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COASTAL EROSION HAZARD ZONES ALONG THE CLATSOP PLAINS, OREGON: GEARHART TO FORT STEVENS

PRELIMINARY
TECHNICAL REPORT TO CLATSOP COUNTY

2001

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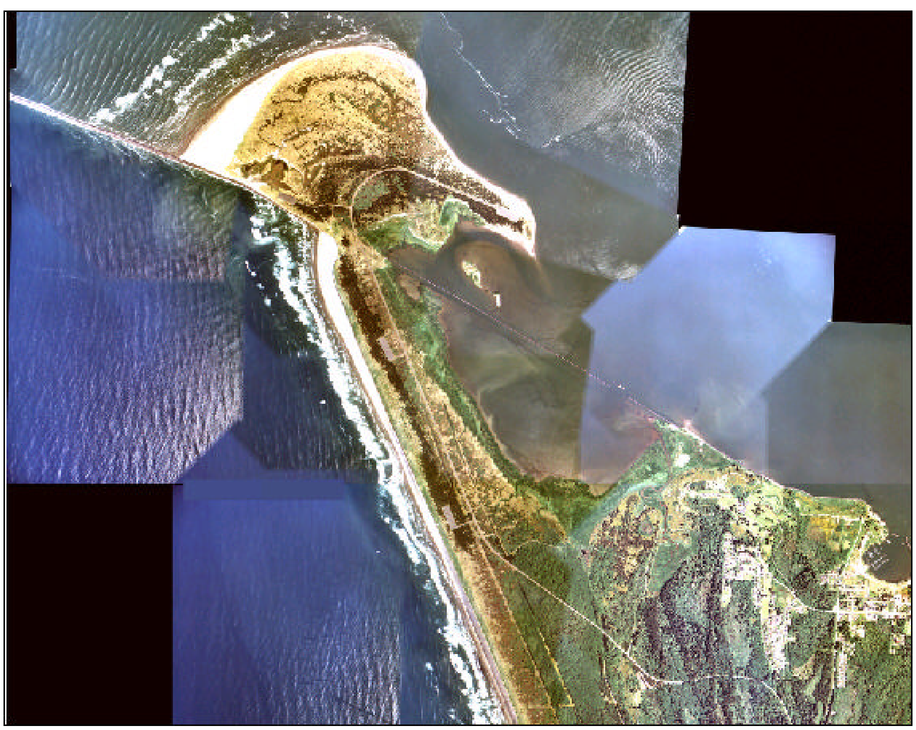

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EXECUTIVE SUMMARY

This report describes and documents a range of coastal hazard zones distinguished for the Clatsop Plains. In particular, the report focuses on identifying maximum potential erosion distances for dune-backed shorelines using the geometric model developed by Komar and others (1999). Four hazard zones have been identified for the Clatsop Plains, an ***active hazard zone*** characterized by existing, active erosion processes, and three zones of potential future erosion, ***high, moderate, and low risk zone*****s** that respectively depict decreasing risks of becoming active in the future. Of most interest to planners are the landward boundaries of the high and low risk zones. The landward boundary of the high-hazard zone defines a conservative but reasonable limit of expansion of the active hazard zone in the next 60-100 years. The landward boundary of the low-hazard zone defines the outermost limit of expansion of the active hazard zone associated with a catastrophic event such as a great earthquake on the Cascadia subduction zone, coupled with severe storms.

Defining these erosion hazard zones was accomplished by detailed analysis of coastal erosion processes affecting the County. The most important conclusions reached from this analysis are:

1) The Clatsop Plains are a barrier-beach ridge system that has prograded (advanced) seaward over the past 4000 years. Between 4050 years BP and AD 1700, the coastline is estimated to have accreted at an average rate of 0.7 m/yr (2.3 ft/yr) (Woxell, 1998). From 1700 (when the last major subduction zone earthquake occurred), to 1885 (prior to jetty construction), the Clatsop Plains accreted at a slightly reduced rate of 0.5 m/yr (1.6 ft/yr).
2) During the past 120 years, the Clatsop Plains have continued to prograde seaward, but at rates exceeding several meters per year due to large sand supplies from the Columbia River, and as a result of jetty construction at the mouth of the Columbia River (Gelfenbaum and others, 1999). These rates ranged from 2.0 to 5.8 m/yr (6.6 to 19 ft/yr), with an average rate of 3.3 m/yr (10.8 ft/yr) (Woxell, 1998).
3) Since about the mid-1920s the rate of coastal advance slowed, while erosion has been the dominant shoreline response along the northern end of the Clatsop Plains (i.e. about 6 km (3.7 miles) of Clatsop Spit is presently eroding).
4) The recent phase of erosion may be a function of either:
    a. A change in the sediment budget of the Columbia River cell. For example, the volume of sand supplied by the Columbia River decreased from an estimated 4.3 x 10^6 m^3/yr (for the period 1878 – 1934) to 1.4 x 10^6 m^3/yr (for the period 1958 – 1997), a decrease by a factor of 3 during historical times (Gelfenbaum and others, 1999). Part of this may be the product of almost 200 dams that have been built along the Columbia and Willamette River, which trap sands carried down the rivers, and/or it may be related to existing dredging practices in the Lower Columbia River, which remove large volumes of sand from the coastal system;
    b. Periodic climate shifts (e.g. the Pacific Decadal Oscillation) which cause sediments to be re-distributed along the coast (e.g. 25 years of relatively persistent El Niño conditions since the mid-1970s), or as a result of an increase in the frequency and magnitude of storms in the North Pacific (e.g. Graham and Diaz,

2001) and hence wave energies along the Oregon coast (e.g. Allan and Komar, 2000a, 2000b).

These types of changes may have important implications for the future stability of coastal shorelines in the Columbia littoral cell, including the Clatsop Plains.

5) Hazard zones were determined along the Clatsop Plains using a geometric model developed by Komar and others (1999), whereby property erosion occurs when the total water level produced by the combined effect of extreme wave runup (*R*) plus the tidal elevation (E_T), exceeds some critical elevation of the fronting beach, typically the elevation of the beach-dune junction (E_J). Three scenarios were used to model erosion hazard zones on dune-backed beaches:

- *Scenario 1* (**<u>HIGH-risk</u>**). This scenario is based on a large storm wave event (wave heights ~47.6 ft high) occurring over the cycle of an above average high tide, coincident with a 3.3 ft storm surge. Under this scenario, the designated HIGH-risk hazard zone was estimated to be **360 ft**, while individual beach sites may vary by a much as 243 ft to 522 ft due to subtle differences in the character of the beach (beach slope and beach/dune junction)

The following two scenarios (MODERATE and LOW-risk events) are one of two "worst case" events identified for the Clatsop coastline. Both scenarios have low probabilities of occurrence.

- *Scenario 2* (**<u>MODERATE-risk</u>**). This scenario is based on an extremely severe storm event (waves ~52.5 ft high) coupled with a large storm surge of 5.6 ft. Under this particular scenario, the maximum potential erosion distances (MPED) vary considerably, with calculated MPED's that ranged from 390 to 825 ft, while the designated width of the moderate hazard zone was established at **572 ft**.

- *Scenario 3* (**<u>LOW-risk</u>**). This scenario is similar to *scenario 2* above but incorporates a 3.3 ft vertical lowering of the coast as a result of a Cascadia subduction zone earthquake. MPED estimated for *scenario 3* ranged from 424 to 938 ft, while the designated width of the low hazard zone was established at **635 ft**.

INTRODUCTION

This report provides an assessment of existing and potential future coastal erosion hazards along the Clatsop Plains, which forms the seaward margin of Clatsop County. The area examined in this report extends from Gearhart in the south to Fort Stevens in the North, a distance of some 25 km (15.5 miles). The purpose of this investigation is to provide County planners with a sound understanding of coastal erosion problems along the Clatsop Plains, and to assist in effective decision-making adjacent to the shoreline. Because the information presented here is regional in its coverage it is not intended for use as a site-specific analysis tool. Nevertheless, the investigation does provide a good guideline to areas in need of more detailed site-specific geotechnical studies.

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 are composed of unconsolidated sediments, including significant stretches of the Oregon coast, 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.

Fundamental to coastal management is the beach, which serves an important role as a natural buffer between the processes that modify them, and the properties and infrastructure that back the beaches. Sound management of coastal shorelines should therefore encourage the growth of beaches and well-vegetated foredunes as a buffer against storm wave erosion and as a barrier to inland penetration of storm wave run-up. Increasingly however, the rapid growth in population and increased urbanization of coastal margins has encroached on the "active zone" of the beach system. As a result, the natural response of coastal shorelines to erode has come into conflict with the "built" environment. Such development is characteristic of much of the Oregon coast (e.g. Gleneden Beach, Pacific City, and Rockaway), 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; Priest, 1999). 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 placed into the hands of decision makers so they can make wise choices regarding shoreline management practices.

The objective of this investigation is to map the projected landward erosion hazard boundaries based on three wave erosion scenarios. The three scenarios are based on essentially the same conditions used by Allan and Priest (2001), but adjusted for local variations in projected sea level rise, storm surge, and possible Cascadia subduction events.

BEACH PROCESSES AND FEATURES

The Oregon coast can be broadly characterized by long stretches of sandy beaches that are bounded by resistant basaltic headlands. These types of systems are referred to as *littoral cells*, and include both a cross-shore extent (*littoral zone*, Figure 1) and a longshore component. Because the headlands extend into deep-water, wave processes are unable to transport sediment around the ends of the headlands. As a result, the headlands 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.

Terminology used to describe the form of a beach is shown in Figure 1 while the specific zones within which important coastal processes are operating is presented in Figure 2. It is important to understand that a beach cannot simply be thought of as the visible sandy foreshore since this represents only a small portion of an onshore-offshore sand exchange system that extends well to seaward (Figure 1). Thus, 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. On the Oregon coast, the seaward limit of onshore-offshore sand exchange is about 14 m.

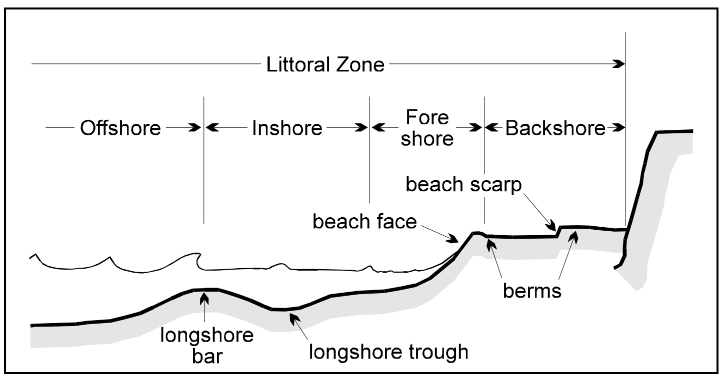

Figure 1 Terminology used to define aspects of the beach (Komar, 1998a).

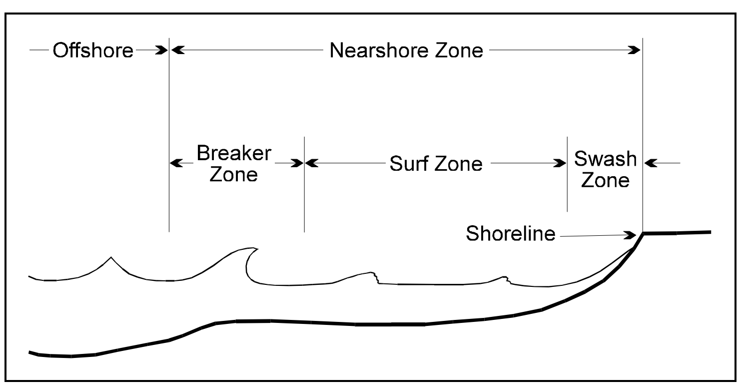

Figure 2 Terminology used to describe the various process zones in the nearshore (Komar, 1998a).

