to 2.0 ft), which suggest that much larger storm surge heights can be experienced along the PNW coast (Allan and Komar, 2002). As a result, any analysis of future coastal change should include a storm surge component. In this study, we have chosen a storm surge component of 0.5 m (1.64 ft) for the HIGH-risk scenarios and 1.0 m (3.3 ft) for the MODERATE-risk scenario, similar to what has been used to estimate beach erosion potential along the northern Oregon coast (Allan and Priest, 2001).

Long-term trends in the level of the sea, which relate to the global (eustatic) rise in mean sea level (MSL) occurring over the past several thousand years, can also be identified along the coast. However, these changes in mean sea level are complicated due to ongoing changes in the level of the land that are also occurring along the Oregon coast. For example, Vincent (1989) has demonstrated that the northern Oregon coast is being slowly submerged by the rise in mean sea level, while the southern Oregon coast, including the area around Brookings, is rising at a faster rate than the global rise in mean sea level (Figure 22). NOS provides online estimates of changes in long-term MSL for selected tide gauges around the U.S. coast (e.g., http://www.co-ops.nos.noaa.gov/sltrends/sltrends.shtml). An examination of the trend for the Crescent City tide gauge indicates that MSL is falling at a rate of -0.48 mm/yr. Assuming this rate of sea level change continues, we can expect a change in MSL of about -0.05 m (-0.16 ft) along the Crissey Field coastline over the next 100 years, which is negligible in erosion hazard calculations.

Finally, a seasonal increase in monthly water levels has been incorporated into the tidal component. The value used here is 0.17 m (0.56 ft), which is based on data from the Crescent City tide gauge.

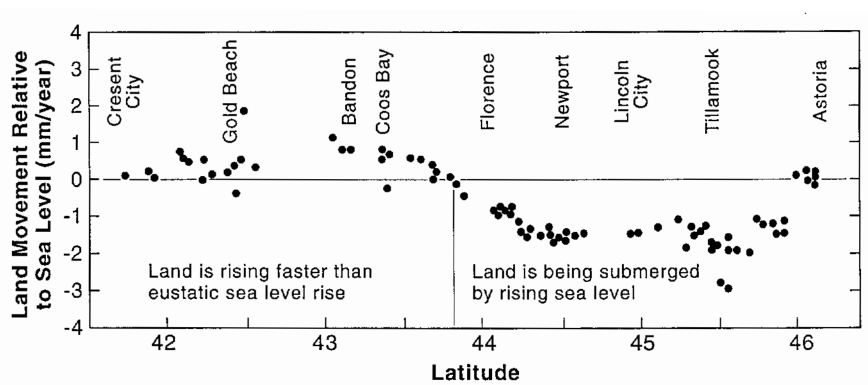


Figure 22. Elevation changes along the Oregon coast, measured by geodetic surveys (Vincent, 1989). The elevation changes are relative to the global increase in sea level, with positive values representing a rise in the land at a higher rate than the increase in sea level and negative values representing the progressive submergence of the land (from Komar, 1997).

***Beach Morphology***

Having described the various process elements that are required as input into the geometric model, it remains for the morphological variables of the beach to be determined. These last variables include determinations of the beach slope (tan ß) and the beach-dune toe elevation ($E_J$).

Several approaches, including direct measurements of slopes and beach-dune junction elevations along beach profiles sites, as well as actual measurement (i.e., walking the line using RTK-DGPS) of the beach-dune junction elevation between Crissey Point and the Winchuck River), have been used to establish the parameters. All GPS data that were measured are in the 1983 Oregon State Plane Coordinate system (meters), and the elevations are relative to the North American Vertical Datum of 1988 (NAVD' 88). These data have been supplemented with 2002 LIDAR data measured jointly by NOAA, NASA, and USGS.

Figures 23 and 24 show variations in the response of beach profiles 1-4 established nearest to the proposed Welcome Center site. As noted previously in the section on shoreline change, the most notable response characterized by these data is the seaward progradation of the shoreline since 1967. The 2002 LIDAR profiles indicate the presence of a high backdune, located landward of the 50-m distance marker. In fact, this feature, identified in Figure 23, is an artifact of the LIDAR data, which has recorded vegetation (i.e., stands of Sitka spruce). Nevertheless, the seaward face of this feature provides an approximate location of where the 1967 beach crest was probably located (Figures 23 and 24). Since 1967, the crest of the beach has advanced seaward by some 10 to 20 m (30 to 60 ft) and has subsequently become stabilized by European beach grass so that it has now begun to develop a new foredune system (Figures 23 and 24). In contrast, the 3-m contour elevation prograded seaward by about 30 to 40 m (100 to 130 ft). Assuming that the beach continues to receive additional sand inputs, one can speculate that the beach may continue to aggrade vertically and advance seaward, further building this foredune. However, there is currently insufficient evidence to indicate if this will indeed occur.

The beach profiles indicate that between the 2002 LIDAR flights and the GPS survey in 2005, a small dune has developed at profile 1 and has been lowered slightly at profiles 2, 3, and 4. This latter response suggests periodic wave overtopping of the dune crest during major storms. In addition, it is worth noting that a small erosion scarp (less than 0.5 m [1.6 ft] high) has developed in front of the developing dune and is likely is the product of a recent storm (e.g., from the 2004/05 winter). The profile response between the March and June 2005 surveys also captures the seasonal buildup of sand on the beach due to the decrease in incoming wave energy between winter and summer. As can be seen in Figures 23 and 24, the bulk of this aggradation is confined to the lower beach face (i.e., below the 4-m contour elevation). In all likelihood, if an updated survey were undertaken late in summer, one would expect to see significant aggradation of sand on the upper beach face, in front of the developing dune. These types of responses are perfectly natural and are consistent with what is observed on other beaches along the Oregon coast.

As can be seen in Figures 23 and 24, the elevation of the beach-dune junction ($E_J$) is relatively similar among the four study sites and ranges from 5.2 to 5.4 m (17.1 to 17.7 ft). However, when viewed along the full length of the subcell (Figure 25), it can be seen that the portion of beach covered by these profiles (grey box in Figure 25) is on average slightly lower when compared with the southern two thirds of the shore. The mean elevation of the beach-dune junction along the entire subcell is ~5.7 m (18.7 ft), while the northern beach section has a mean elevation of ~5.1 m (16.7 ft); the southern two thirds of the shore has a mean beach-dune junction elevation of 6.02 m (19.8 ft). As noted previously, beach slopes identified from the GPS survey indicate slopes that average approximately 3.5° (1-on-16.5) in the summer, increasing to ~5.1° (1-on-11.2) in the winter months.

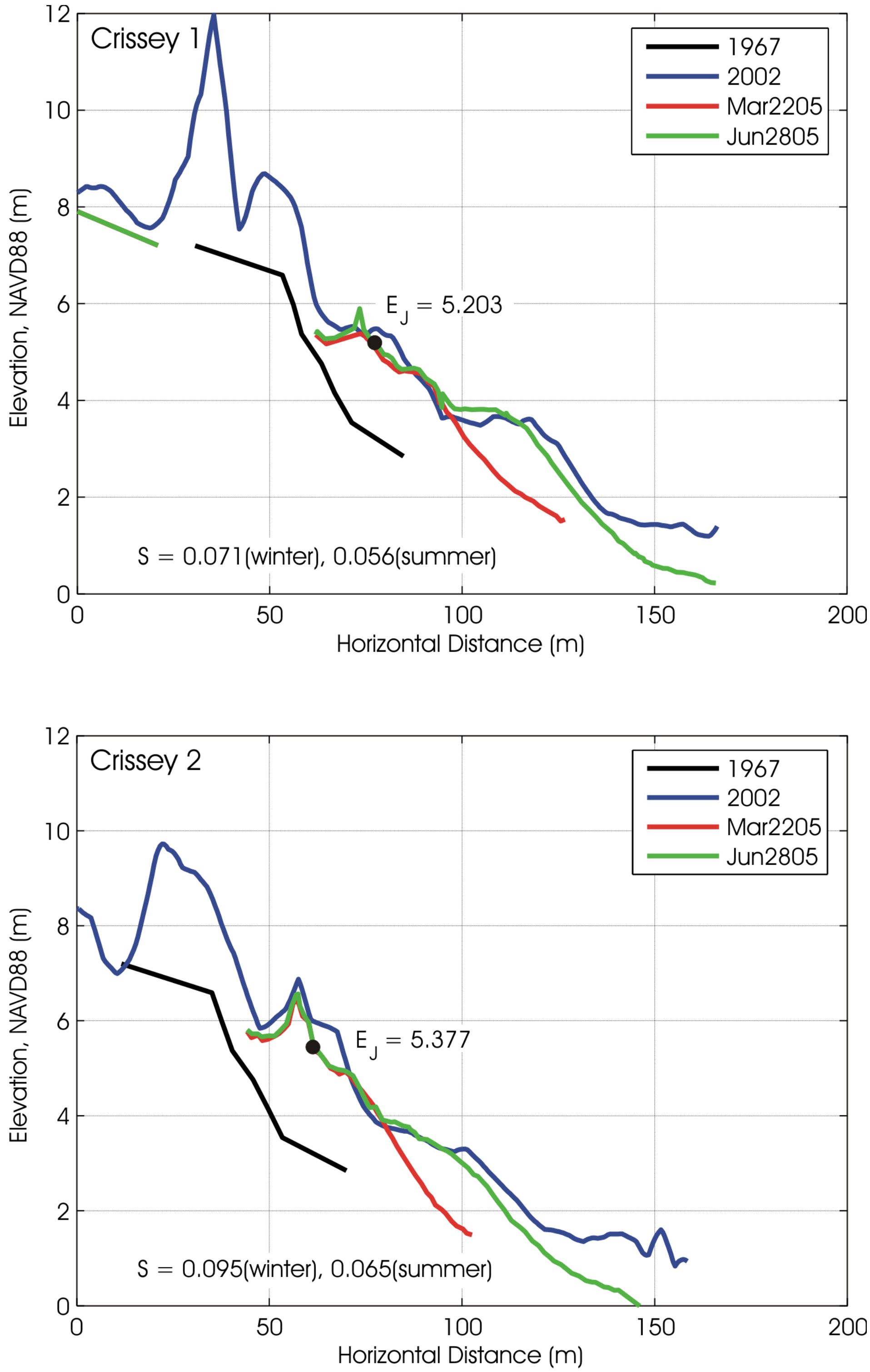


Figure 23. Beach profiles 1 and 2 measured at Crissey Field. Data include information derived from contours provided on 1967 ODOT aerial photographs, 2002 LIDAR data, and GPS survey data measured in 2005.