The visible part of the beach is referred to as the foreshore and backshore (Figure 1). Within the foreshore, swash and backwash processes are important for modifying the shape of beaches (Komar, 1998a). The extent to which these processes influence the beach is a function of the wave breaker height, water levels, current velocities, grain-size, beach slope, and foreshore saturation. Swash processes may contribute to the formation of depositional features on the beach (*berms*), which reflects the limits of wave run-up, or may cause erosion *scarps* to form (Figure 1). Berms or beach ridges located at higher elevations reflect swash run-up elevations produced by larger wave conditions.

The nearshore is the "engine room" of coastal processes. It is the zone dominated by wave and current processes and is especially significant for the entrainment and transportation of beach sediments (Figure 2). It is a zone of wave transformation culminating with the highly turbulent process of wave breaking. This last process tends to occur across a nearshore bar of which several may be present.

Within the nearshore, a distinction can be made between sand movement that is directed in primarily *onshore-offshore* directions, and the movement of sands *parallel* to the beach. 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 to it, *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 a given 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 3). During the summer waves approach the coast from the northwest, causing sand to move southward along the coast, while in winter the waves arrive from the southwest and drive the sand back to the northern ends of the beaches (Komar, 1998b). Thus, over several normal years there is a net equilibrium balance so that the net sand transport is zero.

Beach Erosion – What is it?

The erosion of beaches is a complex phenomenon, which can have one or more of a variety of causes and visible expressions. Integral to an understanding of coastal change is the concept of the beach sediment budget[1] (Figure 4). This notion 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 relating 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.

[1] The beach sediment budget is the time rate of change of sand within the coastal system and is dependent on the rate at which sand is brought into the system versus the rate at which sand leaves the system. The budget of sediments involves making assessments of the sediment contributions (credits) and losses (debits) and relating these to the net gain or loss (balance of sediments) in a given sedimentary compartment or littoral cell (Komar, 1998a).

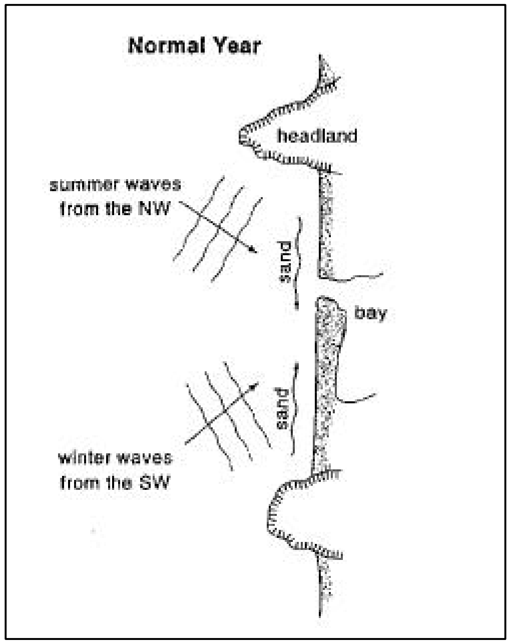

Figure 3 The alongshore-seasonal movement of beach sediments on the Oregon coast (Komar, 1998b).

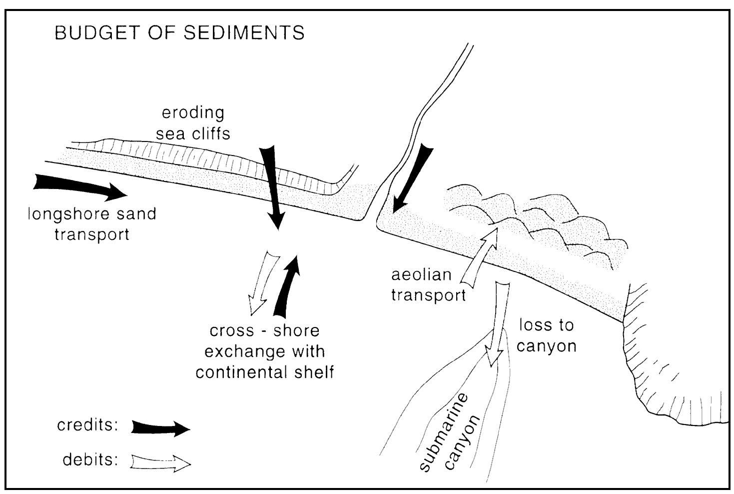

Figure 4 Schematic illustration of the principal components that are involved in the development of a sediment budget (Komar, 1998a).

Coastal changes along the Pacific Northwest (PNW) span an extremely wide range of temporal and spatial scales (Figure 1), due to the diverse range of processes that influence the coastal environment (Shoreland Solutions, 1998). Table 1 presents a summary of features that can be identified on an eroding or accreting beach. The table is broadly divided into short-term, historical, and long-term effects.

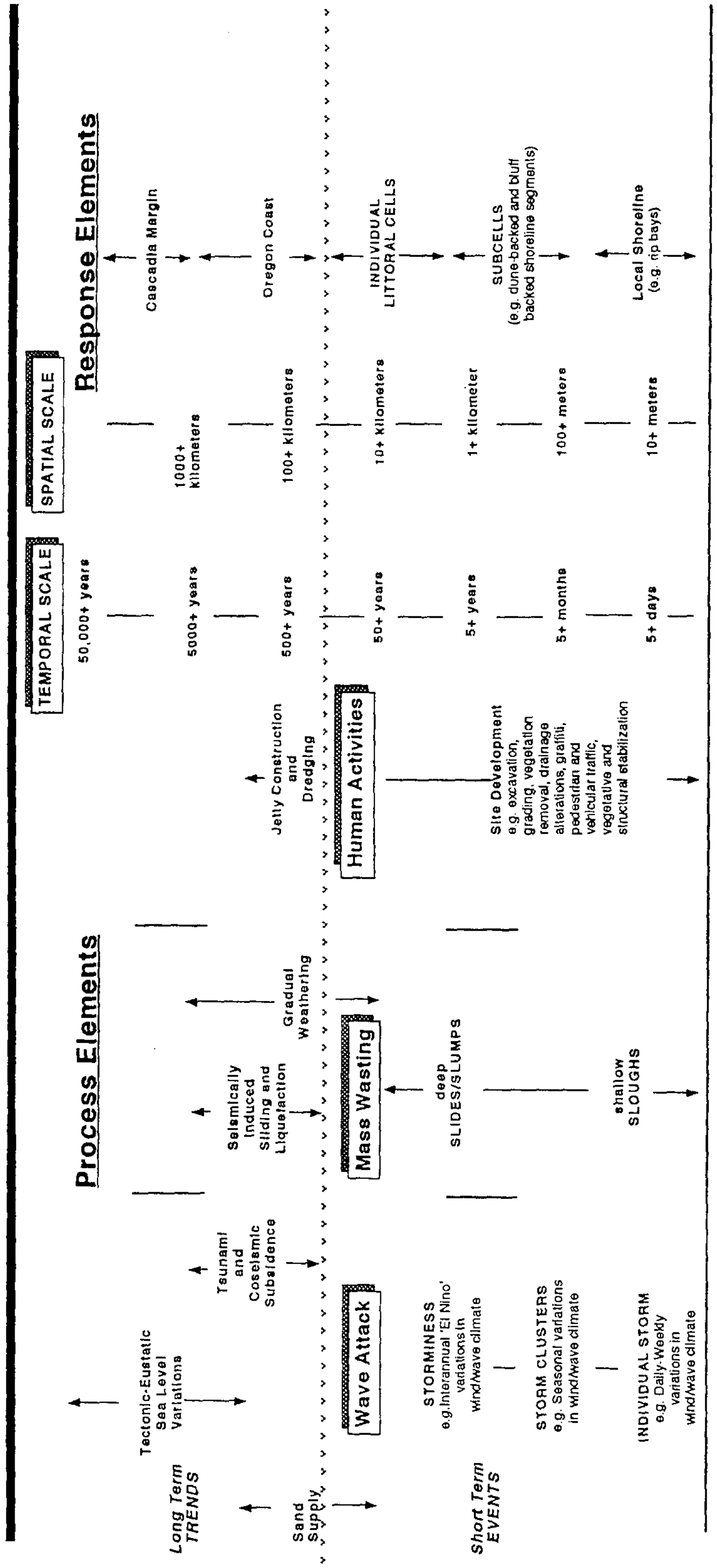

Figure 5 Temporal scales of coastal change and factors that influence the stability of shorelines (Shoreland Solutions, 1998).

Table 1 Beach morphology characteristics that may be identified over a range of time scales (Dr. R.M. Kirk, University of Canterbury, personal communication).

Time Scale	Accretion	Erosion
Short Term (weeks to months, year to year)	Beach wide, steep Soft foreshore Berm/s present Ridges and runnels Accretion of dune face No bars offshore or degraded Characterized by large cross-shore changes in the beach Low water table, free draining beach.	Beach narrow, flat Hard foreshore Berm/s absent Scarp/s present Erosion of dune face Bars present offshore Characterized by small cross-shore changes in the beach High water table, clogged beach pore spaces
Medium Term (period of years to decades) (position of envelope)	Dune growth Incipient new dune on backshore Advancing vegetation lines Changes in the position of the shore (e.g. the mean water line) measurable from ground survey, maps or air photos.	Dune destruction scarps breaches washovers truncated vegetation lines Retreat of duneface, crest, profile locus evident from ground survey, maps, or air photos Rip embayments in foredunes
Long Term (geological years x 10^3 and >er)	Multiple ridges Soil and vegetation sequences Airfall deposits Changes in relative base level (+ve) Raised beaches or other features.	Truncated sequences of ridges, soils, vegetation and associated deposits. Changes in relative base level (-ve) Drowned ridges or other features.

As indicated in Figure 1, the coastal response varies between short and long-term events. Short-term events have time-scales that range from a few days to several years, and can cause highly localized site-specific problems (e.g. rip embayments), or much larger scale changes that influence entire shoreline segments. Beaches may also exhibit characteristic patterns of change that occur over considerably longer periods of time (centuries to thousands of years). These latter changes influence the overall stability and shape of the coastline and are ultimately dependent on adjustments to the beach sediment budget.

Changes to the character of the beach are therefore to be expected. However, any action that results in one or more elements of the sediment budget being altered can be expected to produce a corresponding series of adjustments in the others (Kirk, 1979). As Kirk further observed, such compensating changes will be manifested as adjustments in the form (height and width of a beach) and/or position (advance or retreat) of the beach system. These types of changes are especially important at the historical and longer time scales (Table 1). In the case of the Clatsop Plains, an excellent example of changes to the sediment budget is the effects from jetty construction, which caused the Clatsop Plains shoreline to advance seaward. These changes are described in more detail below.

From a planning perspective, it is important to appreciate the wide range of temporal and spatial scales in which beaches can respond. Of particular importance is distinguishing between movements in the beach form (its height and width) that occur over ***short time***

<u>*scales*</u> (in response to variations in the waves and currents), from those <u>*longer-term changes*</u> that are ultimately dependent on the state of balance or imbalance among the various elements of the sediment budget. <u>From a shore management perspective it is important to clearly distinguish the shorter temporal beach changes from the longer-term adjustments, since they have very different implications for land-use adjacent to any water body</u> (Figure 6). Therefore, sensible shoreline management provides sufficient space in which the natural changes that occur on beaches can eventuate, without either damage to developed assets or infrastructure, or the need to resort to costly shore stabilization structures to protect the assets. This last response not only destroys the aesthetic qualities of a particular shore, invariably they are poorly constructed, more often than not exacerbating or transferring the problem elsewhere.

With respect to the beach sediment budget, if a beach receives more material than it loses it is said to be *'over-nourished'*. Such a beach will accumulate sands and its position will advance seaward. As a result, the foreshore will widen and steepen. Dunes may also begin to form on the backshore. Similarly, the nearshore will also be steep, while longshore sand bars will either be absent or poorly developed (Table 1).

Alternatively, if a beach is losing more material than it is gaining it is said to be *'under-nourished'*. In other words, the beach sediment budget is said to be in deficit (Figure 6). Such a beach will erode and its position will retreat landward. As a result, the beach face will narrow and become flatter. Sediments contained in dunes or in other deposits are removed either offshore or along the shore. Within the surfzone, the underwater profile will widen and the bed will become flatter (Table 1). Longshore sand bars may be prevalent and well developed, particularly if sand exchange is predominantly shore normal.