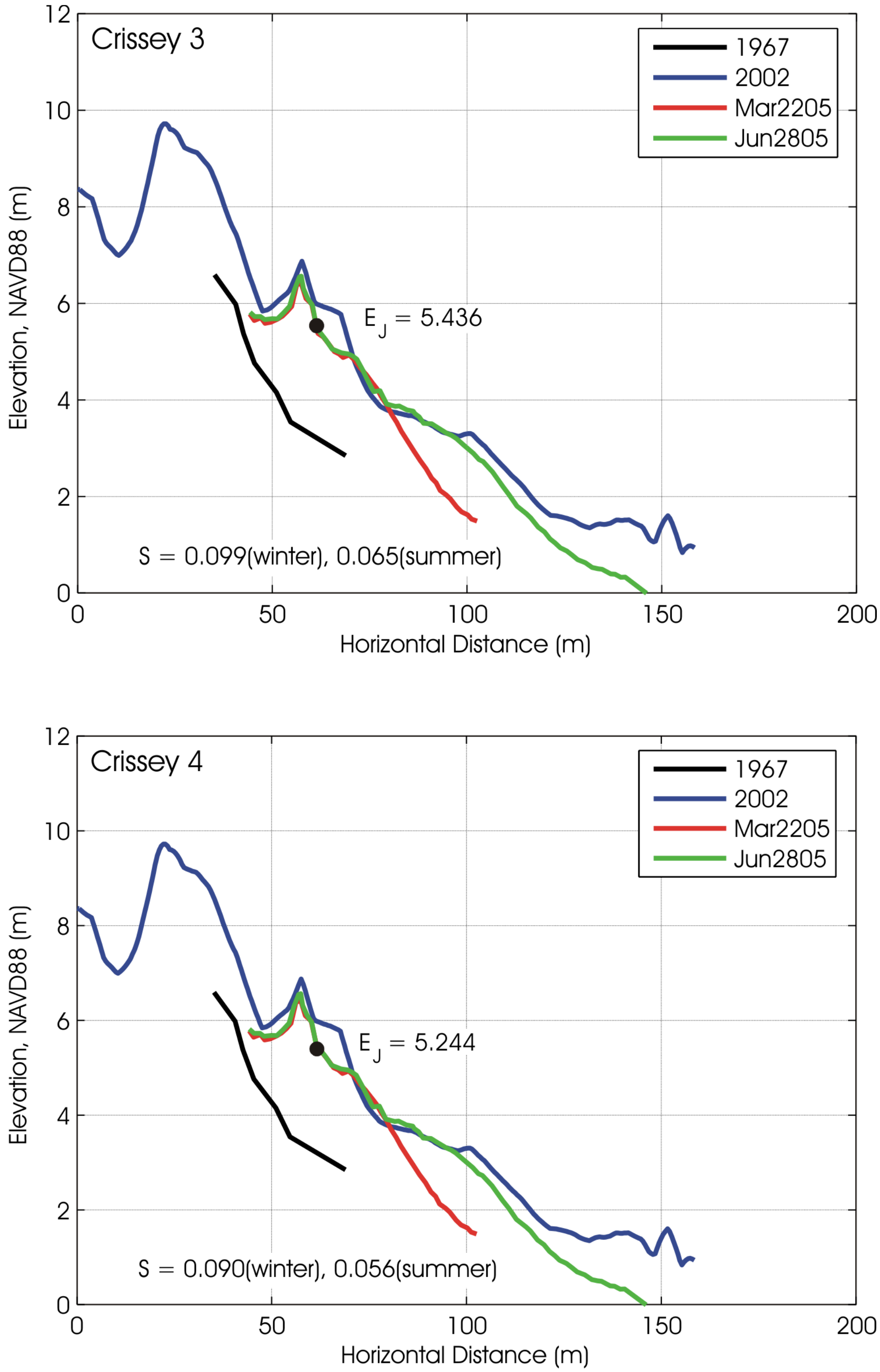


Figure 24. Beach profiles 3 and 4 measured at Crissey Field. Data include information derived from contours provided on 1967 ODOT aerial photographs, 2002 LIDAR data, and GPS survey data measured in 2005.