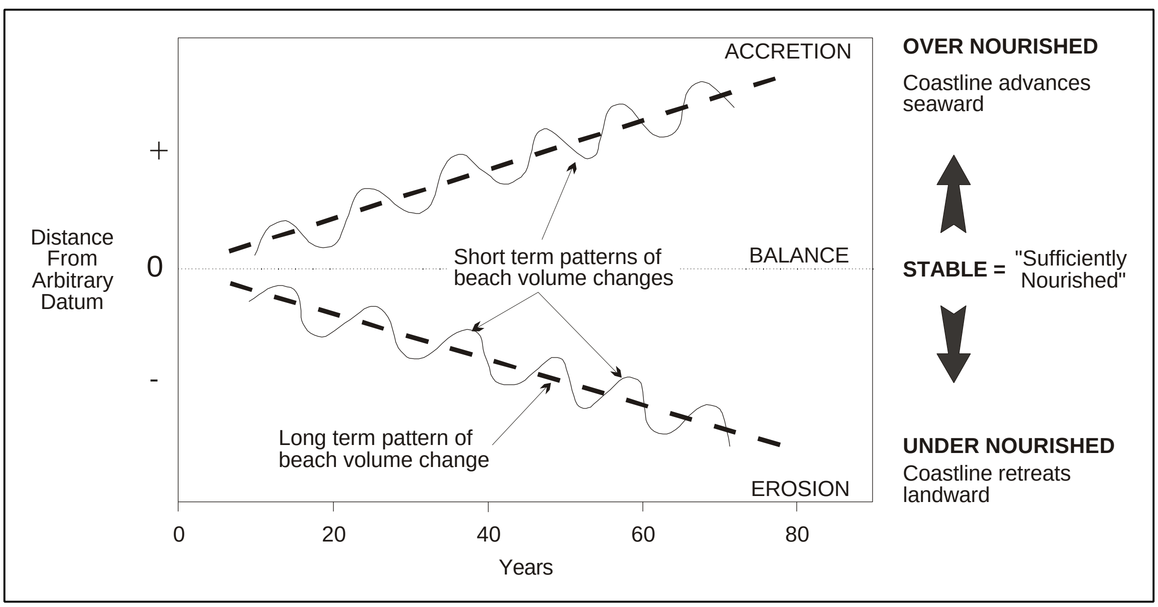

Figure 6 Long-term erosional trend in a sand beach sediment budget (Kirk, 1979).

Beaches that experience no net losses or net gains are said to be *'stable'*. In the long term, such beaches will neither advance nor retreat and thus there is a net balance of sediment. Nevertheless, it is important to note that *'stable'* beaches are far from static, and will periodically erode in response to storm waves, while intervening quiescent periods will contribute to further sediment buildup on the beach foreshore causing it to prograde (Kirk, 1979). Large transfers of sand can also occur from time to time along a particular shore in response to different wave approaches (e.g. Figure 3). On such a beach " the term 'stable' should not be equated with a state of no change, but rather it should be interpreted as variation within some measurable limits about a mean position and efforts should be made to determine where these limits fall " (Kirk, 1979). Hence, in such situations it is important that infrastructure is located outside the identified limits with an additional 'safety' margin of clearance also included. In summary, irrespective of the causes of coastal erosion, ultimately it is a reflection of a negative status in the beach sediment budget.

SCALES OF COASTAL CHANGE IN THE PACIFIC NORTHWEST

Most obvious and simplest to appreciate in the Pacific Northwest (PNW) are those beach changes that occur between summer and winter (i.e. the seasonal response, Figure 5). During the summer months beaches accumulate sediments due to the predominance of low wave heights and long wave periods, while in winter the same beaches erode rapidly in response to an increase in wave energy and changes in the directions of wave approach. Periodically these natural cycles of coastal change are enhanced by the occurrence of infrequent high magnitude storm events that can account for significant amounts of dune retreat. For example, analyses of coastal change along the Clatsop Plains have revealed values of dune recession that are on the order of 125 ft during the 1998-99 La Niña winter (Ruggiero and Voigt, 2000). However, because the record of such occurrences is relatively short, limited to 30 years at best, the effects from extreme storm events, or from storms-in-series remain largely qualitative or unknown (Komar and others, 1999). Perhaps the best example is the winter of 1939, which produced some of the worst storms ever seen along the Oregon coast, causing massive coastwide erosion (Dr. Paul Komar, personal communication). Since then the beaches have undergone periods of rebuilding, interspersed with subsequent erosion and rebuilding phases. The overall result however is that the effects of the 1939 winter storms are now masked by more recent coastal changes. Nevertheless, it is almost certain that such an extreme event will re-occur in the immediate future, and will probably contribute to extensive property damage.

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 7). El Niños exhibit dominant periods of 5 to 6 years (Ghil and Vautard, 1991), but may recur on 2 to 7 year cycles (Kleeman and others, 1996). Figure 7 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 have tended to dominate much of the climate spectrum since about 1976, while La Niñas were more frequent prior to 1976.

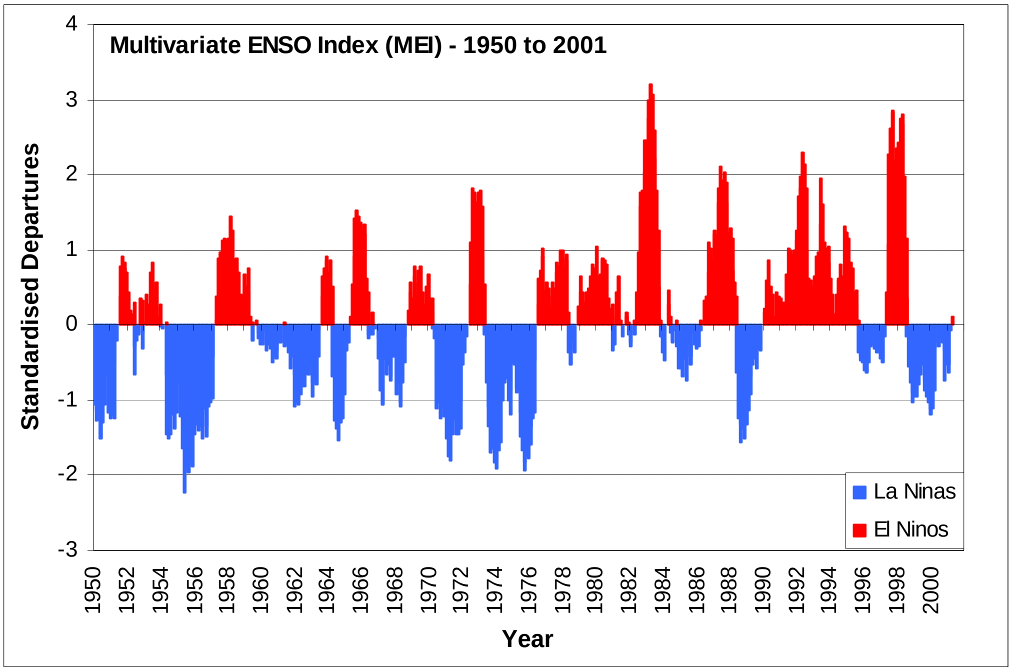

Figure 7 Multivariate ENSO index (MEI) showing the incidence of El Niños and La Niñas since 1950 (Data from Dr. K Wolter, http://www.cdc.noaa.gov/~kew/MEI/).

Under normal oceanographic and climate conditions, the PNW is characterized by a seasonal increase in mean water levels between summer and winter (Figure 8). During the summer months water levels along the PNW coast are lowest, due to coastal upwelling that produces cold, dense water, which depresses the mean level of the sea (Huyer, 1983). In the winter the water is warmer due to the absence of upwelling, and its thermal expansion contributes to an increase in the mean elevation of the sea (Figure 8). Coastal currents also play a role, the northward direction of the current affecting the cross-current geostrophic slope of the water's surface, raising water levels to the right of the current along the PNW coast; the stronger the current, the greater the rise in the water level (Huyer, 1983). The above processes tend to be further enhanced during an El Niño, which typically raises mean water levels along the PNW coast by 0.26 - 0.33 m above the average curve, elevating the levels of the tides (Komar and others, 2000; Allan and Komar, In Press). Because the waves are superimposed on tides they are able to reach much higher elevations on beaches during an El Niño, contributing to significantly higher rates of coastal erosion. Furthermore, because the storm tracks are deflected further south so they mainly cross the California coast, wave approach offshore of the PNW coast is increasingly from the southwest, resulting in “hot spot” erosion along the southern ends of the littoral cells, northern ends of river mouths, and tidal inlets to the bays, with a net drift of beach sands to the north (Figure 9) (Komar, 1986, 1997).

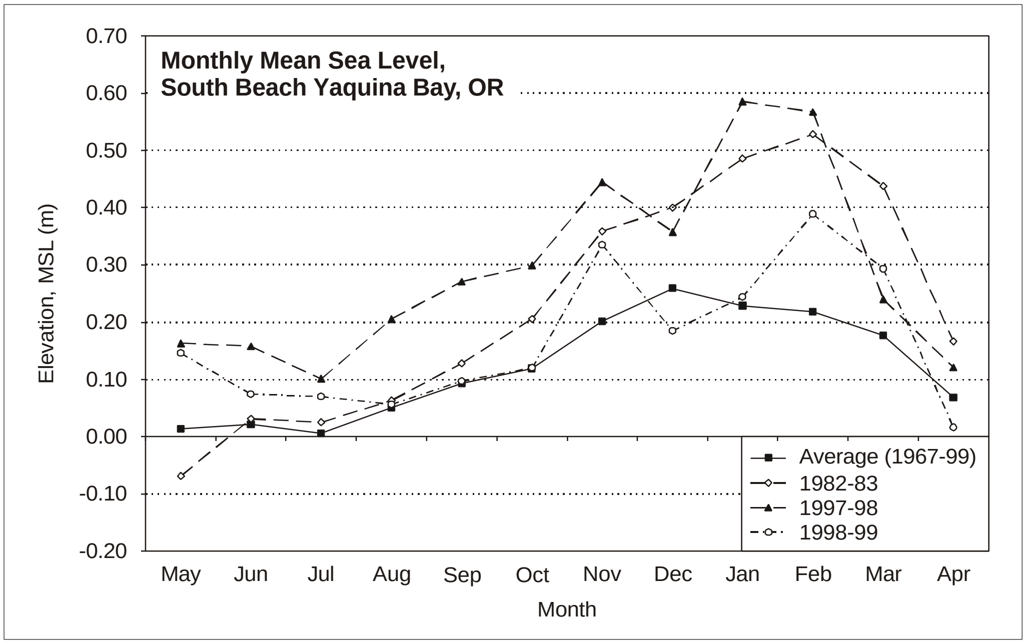

Figure 8 Monthly mean water levels derived from analyses of tide-gauge measurements in Yaquina Bay, Oregon. Included are the 1967-98 long-term averages (excluding El Niño years), and results for the 1982-83 and 1997-98 El Niño years and the 1998-99 La Niña year (Allan and Komar, In Press).

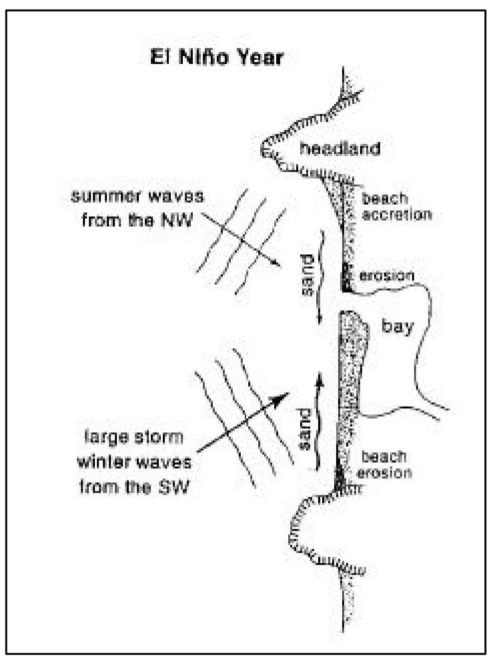

Figure 9 The alongshore movement of beach sediments on the Oregon coast during an El Niño (Komar, 1998b).

Unlike El Niños, the coastal response associated with a La Niña event is less well known, and is mainly due to the relatively few La Niñas that have occurred over the past 20 years (Figure 7). During this climate phenomenon, mean water levels tend to be much closer to normal, while large winter storm systems cross the PNW coast (Komar and others, 2000; Allan and Komar, In Press). As a result of the storm tracks, wave energy levels tend to be elevated during La Niña events and coastal erosion is widespread. This type of response was most apparent during the 1998-99 La Niña event.

ENSO events are superimposed on much longer climate cycles that periodically change on a 20 to 30 year basis (Figure 10). 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 (Figure 10). However, since 1994 there is some suggestion that the PDO may have “flipped” from the warm PDO phase back to a cold PDO phase (Taylor, 1999). The evidence for this is thought to be the generally higher than average rainfall experienced throughout the PNW since about 1994. Furthermore, apart from the 1997-98 El Niño, La Niña conditions have prevailed over the latter half of the 1990s. Thus, it is possible that the rise in coastal 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, studies in the North Atlantic have identified a progressive increase in ocean wave heights off Lands End, United Kingdom (Carter and Draper, 1988; Bacon and Carter, 1991). Recently, a similar upward trend of increasing wave heights and periods (and therefore the wave energy) was discovered offshore from the PNW coast (Allan and Komar, 2000a, 2000b). This progressive increase in the wave statistics is greatest offshore from the Washington coast, amounting to about 0.042 $m.yr^{-1}$ 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, analyses of the North Pacific storm climatology suggest a long-term increase in both the frequency and magnitude of storms since the early 1940s (Graham and Diaz, 2001). Using wave hindcasting techniques, Graham and Diaz were also able to demonstrate a progressive rise in North Pacific wave heights that substantiate the findings of Allan and Komar (2000a; 2000b). 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. This raises the obvious question of what might be expected in the next 25 years or more, with the apparent on-going trend of global warming.

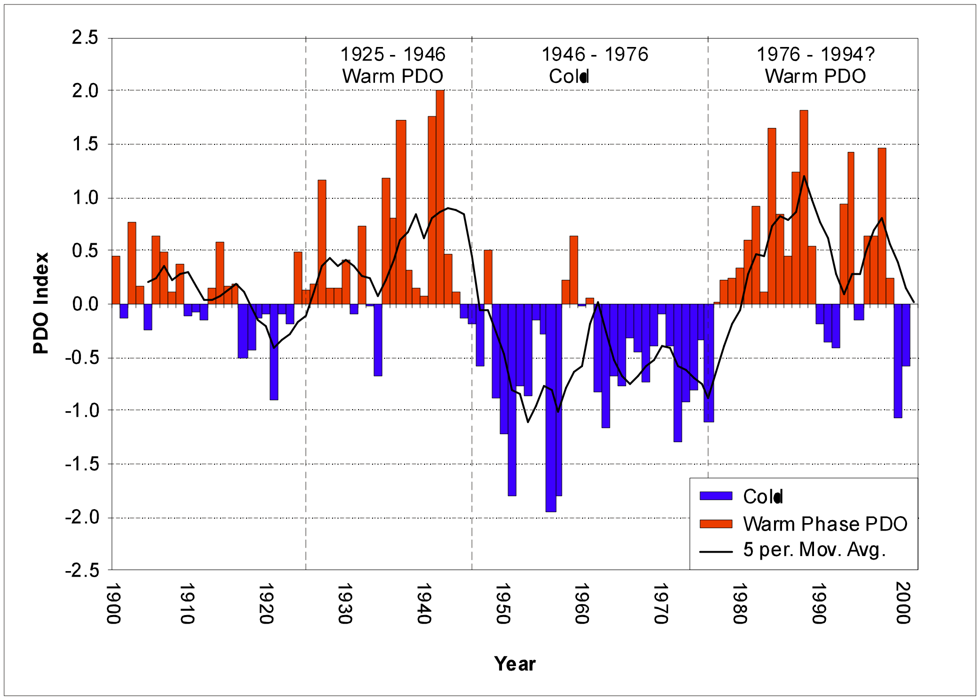

Figure 10 The Pacific Decadal Oscillation (PDO) climate index, 1900-1999 (Data from Dr. N. Mantua, http://jisao.washington.edu/pdo/).

It is apparent from this review that atmospheric and oceanographic forces are far from constant in the PNW over short or even longer time-scales. Furthermore, since coastal change tends to emulate the forcing mechanisms, namely climate, the 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.

As noted earlier, previous studies of coastal change indicate that the beaches of the PNW 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 Nino 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. For the purpose of this investigation, we have used the geometric model to estimate the MPED based on three scenarios, high, moderate, and low risk events. Each of the three scenarios is fully described below. It should be stressed however, that such models do not account for long-term changes in the beach sediment budget. As a result, further analyses is likely to be necessary to better understand the role of changing sediment budgets and how this might impact on the future stability of the Clatsop Plains.

STUDY AREA

The Clatsop Plains are an arcuate shaped coastline that extends from Tillamook Head in the south to the mouth of the Columbia River (MCR) (Figure 11). The plains form part of a smaller sub-cell (34 km in length) located within the much larger Columbia River littoral cell, a 165 km coastal system that extends from Tillamook Head, Oregon, to Point Grenville, Washington (Figure 11).

The coastline of the Clatsop Plains is characterised by wide surf zones and prominent longshore bars in the nearshore, while the beaches are backed by an extensive dune sequence (Cooper, 1958; Woxell, 1998; Kaminsky and others, 1999a). The frontal foredunes that immediately back the beaches range in height from several meters to over 16 m. These dunes increase in height from Seaside to Kyle Lake, and then decrease in height towards Clatsop Spit (Ruggiero and Voigt, 2000). The beaches are gently sloping (mean slope (S) of 0.032, ± 0.007), and have a somewhat lower beach slope when compared with those slopes identified along the Tillamook County coastline (Allan and Priest, 2001). The sediments that comprise the beaches range in size from 0.14-0.25 mm (classified as medium- to fine-grained sand) (Schlicker and others, 1972; Peterson and others, 1994; Ruggiero and Voigt, 2000).

For the past few thousand years, the shorelines of the Columbia littoral cell, including the Clatsop Plains, have accreted, causing the coastline to advance seawards (prograde) by a few hundred to several thousand meters. This process is thought to have begun around 4000 years ago, as the rate of sea-level rise slowed (Woxell, 1998). Evidence for this comes from a beach-sand wood sample that was dated at 4050 years BP (before present), and from an archaeological site at Palm Rose that was first occupied around 3650 years BP (Figure 12). Using these data as a baseline, Woxell (1998) determined that the Clatsop Plains accreted at an average rate of 0.7 m/yr (2.3 ft/yr) from about 4000 years BP to AD 1700. This latter date coincides with the last major subduction zone earthquake, which caused the PNW coastline to drop in elevation by 0 to 2 m (Peterson and others, 2000). Between 1700 and 1885, accretion rates along the Clatsop Plains fell slightly to around 0.5 m/yr (1.6 ft/yr). The year 1885 is significant since this was when construction of the south jetty began.

The seaward progradation of the Clatsop Plains has continued throughout the past 120 years, but at rates exceeding several meters per year due to large supplies of sand from the Columbia River, and as a result of jetty construction at the MCR (Gelfenbaum and others, 1999). Of particular significance has been the construction and subsequent extensions of the south jetty, which caused a dramatic increase in the rate of shoreline advance. According to Woxell (1998), historic accretion rates along the Clatsop Plains ranged from 2.0 to 5.8 m/yr (6.6 to 19 ft/yr), with an average rate of 3.3 m/yr (10.8 ft/yr). Furthermore, the highest accretion rates were identified near the MCR. However, since about the mid-1920s the rate of coastal advance has slowed, while erosion has been the dominant shoreline response along Clatsop Spit. These latter adjustments suggest a change in the overall sediment budget of the Columbia River cell, which may have important implications to the future stability of coastal shorelines adjacent to the MCR.

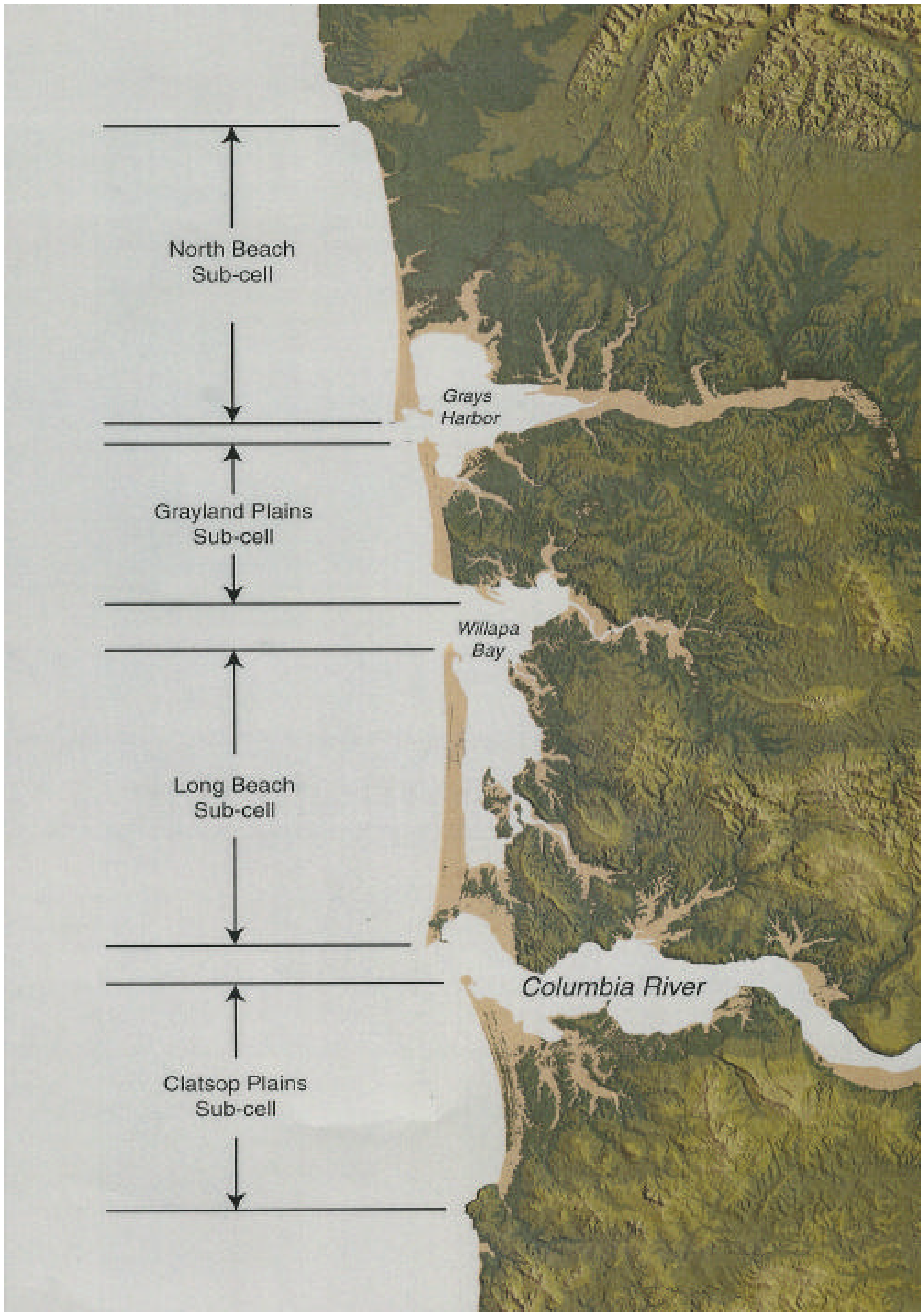

Figure 11 Map of the Columbia River littoral cell and four sub-cells including the Clatsop Plains sub-cell (Gelfenbaum and Kaminsky, 2000).