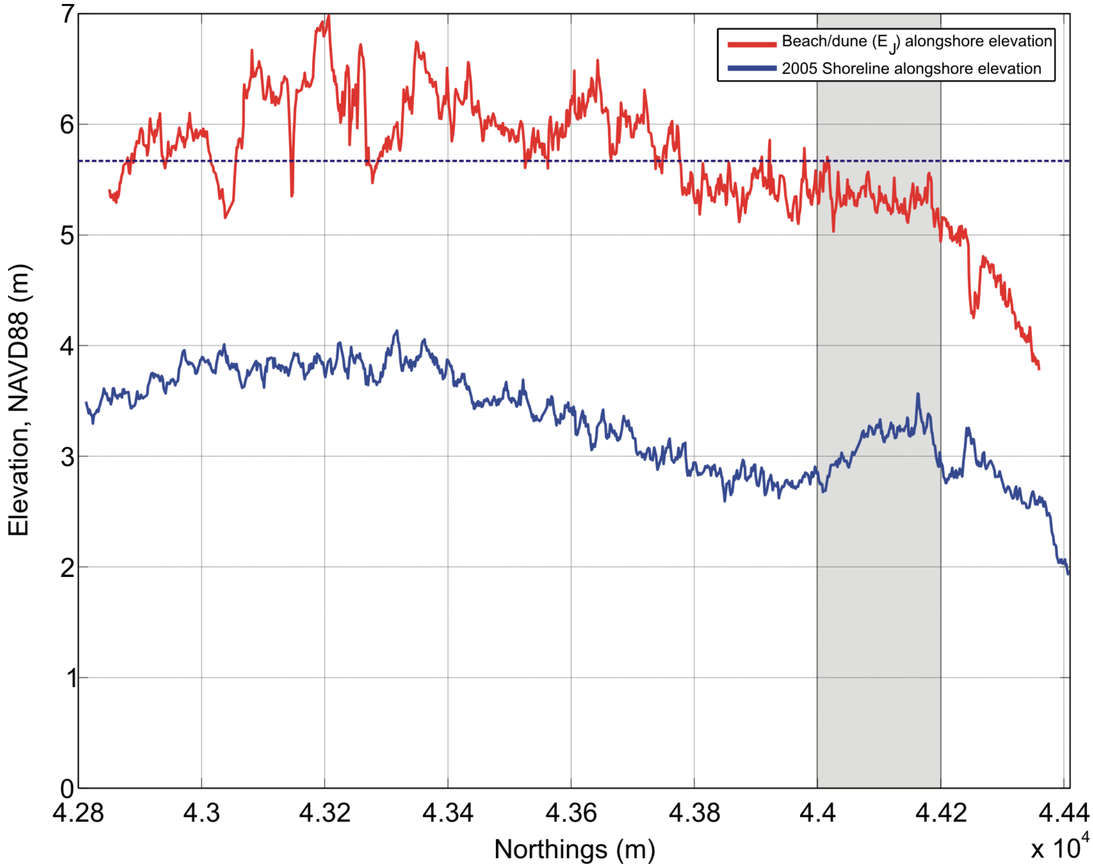


Figure 25. Alongshore variability in the beach-dune junction elevation measured between Crissey Point and the Winchuck River by a Real Time Kinematic Differential Global Positioning System (RTK-DGPS) survey in June 2005. The grey shaded box depicts the portion of beach covered by profiles 1 to 4, and the dashed blue line is the average elevation of the beach/dune junction (5.66 m). Alongshore variability in the elevation of the MHHW shoreline position is also shown.

## Erosion Hazard Zones for the Crissey Field Shore

Apparent from the previous discussions is the wide range of processes and responses that characterize this portion of shore. In order to accommodate this level of variability, three scenarios of coastal change have been developed for the Crissey Field subcell and range from high to low in terms of their level of risk.

**Scenario 1** describes a HIGH-risk hazard zone or 50-year erosion zone. The variables for this scenario are:

- 12 m (39.4 ft) significant wave height,
- 20-s peak spectral wave period,
- 2.095 m (6.87 ft) Mean Higher High Tide,
- 0.173 m (0.57 ft) monthly mean water level,
- 0.5 m (1.64 ft) storm surge.

This particular scenario is similar to a storm that impacted the area in February 1984. When combined, these data yield a tidal elevation of 2.652 m (8.7 ft) relative to the NAVD’88 datum.

**Scenario 2** describes a second HIGH-risk hazard zone. The variables for this scenario are:

- 12 m (39.4 ft) significant wave height,
- 20-s peak spectral wave period,
- 2.095 m (6.87 ft) Mean Higher High Tide,
- 0.173 m (0.57 ft) monthly mean water level,
- 0.5 m (1.64 ft) storm surge
- 0.234 m (0.77 ft) increase in MSL due to an El Niño.

This particular scenario is similar to the previous one with the exception that it now includes the effects of a rise in MSL due to an El Niño, which produces a total water elevation of 2.89 m (9.47 ft) relative to the NAVD'88 datum.

**Scenario 3** describes a MODERATE-risk hazard zone or 100-year erosion zone. The variables for this scenario are:

- 14.4 m (47.3 ft) significant wave height,
- 17-s peak spectral wave period,
- 2.095 m (6.87 ft) Mean Higher High Tide,
- 0.173 m (0.57 ft) monthly mean water level,
- 1.0 m (3.3 ft) storm surge,
- -0.05 m (-0.16 ft) decrease in MSL.

Because the 100-year storm wave for the Eel River is not statistically valid due to its short history of measurement, this scenario includes wave statistics associated with the March 2-3, 1999, storm that impacted the central to northern Oregon coast. This particular event contributed to widespread erosion of beaches on the central to northern Oregon coast. This scenario includes a 0.5-m increase in the storm surge component to yield a storm surge of 1.0 m, and a 0.05-m decrease in MSL due to tectonic uplift in the area. When combined, these data yield a tidal elevation of 2.992 m (9.8 ft) relative to the NAVD'88 datum, which is approximately 0.3 m (0.8 ft) below the highest observed water level measured by the Crescent City tide gauge.

Having described the three scenarios used in this study, estimates of maximum potential erosion distances (MPED) for the dune-backed beaches were calculated using the geometric model (Figure 19). This was accomplished for 18 sites, spaced 100 m (300 ft) apart along the shore between Crissey Point and the mouth of the Winchuck River. Beach-dune junction ($E_J$) elevations measured in June 2005 by RTK-DGPS were subdivided into 18 sections and averaged to yield a single $E_J$ value for each section along the shore; the averaging process typically included some 61 data points that were derived in the GPS survey. Beach slopes were also determined for each section along the shore. Because of the considerable variability in the morphology of the beach environment along the shore, specifically in terms of the beach-dune toe elevations ($E_J$) and the slopes of the beach, the estimated MPED data were similarly characterized by a wide range of values. However, unlike Allan and Priest (2001), this study has not adopted an average MPED to define the hazard zones. Again, this approach yields a more conservative result, particularly in the area adjacent to the Welcome Center.