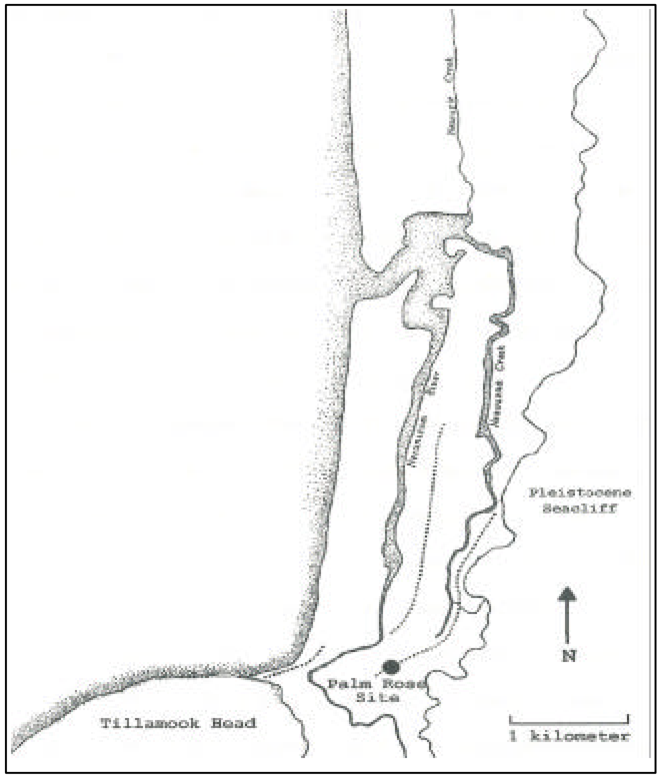

Figure 12 The Palm Rose site (dated using ^{14}C at 3650 BP) located at the southern end of the Clatsop Plains. Dotted lines indicate buried cobble ridges (Woxell, 1998).

Figure 13 presents historic shoreline change rates for selected sites along the Clatsop Plains. Apparent in the figure are the large amounts of accretion that has taken place over the past 200 years. For example, Clatsop Spit advanced seaward by some 1100 m (3600 ft), while shoreline changes near Gearhart were on the order of +350 m (+1150 ft). Also evident in Figure 13 is a decline in the rate of shoreline advance during the last century, with evidence of a switch to erosion along Clatsop Spit. This last response has been occurring since the mid-1920s, and includes about 6 km (3.7 miles) of the spit tip. The recent phase of erosion identified along Clatsop Spit, including several other sites in the Columbia River littoral cell, may be related to an overall decrease in the supply of sand from the Columbia River. For example, the volume of sand supplied by the Columbia River decreased from an estimated 4.3×10^6 m^3/yr (for the period 1878 – 1934) to 1.4×10^6 m^3/yr (for the period 1958 – 1997), a decrease by a factor of 3 during historical times (Gelfenbaum and others, 1999).

The reduction in sand supplied by the Columbia River may be a function of several processes, including:

- The construction of over 200 dams, which provide an effective trap for sediment that is transported down the Columbia and Willamette rivers (Gelfenbaum and others, 1999);

- A reduction in the peak Columbia River flow statistics over the past 60 years, which may have contributed to a reduction in the rivers ability to transport sediment (Sherwood and others, 1990);
- Dredging of the lower Columbia River estuary by the U.S. Army Corps of Engineers (Sherwood and others, 1990; Gelfenbaum and others, 1999), and;
- Continued re-adjustments of the Columbia River littoral system to jetty construction.

Despite a plethora of information obtained as a result of the Southwest Washington Coastal Erosion Study (SWCES) (http://www.ecy.wa.gov/programs/sea/swce/) run by the U.S. Geological Survey and the Washington Department of Ecology, a number of important questions remain unanswered. These include questions about the transportation of sediment within the Columbia littoral cell (i.e. where it is coming from and going to), the sources of sediment (e.g. whether the inner continental shelf is a major source of sand), and the role of climate shifts (e.g. 25 years of relatively persistent El Niño conditions). The latter in particular may account for some of the recent erosion problems identified along the coast.

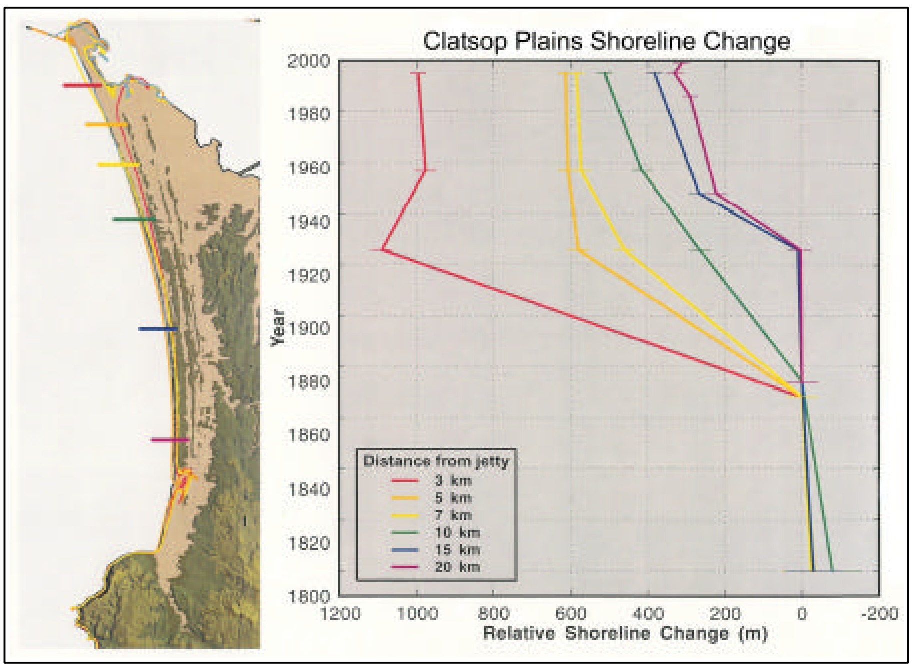

Figure 13 Historical and recent shoreline changes measured along the Clatsop Plains (Figure courtesy of Department of Ecology, Washington).

METHODS

The approach used to define coastal hazard zones along the Clatsop Plains is comprehensively described in Appendix A and B, while Figure 14 presents a conceptual diagram of the hazard zones.

In brief, coastal hazard zones have been determined using the geometric model developed by Komar and others (1999). The basis for this model is that property erosion occurs when the total water level produced by the combined effect of extreme wave runup (*R*) plus the tidal elevation (E_T), exceeds some critical elevation of the fronting beach, typically the elevation of the beach-dune junction (E_J). As a result, when $E_T > E_J$, erosion occurs and the beach erodes until E_T approximately equals the E_J. 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). Appendix A presents a summary of such analyses for the Oregon coast.

Four hazard zones have been identified for Clatsop County. These include an ACTIVE HAZARD ZONE, which identifies the currently active beach environment, and three other zones that identify potential erosion hazards associated with specific extreme events. These last zones are defined as HIGH, MODERATE, and LOW risk zones. The locations and descriptions of the various hazard zones have subsequently been incorporated into MapInfo, Geographic Information System (GIS) software.

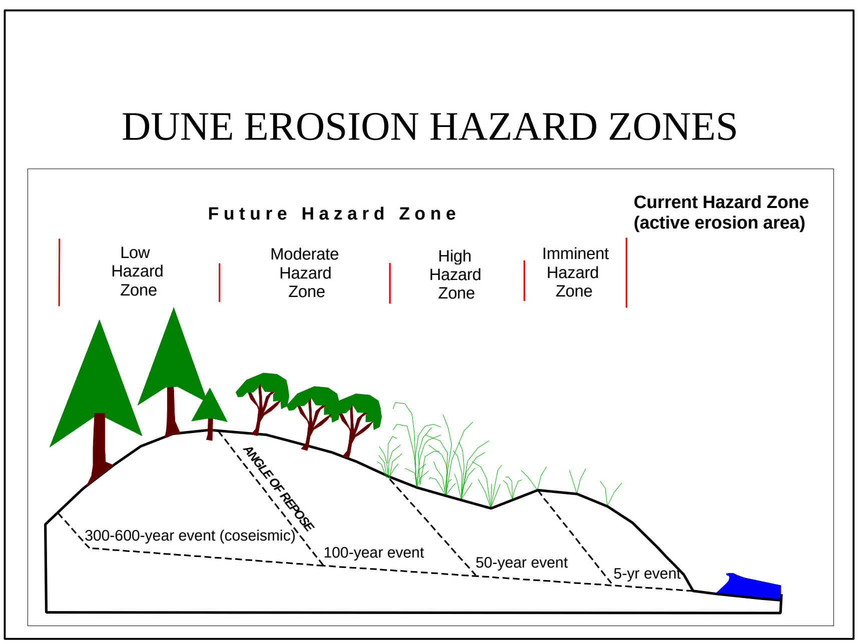

Figure 14 Schematic diagram showing possible dune erosion hazard zones (Allan and Priest, 2001).

Active Erosion Zone

An active erosion hazard zone (AEZ) (Figure 14) was mapped for the dune-backed shorelines throughout the study area based on an analysis of historical shoreline positions, geomorphic features identified from aerial photographs (e.g. erosion scarps), and from an analysis of the total wave runup elevation (tides + wave runup) at the shore. The approach used to define the AEZ is described in Appendix B. On dune-backed beaches, the AEZ distinguishes the zone of beach variability, a region in which beaches undergo considerable change (e.g. changes in the position of the shoreline (height and width) relative to some known datum point). Thus, it represents the portion of beach that is known to have changed in recent times due to large wave events and changes in sediment supply. It is therefore the zone that can be expected to change in the immediate future. As a result, there can be no doubt that building within the active hazard zone represents considerable risk.

It is important to note that the AEZ as defined here should not be confused with the "active dune" or "active foredune" used by State regulators (e.g. OCZMA, 1979; DLCD, 1995). For example, OCZMA (1979) defines the Active Foredune as those dunes that possess insufficient vegetative cover to retard wind erosion, while Goal 18 (Beaches and Dunes) of Oregon's Statewide Planning Goals and Guidelines prohibits the residential and commercial development of beaches and active foredunes (DLCD, 1995).

Scenarios of Coastal Change used for the Clatsop Plains

The maximum extent of shoreline variability on dune-backed beaches can also be estimated from oceanographic factors using empirical modeling techniques rather than direct geomorphic observations. The advantage of these techniques is that they can depict erosion events that may be difficult or impossible to define by geomorphic field observations of the effects of past erosion events. This report presents the results of maximum potential erosion distances (MPED) for the Clatsop Plains based on three scenarios. In developing the three scenarios, we have attempted to steer clear of such terminology as the 100-year extreme event, which can often be misconstrued. Instead, we have defined our scenarios according to HIGH, MODERATE, and LOW risk hazard zones. Furthermore, although the following scenarios indicate increasing levels of potential erosion (especially the two "worst case" scenarios), they respectively represent decreasing levels of risk of becoming active over the next 60-100 years. Because of the difficulties of identifying the most appropriate combination of extreme high waves and tides, the following scenarios assume that a major storm occurs over the course of an above average high tide. Along the northern Oregon coast, the Mean Higher High Tide averages about 2.57 m (8.42 ft) at the Astoria tide gauge and is relative to Mean Lower Low Water (MLLW). When converted to the NAVD'88 datum, this amounts to an elevation of 2.66 m (8.74 ft). Thus, when other variables are added to this, all of the elevations will be relative to the NAVD'88 datum.

Scenario 1 describes a HIGH-risk hazard zone. The variables included in this scenario are:

- 14.5 m (47.6 ft) significant wave height,
- 17 second peak spectral wave period,
- 2.66 m (8.74 ft) Mean Higher High Tide,
- 0.4 m (1.31 ft) monthly mean water level,
- 1.0 m (3.28 ft) storm surge.

This particular scenario is similar to the 2-3 March 1999 La Niña storm, which caused widespread damage along the Oregon coast (Allan and Komar, in press). The scenario assumes that a major storm occurs over the course of an above average high tide. To accommodate the monthly rise in mean water levels between summer and winter, an additional 0.4 m (1.31 ft) has been added to the high tide. Furthermore, because the extreme storms that occurred during the 1997-98 El Nino and 1998-99 La Nina winter produced significant storm surges, we have included a 1.0 m (3.28 ft) storm surge component as part of this scenario. When combined, these data yield a water elevation of 4.1 m (13.33 ft) relative to the NAVD'88 datum.

Scenario 2 describes a MODERATE hazard zone, and includes the following variables:

- 16.0 m (52.5 ft) significant wave height,
- 20 second peak wave period,
- 2.66 m (8.74 ft) Mean Higher High Tide,
- 0.4 m (1.31 ft) monthly mean water level,
- 1.7 m (5.58 ft) storm surge,

The MODERATE hazard zone is one of two "worst case" scenarios. This particular scenario assumes that the rise in wave heights identified offshore from the PNW coast by Allan and Komar (2000a; 2000b; in review) continues over the course of the next century. In effect, the 16.0 m (52.5 ft) significant wave heights used in this scenario is similar to the predicted 100-year storm wave shown in Appendix A (Table A2). The variables used to generate the water levels are the same as those shown in scenario 1, except that we have incorporated a larger storm surge component, 1.7 m (5.58 ft). According to Flick and others (1999), the Astoria gauge shows no evidence of a long-term rise in mean sea level. As a result, we have excluded such a term in scenario 2. This combination of events has an extremely low probability of occurrence. However, the results are still useful in that they provide a landward limit of potential erosion (assuming no long-term trends in the coast) due to an especially severe storm.

Scenario 3 describes a LOW hazard zone, and includes the following variables:

- 16.0 m (52.5 ft) significant wave height,
- 20 second peak wave period,
- 2.66 m (8.74 ft) Mean Higher High Tide,
- 0.4 m (1.31 ft) monthly mean water level,

- 1.7 m (5.58 ft) storm surge,
- 1.0 m (3.28 ft) lowering of the coast due to a Cascadia subduction zone earthquake.

The LOW hazard zone is the second "worst case" scenario, and incorporates all of the variables used in scenario 2, but with the added feature of a Cascadia subduction zone event. These events have been shown to occur in response to large earthquakes in the Cascadia margin, and have a recurrence interval of approximately 500 years (Geometrics Consultants, 1995; Darienzo and Peterson, 1995; Atwater and Hemphill-Haley, 1996). These types of events can cause some parts of the PNW coast to be abruptly lowered by 0 - 2 m (0 - 6.6 ft) (Peterson and others, 2000). Because of the lower coastal elevations, wave processes will therefore be able to reach much further up the beach. As a result, it can be expected that erosion would be widespread under this scenario with extensive coastal retreat. Furthermore, the process of erosion is likely to persist for several decades until the coastal environment has achieved a new state of dynamic equilibrium, and as interseismic strain builds up on the locked Cascadia subduction zone interface. Under this scenario, we have adopted a value of 1.0 m (3.28 ft) coseismic subsidence for the Clatsop Plains, which is “typical” for this part of the northern Oregon coast based on paleoseismic analyses of previous subduction events (Peterson and others, 2000).

RESULTS AND DISCUSSION

Clatsop County Historical Shoreline Positions

This section presents a qualitative discussion of large-scale changes in shoreline positions identified along the Clatsop Plains from the NOS T-sheets, aerial photographs, and LIDAR data. The approach adopted here is to describe the broad changes identified at three locations along the Clatsop Plains; Clatsop Spit, Slusher Lake (located mid-way along the Clatsop Plains), and Gearhart in the south.

Figure 15 identifies those shoreline changes along Clatsop Spit over the past 120 years. With the construction and subsequent extensions of the south Columbia River jetty, it is apparent that the coastline advance seaward at an extremely rapid rate. For example, between the 1870s and 1926 the coastline prograded by some 500 m (1640 ft), measured near the bottom of Figure 15, and by ~1000 m (3280 ft) around mid photo. Of particular significance, was the extension of Clatsop Spit by about 4.6 km (2.86 miles) over a period of 50 years. A major source of the sand that accumulated along Clatsop Spit was likely from changes in the Columbia River inlet, and offshore from the Clatsop Plains (i.e. the mid-continental shelf region). For example, between the 1870s and 1926 these areas combined lost about 364 million m^3 of sand (Gelfenbaum and others, 2001). Between 1926 and the 1950s, the northern end of Clatsop Spit eroded by some 200 to 250 m (650 ft to 820 ft) (Figure 15). However, since the 1950s erosion of the spit appears to have stabilized, indicated by the close proximity of the 1950s shoreline to the more recent shoreline positions (i.e. 1990s). Nevertheless, photographic evidence from the most recent aerial photography flight (1999) indicates that Clatsop Spit continues to erode.

This is shown in Figure 16, which identifies an erosion scarp that probably formed over the 1998-99 La Niña winter.

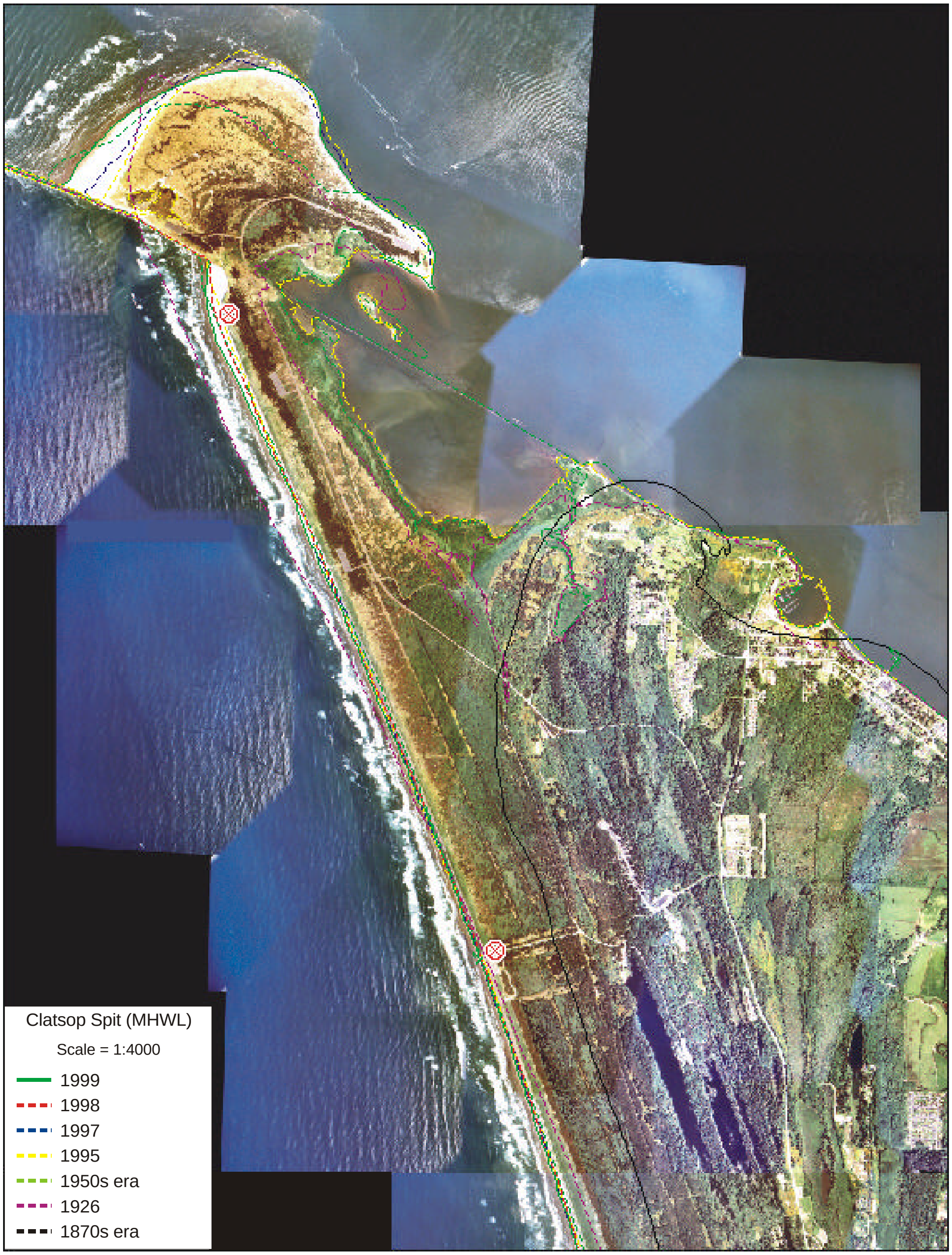

Figure 15 Historical shoreline changes along Clatsop Spit (1870s era, 1926, 1950s era, 1995, shoreline data courtesy of the SWCES).

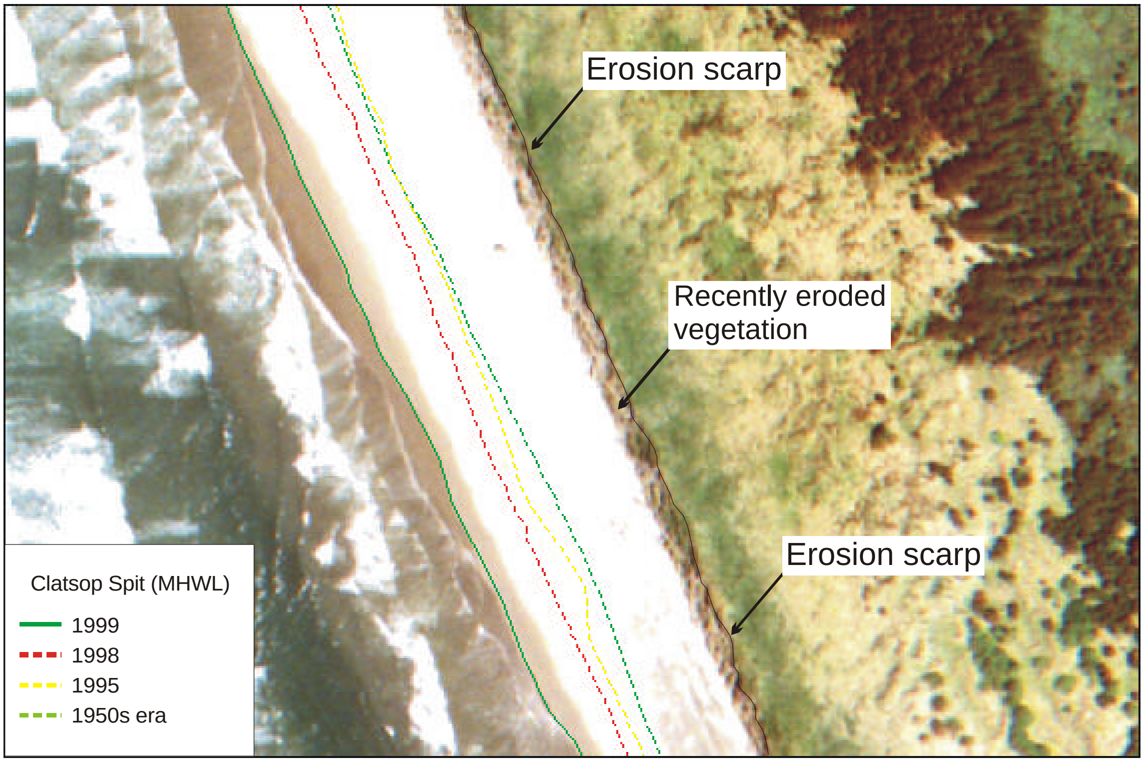

Figure 16 Recent evidence of erosion along Clatsop Spit.