Figures 26 and 27 identify the derived hazard zones for the area between Crissey Point and the Winchuck River. The HIGH-risk scenario 1 estimate is depicted by the red polygon, while the HIGH-risk scenario 2 estimate is portrayed by the orange polygon. Neither figure includes the moderate risk zone (i.e., scenario 3), which was found to produce an estimated MPED that was only marginally larger than scenario 1. This is entirely a function of the lower peak spectral wave period (and despite the higher wave heights) that was used (i.e., 17 s versus 20 s used in scenarios 1 and 2) and highlights the importance of the wave period in the erosion calculation.

The estimated MPED for the HIGH-risk hazard zone was found to range from 36 m (118 ft) at the south end of the subcell to as much as 93 m (305 ft) in the north, immediately adjacent to the Winchuck River (Figures 26 and 27). As expected, portions of the beach characterized by higher beach-dune junction elevations such as along the southern two thirds of the shore (Figure 26), exhibit narrower hazard zones that average about 41 m (135 ft) wide. In contrast, the area of beach immediately adjacent to the proposed Welcome Center site has an average hazard zone width of ~54 m (178 ft) wide due to its lower beach-dune junction elevations. The average MPED estimated for the entire subcell is 47 m (154 ft). Under Scenario 2, which includes a 0.2-m increase in MSL due to an El Niño, the estimated MPED increases slightly by about 2.5 to 5.8 m (8.2 to 19 ft).

Accordingly, it is evident from Figure 27 that the proposed Welcome Center site falls outside the HIGH-risk scenario 1 and HIGH-risk 2 hazard zones by about 18 to 15 m (59 to 49 ft), respectively (including the MODERATE-risk zone [not drawn], which is associated with a much larger storm event). In addition, these results are conservative as, unlike the Tillamook County shoreline where an average

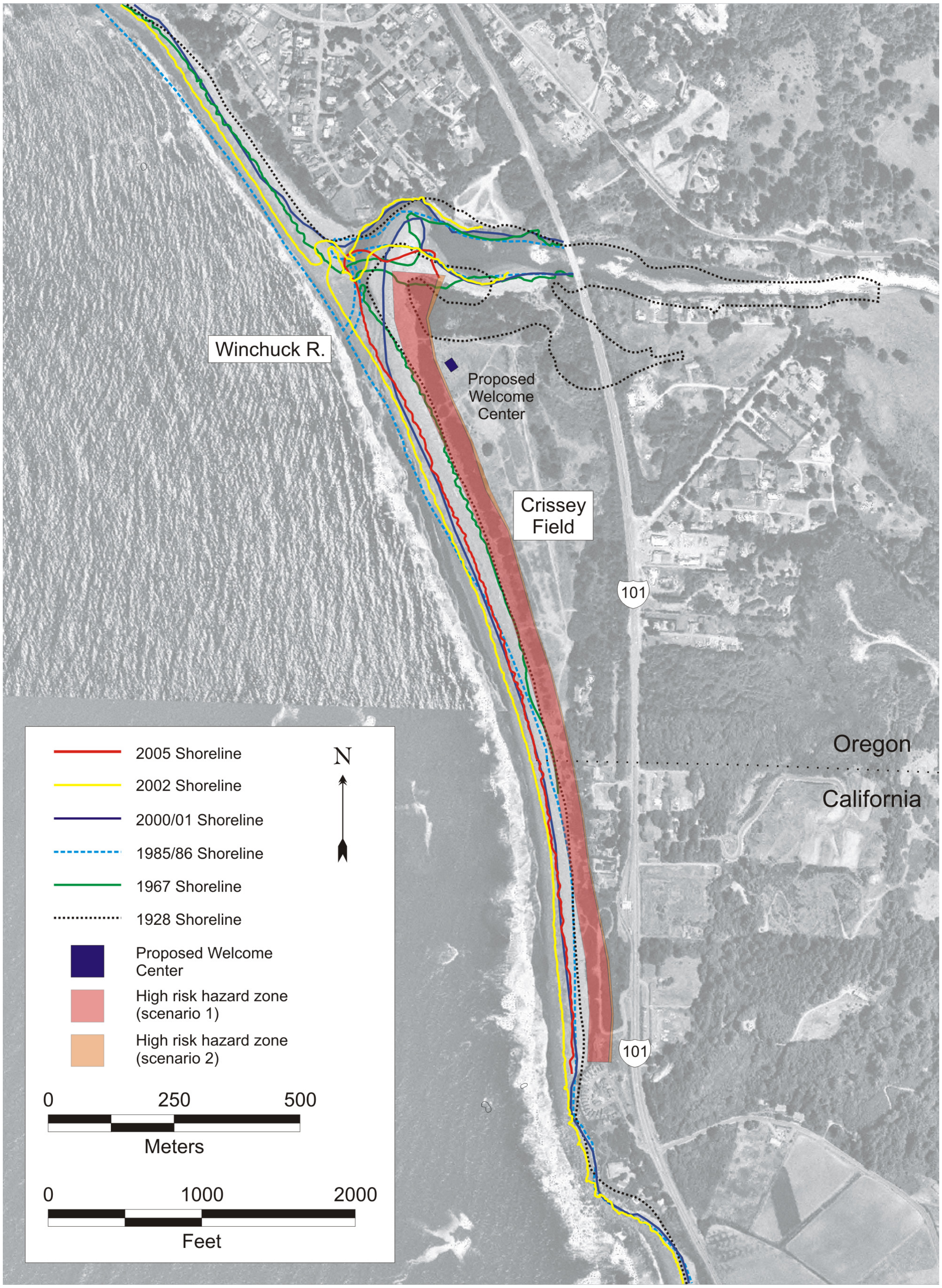


Figure 26. Map showing the designated HIGH-risk scenario 1 and HIGH-risk scenario 2 maximum potential erosion distances for the Crissey Field subcell overlaid on a 2000/01 digital orthophoto. The proximity of the proposed Welcome Center site to the two hazard zones is estimated to be ~18 m (59 ft) and 15 m (49 ft), respectively.