Shoreline changes identified near Slusher Lake (located mid-way along the Clatsop Plains) are shown in Figure 17. The results again indicate the dramatic effect jetty construction has had on the beach system with the coastline having advanced seaward by about 450 m (1476 ft). Unlike Clatsop Spit, changes in the position of the shore between the 1870s and 1926 were relatively minor. More significant was the amount coastal progradation that took place between 1926 and the 1950s (+350 m (+1150 ft)), which occurred along almost the entire length of the Clatsop Plains (except for Clatsop Spit). These changes are likely the product of continued erosion and deepening of the Columbia River inlet, and further deepening offshore from the Clatsop Plains (i.e. the mid-continental shelf region). These two regions combined lost an additional 147 million m^3 of sediment (Gelfenbaum and others, 2001). The coastline continued to prograde after the 1950s (Figure 17), though at a much-reduced rate. These latter changes may be related to a reduction in the rate of erosion identified adjacent to Columbia River inlet, and on the mid-continental shelf region offshore from the Clatsop Plains. For example, these regions lost an additional 100 million m^3 between the 1950s and 1999. The close proximity of the more recent shoreline positions (i.e. 1990s era) indicates that there has been very little change in the position of the shorelines during the last 10 years. This raises the question whether such changes (or lack of) is a function of a general slowing in the rate of sediment accumulation on the Clatsop Plains, or whether the system may switch over and begin to erode (as identified along Clatsop Spit).

Figure 17 Historical shoreline changes near Slusher Lake (1870s era, 1926, 1950s era, 1995, shoreline data courtesy of the SWCES).

Figure 18 identifies those shoreline changes that occurred adjacent to Gearhart. The results indicate that the coastline initially retreated between the 1870s and 1926. It is possible that this initial phase of erosion was associated with a general reorientation of the Clatsop Plains. Unfortunately there is no shoreline information for the 1950s for the Gearhart region.

Between 1926 and 1995, the shoreline advanced seaward by about 250 m (820 ft). Since about 75% of the coastal change identified at Slusher Lake to the north occurred between 1926 and the 1950s, it quite possible that the shoreline adjacent to Gearhart moved seaward by about 190 m (623 ft). This would place the 1950s era shoreline close to the dark green vegetation line that can be identified running just landward (about 100 ft) of the beach (Figure 18). Unlike the central and northern Clatsop coastline, the latter half of the 1990s appears to have been dominated by erosion. For example, the 1998 and 1999 shorelines are about 30 m to 60 m (100 ft to 200 ft) landward of the 1995 and 1997 shoreline positions. These estimates are outside the margin of error associated with the 1995 and 1999 aerial photographs (see Table B1, Appendix B). Finally, it can be seen from Figure 18 that the mouth of the Necanicum Bay has fluctuated significantly over the past 120 years. Figure 18 indicates that the bay mouth was much wider (870 m (2850 ft)) during the early part of last century, narrowing to about 70 m (230 ft) wide in 1999. These latter changes highlight the dynamic nature of bay mouths, and reinforce the importance of limiting the development of such areas.

Coastal Hazard Zones in Clatsop County

This section examines the possible future coastal response that may occur under a variety of extreme scenarios. It is important to stress that the erosion estimates that are presented below are associated with specific scenario events. Thus, the hazard zones do not account for any possible reductions in the overall sediment budget. For example, continued removal of sand through dredging could conceivably alter the stability of the entire Columbia River littoral cell, and hence the Clatsop Plains.

Estimates of maximum potential erosion distances (MPED) for the dune-backed beaches have been determined by the geometric model (Appendix A) for each 100 m section of beach according to the three scenarios presented previously. These data have subsequently been tabulated in an EXCEL spreadsheet for each littoral cell. Because of the variability in the morphology of the beaches along the Clatsop Plains, specifically in terms of the beach-dune toe elevations (E_J) and the slopes of the beach (*tan ß*), the estimated MPED data were similarly characterized by a wide range of values. To standardize the data somewhat, an average MPED was determined for each littoral cell. In a sense, this approach is similar to taking an average of all the beach slopes and beach-dune toe elevations, and then applying the geometric model to the average data. The average MPED data have subsequently been used to generate the HIGH (red zone), MODERATE (orange zone), and LOW-risk (yellow zone) hazard zones shown in Appendix C, along with the existing ACTIVE HAZARD ZONE.

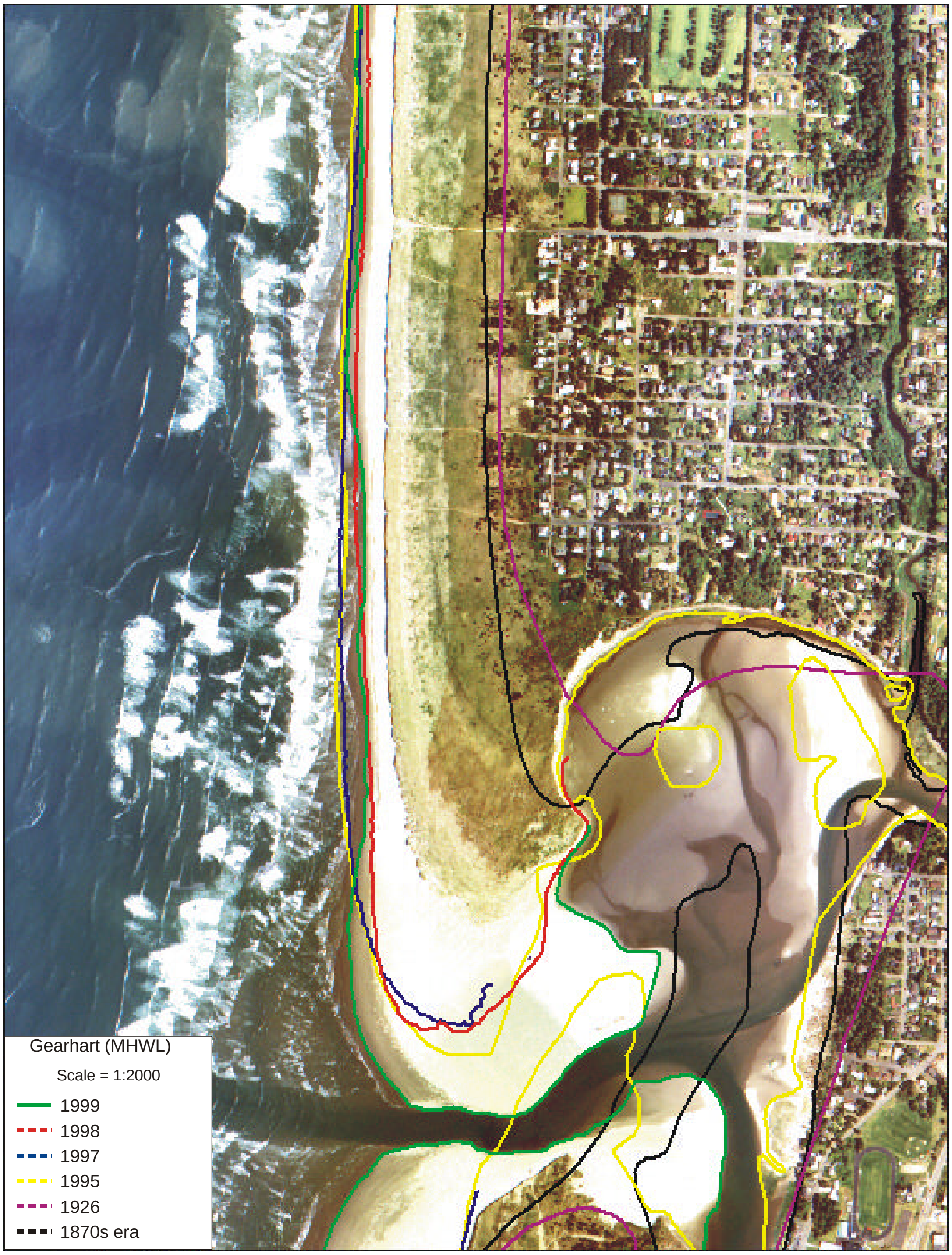

Figure 18 Historical shoreline changes near Gearhart (1870s era, 1926, 1950s era, 1995, shoreline data courtesy of the SWCES).

Table 2 presents values of the calculated MPED identified for the Clatsop Plains. As can be seen for the HIGH-risk hazard zone, estimated erosion distances range from 240 to 522 feet, with an average MPED of 360 feet. It is this last value that has been incorporated into a GIS layer in MAPINFO, and is shown as the HIGH-risk coastal hazard zone in Appendix C. As expected, a much broader range of values characterize the MODERATE and LOW risk scenarios (Table 2), with some potential erosion distances that extend up to 940 feet. Such variation reflects the broad characteristics of the beach morphology at the end of the 1997-98 El Niño winter. For example, the narrowest MPED estimates were typically associated with those beaches with high dune-toe elevations and steep beach slopes, essentially stretches of coast that had not undergone significant erosion during the 1997-98 El Niño winter. Average maximum potential erosion distance estimates for the MODERATE and LOW risk hazard zones were determined to be 572 ft and 635 ft respectively (Table 2). These zones are shown graphically in Appendix C.

Table 2 Maximum potential erosion distances determined for the Clatsop Plains.

Hazard zone scenarios	*Min (ft)*	*Max (ft)*	*Average MPED (ft)*
HIGH	243	522	**360**
MODERATE	390	825	**572**
LOW	424	938	**635**

The above calculations provide an estimate of the average maximum potential erosion distance for sandy beaches located along the Clatsop Plains. These estimates have been based on three scenarios, two of which, 2 and 3 are "worst case" scenarios, since they assume a major storm coincident with a large storm surge, or a subduction event occurring simultaneously. Clearly, these latter events have an extremely low probability of occurrence, though the results are likely still meaningful in that they provide an understanding of the potential upper limit of extreme erosion.

Of greater value to planners are those estimates of maximum potential erosion associated with the HIGH-risk scenario (*scenario 1),* since it is this scenario that is most likely to take place along the Oregon coast. As indicated in Table 2, the average MPED determined for the Clatsop Plains is 360 ft. However, even under the HIGH-risk scenario some beach sites have predicted coastal retreat of up to 522 ft. Generally, these sites tend to be located adjacent to rip embayments (e.g. the south jetty), Necanicum Bay mouth, and areas where access tracks (which may be further associated with a region where the dune has opened up) join the beach. Because of the lower beach elevations (E_J) and slopes that characterize such areas, very large potential erosion distances are always going to be predicted by the geometric model. Nevertheless, beach measurements by Ruggiero and Voigt (2000) revealed that the Clatsop beaches have recently eroded by as much as 125 ft.

The reality is, that it is unlikely that a single storm event would contribute toward coast-wide erosion of the magnitudes shown in Table 2 along the Clatsop County coastline, because of certain assumptions that are characteristic of the geometric model:

- 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 (Komar and others, 1999);
- The 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 time lag in the erosional response behind the forcing mechanism. As noted by Komar and others, the extreme high runup elevations calculated from Equation 1 (Appendix A) 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. Since 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 the amounts of coastal retreat shown in Table 2, and;
- As beaches erode, the sediment is removed offshore (or further along the shore) into the surf zone where it accumulates as nearshore sand bars. This process helps to reduce 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 to reduce the rate of beach erosion that occurs.

Despite these limitations, it is conceivable that several severe storms could occur in relatively quick succession (storm-in-series) as occurred in February 1999, which would contribute to widespread coastal retreat. Furthermore, although the most recent winters (1997-98 El Niño and 1998-99 La Niña winters) were exceptional stormy, previous events (e.g. the 12 October 1962 "Columbus Day" storm, or the 1939 storms) have produced coastwide damage on a scale not seen in the last two decades. As a result, the geometric model remains a useful approach for estimating maximum potential erosion distances along dune-backed beaches.

CONCLUSIONS

Hazard zones on dune-backed beaches were determined for the Clatsop Plains using a geometric model, whereby property erosion occurs when the total water level produced by the combined effect of extreme wave runup (R) plus the tidal elevation (E_T), exceeds some critical elevation of the fronting beach, typically the elevation of the beach-dune junction (E_J). Three scenarios were used to model erosion hazard zones on dune-backed beaches:

- *Scenario 1* (HIGH-risk) is analogous to the 2-3 March 1999 La Niña winter storm. This scenario is based on the storm waves occurring over the cycle of an above average high tide, coincident with a 3.3 ft storm surge. Under this scenario, the designated HIGH-risk hazard zone was estimated to be 360 ft, while individual beach sites may vary by a much as 243 ft to 522 ft due to subtle differences in the character of the beach (beach slope and beach/dune junction).