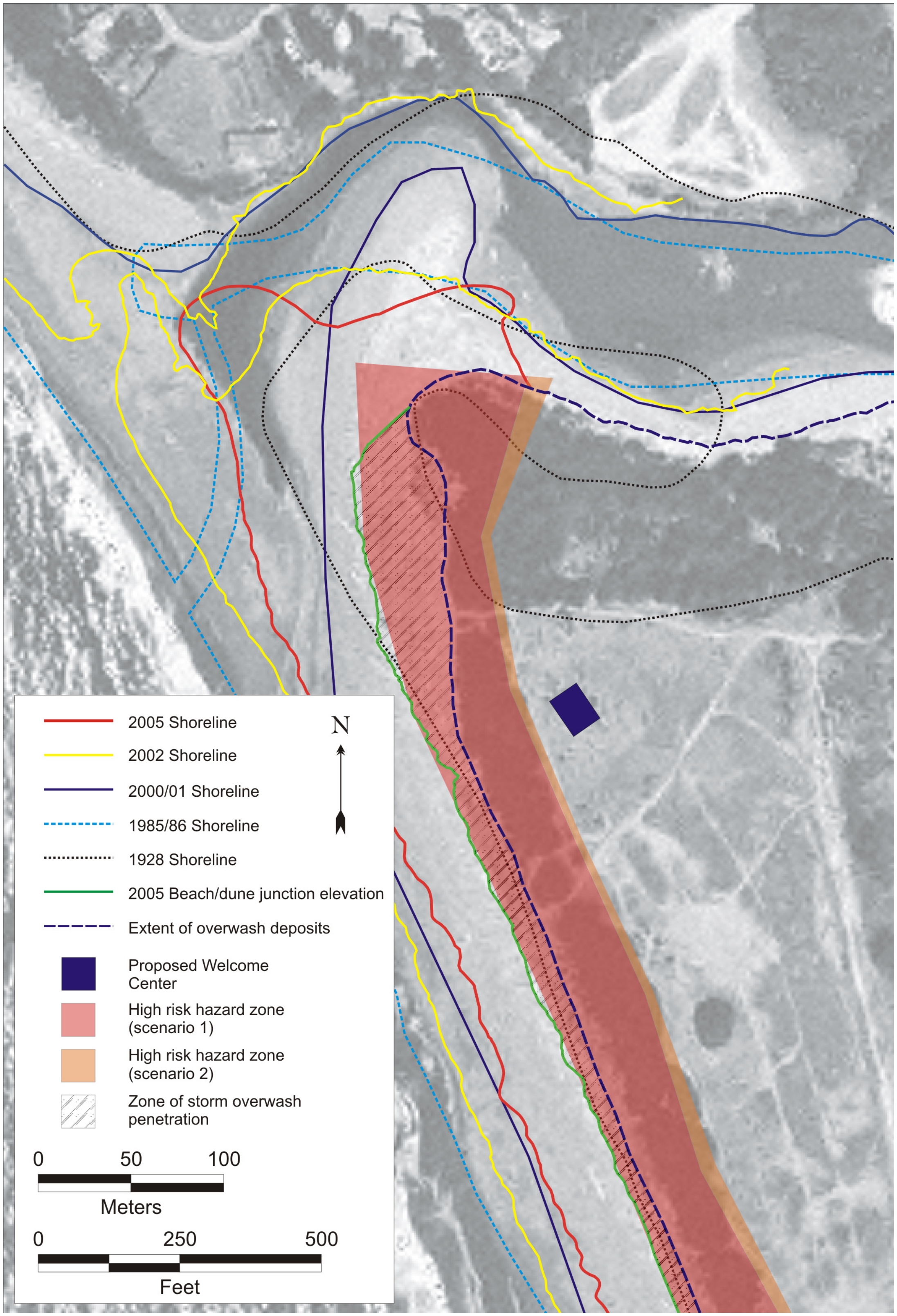


Figure 27. Close-up map of the designated HIGH-risk scenario 1 and HIGH-risk scenario 2 maximum potential erosion distances for the area nearest to the proposed Welcome Center (overlaid on a 2000/01 digital orthophoto). The hazard zones are estimated to be approximately 18 m (59 ft) and 15 m (49 ft), respectively, from the proposed Welcome Center site.

Figure 28. The north end of the beach at Crissey Field and just south of the Winchuck River. Note the considerable accumulation of woody debris that has built up over the years. Much of this material extends up to the old 1967 vegetation line. Although some of this material is likely relict from storms during the late 1960s and early 1970s, considerable reworking of the debris continues today as waves overtop the currently developing dune system and flood the backshore.

MPED was adopted for delineating the hazard zones (Allan and Priest, 2001), the results presented here are based on the actual estimates made along each section of shore. Figure 27 also includes a hatched zone where wave overtopping is currently observed to occur and was derived from field observations of overwash debris in March 2005. This zone reflects a region where waves are capable of overtopping the developing dune crest, inundating and flooding the backshore with woody debris and seawater (Figure 28). As a result, this last zone remains extremely dynamic, and infrastructure should not be constructed in this area.

The reality is that it is unlikely that coastwide erosion of the magnitudes indicated above would take place along the Crissey Field subcell, because of certain assumptions that are characteristic of the geometric model. For example, as noted by Komar and others (1999), in the first instance the geometric model projects a mean linear beach slope. As a result, if the beach is more concave, it is probable that the amount of erosion would be less, though not by much. Perhaps of greater significance is that the geometric model assumes an instantaneous erosional response, with the dunes retreating landward as a result of direct wave attack. However, the reality of coastal change is that it is far more complex than this so that there is in fact a lag in the erosional response behind the forcing mechanism. As noted by Komar and others (1999), the extreme high runup elevations calculated from Equation 1 occur for only a very short period of time, i.e., the period of time in which the high wave runup elevations coincide with high tides. As the elevation of the tide varies with time (e.g., daily), the amount of erosion can be expected to be much less when the water levels are lower. Thus, it is probable that several storms similar to those used in the current modeling are in fact required to cause such widespread coastal retreat along this shore. Finally, as beaches erode, the sediment is moved offshore (or farther along the shore) into the surf zone where the sediment accumulates as nearshore sand bars. This process helps to mitigate the incoming wave energy by causing the waves to break further offshore, dissipating much of the wave energy, and forming the wide surf zones that are characteristic of the Oregon coast. In turn, this process helps reduce the rate of beach erosion that occurs.

In the absence of high-quality coastal data required to run more sophisticated models of coastal change, the geometric model remains a useful approach for estimating maximum potential erosion distances along dune-backed beaches, particularly when viewed in context of measured beach and dune responses to storms now being determined for other sites along the Oregon coast. In addition, it is apparent from field visits to the site that the contemporary dune crest, which has a crest elevation that ranges from 6 to 6.6 m (19.7 to 21.7 ft), is being periodically overtopped by winter storm waves (Figure 28). Furthermore, although some of the woody debris present landward of the dune crest (between the existing dune crest and the 1967 vegetation line) is likely relict from past major storms (e.g., those that occurred during the late 1960s and early 1970s) as evident on the 1967 aerial photographs of the beach, some of this debris is being reworked by more contemporary storms. As a result, this aggraded portion of the beach remains extremely dynamic, and every effort should be taken to preserve as much of it as possible so that it may protect the older dune system from future erosion events.

Three final considerations are worth noting. First, the Crissey Field area may be affected periodically by flooding from the Winchuck River, as a large portion of the site is located within the 100-year flood boundary; appropriate design considerations must be adopted to mitigate such an issue. Second, the mouth of the Winchuck River is subject to periodic and abrupt movements that could impact infrastructure constructed adjacent to the river mouth (Figure 17). For example, analyses of historical shorelines reveal that the location of the river mouth has varied from year to year by some 150 to 200 m (492 to 656 ft); the river's southernmost position occurred in 2000, whereas its northernmost position occurred in 1928 (Figure 17). Such fluctuations may locally exacerbate beach erosion that could impact infrastructure constructed near the river mouth. Despite this concern, existing aerial photography of the area shows no evidence that the river mouth has migrated far enough to the south to directly impact the beach adjacent to the proposed "Welcome Center" site. Finally, the proposed site is located within the Senate Bill 379 tsunami inundation line drawn for this area (Priest, 1995a, b). As noted by OPRD, certain tsunami-related requirements must be incorporated into the building and site design and management of the facility. This may include establishing appropriate evacuation routes and information relating to risks associated with a tsunami.

# CONCLUSIONS

The purpose of this study has been to provide an assessment of the coastal geomorphology of the Crissey Field littoral system, in order to determine the susceptibility of the proposed siting location for a Welcome to Oregon Information Center on a foredune overlooking the ocean, located some 200 to 250 ft from the beach. The main findings of this study are:

- The Crissey Field littoral cell, bounded in the north by Brookings and Crissey Point in the south, is part of a much larger littoral cell system that extends all the way to Point St. George adjacent to Crescent City located in northern California. The total length of the littoral cell is approximately 34 km (21 mi);

- The larger littoral system likely receives significant sand inputs from three main sources: the Chetco, Winchuck, and Smith Rivers. Of these, the Smith River probably supplies the largest volume of sand to the beach system;

- The beach is characterized by coarse sand with a mean grain size of 0.57 mm; grain sizes range from 0.31 to 0.99 mm. As a result, the slope of the beach at Crissey Field is steeper (~3.5° in the summer, increasing to ~5.1° to 5.7° in the winter) when compared with beaches on the central to northern Oregon coast. These beaches are classified as intermediate to reflective using the nomenclature of Wright and Short (1983) and are thus capable of responding extremely rapidly to large storm wave events;

- Estimates of the seasonal variability of the beach at Crissey Field indicates that it varies by some 7 to 20 m (23 to 66 ft). Thus, it can be expected that the beach will erode landward and rebuild seaward by this amount over the course of several normal seasons. During periods of heightened storm activity, it can be expected that the response will be significantly greater;

- Unfortunately, there is no quantitative information on how the beach responded to the extreme storms that impacted much of the central to northern Oregon coast during the 1997-98 El Niño and 1998-99 winters. As noted in this report, however, although the 2-3 March 1999 storm generated 14.1 m (47.6 ft) significant wave heights offshore from Newport, measurements made at the Eel River buoy indicated that the wave heights did not exceed 6.7 m (22 ft). As a result, the response of the beach for this event alone was likely mild. Certainly, there is no field evidence (e.g., erosion scarps) to indicate the effects of the 1997-98 and 1998-99 extreme winter storms. This contrasts with sites along the central to northern Oregon coast, which continue to be characterized by the effects of those two extreme winters;

- Since 1967 the Crissey Field shoreline has prograded (advanced) seaward by some 70 m (230 ft). As a result, the area characterized by the 1967 statutory vegetation line is now depicted by a stable backdune that has been stabilized by the growth of European beach grass, stands of Sitka spruce, and Salal.

- We speculate in this study that the progradation of the beach system since 1967 may be related to sand passing around Pyramid Point, adjacent to the mouth of the Smith River, where it is then redistributed to the north toward Crissey Field as well as southward toward Crescent City. Periodically, these processes may be enhanced by the occurrence of an El Niño, which can result in much larger volumes of sand being transported northward along the littoral cell;

- Although the shoreline did erode slightly landward between the mid 1980s and 1994, by 2002 the shore had advanced seaward once more and was located close to its previous position as documented by 1985/86 DRGs. Since 2002, the shoreline has retreated about 20 m (66 ft) along the entire Crissey Field subcell but still remains some 30 to 40 m (100 to 130 ft) seaward of its position in 1967. During this latter period of change, the dune crest did not recede landward, although its crest elevation was lowered slightly, indicating that the crest of the dune was overtopped.

- In March 2005, a beach profile monitoring network was established adjacent to the proposed Welcome Center site. This initial network consisted of four profile sites and was eventually expanded to include six additional sites in June 2005. Presently, the network covers the entire shore between Crissey Point and the Winchuck River. Information from these sites and from an RTK-DGPS survey of the beach-dune junction elevation (akin to the most current vegetation line) along the entire shore indicates that the northern one third of the shore has a mean elevation of 5.1 m (16.7 ft), while the southern two thirds of the shore has a mean elevation of 6.02 m (19.8 ft).

- Coastal erosion hazard estimates of the beach in response to an extreme event were undertaken using a geometric model developed by Komar and others (1999). The model requires knowledge of the offshore wave climate (specifically the deepwater significant wave height and the peak spectral wave period) and the slope of the beach, in order to calculate the runup of the waves at the shore. These data are combined with a tidal component to yield a total water level at the shore;

- Three scenarios that account for different combinations of wave and tidal statistics unique to the area were developed for modeling the extent of dune erosion. These included the occurrence of a 50-year storm wave ($H_S$ = 12 m [39.4 ft]) characterized by a 20-s peak spectral wave period occurring over the course of an average higher high tide (2.095 m [6.87 ft]), a monthly increase in MSL of 0.173 m (0.57 ft) and a 0.5-m (1.64 ft) storm surge component. Scenario 2 incorporates the same parameters as above, with the inclusion of an increase in MSL due to an El Niño, while the third scenario incorporates a larger wave height (14 m [47.3 ft]) and shorter wave period (17 s) and a larger storm surge component (1.0 m [3.3 ft]);

- Using these parameters in the geometric model yielded a HIGH-risk erosion estimate (scenario 1) that ranges from 36 m (118 ft) at the south end of the Crissey Field subcell to as much as 93 m (305 ft) adjacent to the Winchuck River (Figures 26 and 27). The average maximum potential erosion distance estimated for this subcell is 47 m (154 ft). Immediately adjacent to the proposed Welcome Center site, the HIGH-risk erosion hazard zone (scenario 1) is approximately 54 m (178 ft) wide;

- The HIGH-risk scenario 2 estimate yielded a hazard zone that is approximately 2.5 to 5.8 m (8.2 to 19 ft) wider than the scenario 1 estimate;

- The MODERATE-risk scenario 3 estimate yielded a hazard zone that was marginally smaller than that predicted for scenario 1, despite the larger wave height used in the modeling. This result is due to the shorter wave periods used in the modeling (17 s as opposed to 20 s used in scenario 1);

- On the basis of these results, the proposed Welcome Center site lies approximately 18 and 15 m (59 and 49 ft) outside of the HIGH-risk scenario 1 and 2 estimated erosion distances, respectively. Given the amount of conservatism that has been built into these calculations, it appears that the proposed Welcome Center site is safe from the effects of dune erosion that may be caused by an extreme storm event; and,

- Field visits to the site, however, indicated that portions of the backshore (Figure 27) located between the 1967 vegetation line and today's active dune remain subject to periodic wave overtopping, inundating the backshore with seawater and woody debris. Accordingly, this designated zone of storm wave penetration should be free of infrastructure due to the ongoing dynamic nature of this portion of the beach.

Finally, consideration should also be made of two other hazards that could impact the area. First, a large portion of the Crissey Field area falls within the

100-year Winchuck River flood boundary. Second, the area is well within the Senate Bill 379 tsunami inundation line. Accordingly, consideration of these additional hazards should be incorporated into the design and siting of the Welcome Center building and its accompanying infrastructure. In addition, due to some level of uncertainty in the long-term response of this shore, we recommend adopting additional safety measures. These include:

- Designing the structure so that the center is located at an elevation above the 100-year flood boundary level (e.g., on pilings);
- Possibly incorporating some design aspects that would allow the building to be pulled off its foundations and relocated to an alternate site should the need arise;
- Placing the proposed building landward of a line drawn between the following points: 1192426.043E and 44253.819N, and 1192462.664E and 44152.159N. These points are in the Oregon State Plane Coordinate System (meters), southern zone;
- Incorporating suitable information on the risks of tsunamis, including installing appropriate tsunami evacuation signs; and,
- Commissioning the Oregon Department of Geology and Mineral Industries to undertake periodic updated surveys of the beach profile network established in the area. These surveys should be done at least once every 5 years, and/or after a major storm or storms in series, or a major El Niño winter.

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