- *Scenario 2* (MODERATE-risk) is one of two "worst case" situations in which a severe storm event is coupled with a large storm surge of 5.6 ft. Maximum potential erosion distances (MPED) estimated for the Clatsop Plains under this particular scenario vary considerably, with calculated MPED's that ranged from 390 to 825 ft, while the designated width of the moderate hazard zone was established at 572 ft.

- *Scenario 3* (LOW-risk) is the second "worst case" scenario, and is the same as *scenario 2*, but incorporating a 3.3 ft subsidence from a Cascadia subduction zone earthquake. MPED estimated for *scenario 3* ranged from 424 to 938 ft, while the designated width of the low hazard zone was established at 635 ft.

The range of shoreline retreat predicted for dune backed beaches is clearly quite large for Clatsop County, and reflects the uncertainty in predicting future shoreline behavior based purely on extreme wave erosion events. Despite the low probabilities of some of the extreme water level scenarios adopted for Clatsop County, the width of the resulting average hazard zones is still justified since it can accommodate in a gross sense such changes as migrating rip current embayments, the wholesale transport of sand by longshore drift, and the on-offshore transport of sand. This type of modeling however ignores any long-term change in the sediment budget of the Columbia River littoral cell. For example, analyses of previous studies (particularly the results of the SWCES) indicate that the there has been a reduction in the amount of sand sourced from the Columbia River. Evidence for this includes the large-scale loss of sand in the Columbia River inlet, and the mid-continental shelf region offshore from the Clatsop Plains. These latter changes could conceivably contribute to further erosion of the Clatsop Plains in the future, particularly along Clatsop Spit, which has been eroding since 1926.

Finally, we strongly recommend that the County continue to monitor coastal changes along the Clatsop Plains on a regular basis. Such monitoring may include repeated surveys of beach cross-sections established as part of the SWCES (e.g. re-survey on a bi-annual basis), or analyses of coastal changes determined from any future aerial photography or LIDAR flights. Monitoring shoreline changes in the future is particularly critical for two reasons. Perhaps most importantly, regular monitoring can provide early warning of shoreline changes that could threaten lives and property. Monitoring is also fundamental to testing the validity of the assumptions made in the geometric model for dune-backed shorelines and the bluff retreat scenarios mapped for bluff-backed shorelines. At this stage, the geometric model does not account for "hotspot" erosion that occurs at the southern ends of littoral cells and mouths of the bays. As a result, further efforts are required to better define maximum potential erosion distances in these regions by incorporating empirical observations into the analysis. In addition, it is evident that the geometric model predicts an instantaneous beach response to a major storm. The reality however, is that there is some lag in the response time of the beach. In other words, does the beach require several storms to produce the type of maximum erosion predicted by the geometric model? or are the erosion estimates achieved over an entire season? Further efforts directed towards examining these issues would provide greater confidence in the predictions made by the geometric model.

ACKNOWLEDGMENTS

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REFERENCES CITED

Allan, J.C. and P.D. Komar, 2000a, Are ocean wave heights increasing in the eastern North Pacific? EOS, Transaction of the American Geophysical Union, 47: 561-567.

Allan, J.C. and P.D. Komar, 2000b, Spatial and temporal variations in the wave climate of the North Pacific: Unpublished report to, Department of Land Conservation and Development, 46.

Allan, J.C. and P.D. Komar, In Press, Extreme storms on the Pacific Northwest Coast during the 1997-98 El Niño and 1998-99 La Niña: Journal of Coastal Research.

Allan, J.C. and P.D. Komar, In review, The wave climate of the eastern North Pacific: Long-term trends and El Niño/La Niña dependence: Journal of Coastal Research.

Allan, J.C. and G.R. Priest, 2001, Evaluation of coastal erosion hazard zones along dune and bluff backed shorelines in Tillamook County, Oregon: Cascade Head to Cape Falcon: Oregon Department of Geology and Mineral Industries, Portland, Oregon: 111.

Atwater, B.F. and E. Hemphill-Haley, 1996, Preliminary estimates of recurrence intervals for great earthquakes of the past 3500 year at northeastern Willapa Bay, Washington: U.S. Geological Survey, 87.

Bacon, S. and D.J.T. Carter, 1991, Wave climate changes in the North Atlantic and North Sea: International Journal of Climatology, 11: 545-558.

Carter, D.J.T. and L. Draper, 1988, Has the north-east Atlantic become rougher?: Nature: 332, 494.

Geometrics Consultants, 1995, Seismic source characterization, in Geometrics Consultants, Seismic design mapping, State of Oregon: Project number 2442, Final report prepared for Oregon Department of Transportation, 2-1 to 2-153.

Cooper, W.S., 1958, Coastal sand dunes of Oregon and Washington: Geological Society of America. Memoir 72: 169.

Daniels, R.C., R.H. Huxford and D. McCandless, 1998, Coastline mapping and identification of erosion hazard areas in Pacific County, Washington: ESRI 1998 User Conference, San Diego, California.

Daniels, R.C., P. Ruggiero and D. McCandless, 2000, Interpretation of the average high water line from aerial photography: Variability and repeatability: in G. Gelfenbaum and G. M. Kaminsky, Southwest Washington coastal erosion workshop report 1998: Washington Department of Ecology, Olympia, WA, and U.S. Geological Survey, Menlo Park, CA, OFR 99-524: 182.

Darienzo, M.E. and C.D. Peterson, 1995, Magnitude and frequency of subduction zone earthquakes along the northern Oregon coast in the past 3,000 years: Oregon Geology, 57(1): 3-12.

DLCD, 1995, Oregon's statewide planning goals & guidelines: Department of Land Conservation and Development, 42.

Flick, R.E., J.F. Murray and L.C. Ewing, 1999, Trends in U.S. tidal datum statistics and tide range a data report atlas: SIO Reference Series No. 99-20, Scripps Institution of Oceanography, 22.

Gelfenbaum, G., M.C. Buijsman, C.R. Sherwood, H.R. Moritz and A.E. Gibbs, 2001, Coastal evolution and sediment budget at the mouth of the Columbia River, USA: 4th International Conference on Coastal Dynamics, Lund, Sweden.

Gelfenbaum, G. and G.M. Kaminsky, 2000, Southwest Washington coastal erosion workshop report 1999: Washington Department of Ecology, Olympia, WA, and U.S. Geological Survey, Menlo Park, CA, OFR 00-439, 187.

Gelfenbaum, G., C.R. Sherwood, C.D. Peterson, G.M. Kaminsky, M.C. Buijsman, D.C. Twichell, P. Ruggiero, A.E. Gibbs and C. Reed, 1999, The Columbia River cell: A sediment budget overview: Proceedings of Coastal Sediments '99, Hauppauge, Long Island, New York, American Society of Civil Engineers: 1660-1675.

Ghil, M. and R. Vautard, 1991, Interdecadal oscillations and the warming trend in global temperature time series: Nature, (350): 324-327.

Graham, N.E. and H.F. Diaz, 2001, Evidence for intensification of North Pacific Winter Cyclones since 1948: Bulletin of the American Meteorological Society.

Huxford, R.H., 1998, Historical map recovery using multiple, integrated ESRI programs: ESRI 1998 User Conference, San Diego, California.

Huyer, A., 1983, Coastal upwelling in the California current system: Progress in Oceanography, 12: 259-284.

Huyer, A., W.E. Gilbert and H.L. Pittock, 1983, Anomalous sea levels at Newport, Oregon, during the 1982-83 El Niño: Coastal Oceanography and Climatology News, 5: 37-39.

Kaminsky, G.M., M.C. Buijsman, G. Gelfenbaum, P. Ruggiero, H.M. Jol, A.E. Gibbs and C.D. Peterson, 1999a, Synthesizing geological observations and processes-response data for modeling coastal change at management scale: Proceedings of Coastal Sediments '99, Hauppauge, Long Island, New York, American Society of Civil Engineers: 1708-1723.

Kaminsky, G.M., R.C. Daniels, R.H. Huxford, D. McCandless and P. Ruggiero, 1999b, Mapping erosion hazard areas in Pacific County, Washington: Journal of Coastal Research, SI(28): 158-170.

Kirk, R.M., 1979, Dynamics and management of sand beaches in southern Pegasus Bay: Morris and Wilson Consulting Engineers Technical Report to, Christchurch City Council and Waimari District Council, Christchurch, NZ: 121.

Kleeman, R., R.A. Colman, N.R. Smith and S.B. Power, 1996, A recent change in the mean state of the Pacific basin climate: Observational evidence and atmospheric and oceanic responses: Journal of Geophyscial Research, 101(C9): 20483-20499.

Komar, P.D., 1986, The 1982-83 El Nino and erosion on the coast of Oregon: Shore and Beach, 54(2): 3-12.

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

Komar, P.D., 1998a, Beach processes and sedimentation: New Jersey, Prentice Hall, Inc. Englewood Cliffs: 544.

Komar, P.D., 1998b, The 1997-98 El Niño and erosion on the Oregon coast: Shore & Beach, 66(3): 33-41.

Komar, P.D. and J.C. Allan, 2000, Analyses of extreme waves and water levels on the Pacific Northwest coast: Unpublished, Department of Land Conservation and Development, 24.

Komar, P.D., J.C. Allan, G.M. Dias-Mendez, J.J. Marra and P. Ruggiero, 2000, El Niño and La Niña - erosion processes and impacts: Proc. 27th International Conference on Coastal Engineering.

Komar, P.D., W.G. McDougal, J.J. Marra and P. Ruggiero, 1999, The rational analysis of setback distances: Applications to the Oregon coast: Shore & Beach, 67: 41-49.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace and R.C. Francis, 1997, A Pacific interdecadal oscillation with impacts on salmon production: Bulletin of the American Meteorological Society, 78: 1069-1079.

Moore, L.J., 2000, Shoreline mapping techniques: Journal of coastal research, 16(1): 111-124.

OCZMA, 1979, Beaches and Dunes Handbook for the Oregon Coast: Report to the Oregon Department of Land Conservation and Development, Newport, Oregon:

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

Peterson, C.D., D.L. Doyle and E.T. Barnett, 2000, Coastal flooding and beach retreat from coseismic subsidence in the Central Cascadia Margin, USA: Environmental and Engineering Geoscience, 6(3): 255-269.

Priest, G.R., 1999, Coastal shoreline change study Northern and Central Lincoln County, Oregon: Journal of Coastal Research, SP Issue(28): 140-157.

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

Ruggiero, P., P.D. Komar, W.G. McDougal, J.J. Marra and R.A. Beach, 2001, Wave runup, extreme water levels and the erosion of properties backing beaches: Journal of Coastal Research, 17(2): 407-419.

Ruggiero, P. and B. Voigt, 2000, Beach monitoring in the Columbia River littoral cell, 1997-2000: Publication No. 00-06-026, Coastal Monitoring & Analysis Program, Washington Department of Ecology, Olympia, WA: 113.

Schlicker, H.G., R.J. Deacon, J.D. Beaulieu and G.W. Olcott, 1972, Environmental geology of the coastal region of Tillamook and Clatsop Counties, Oregon: Oregon Department of Geology and Mineral Industries Bulletin, Portland, OR: 164.

Sherwood, C.R., D.A. Jay, R.B. Harvey, P. Hamilton and C.A. Simenstad, 1990, Historical changes in the Columbia River Estuary: Progress in Oceanography, 25: 299-352.

Shih, S.M., P.D. Komar, K.J. Tillotsen, W.G. McDougal and P. Ruggiero, 1994, Wave run-up and sea-cliff erosion: 24th International Conference on Coastal Engineering, American Society of Civil Engineers: 2170-2184.

Shoreland Solutions, 1998, Chronic coastal natural hazards model overlay zone: Technical report, Department of Land Conservation and Development, 43.

Taylor, G., 1999, Long-term wet-dry cycles in Oregon: http://www.oce.orst.edu/ats/.

USGS, 2000, Coastal and Nearshore Mapping with Scanning Airborne Laser (Lidar): http://coastal.er.usgs.gov/lidar/.

Vincent, P., 1989, Geodetic Deformation of the Oregon Cascadia Margin: Master's thesis, University of Oregon, Eugene:

Wolter, K. and M.S. Timlin, 1993, Monitoring ENSO in COADS with a seasonally adjusted principal component index: 17th Climate Diagnostics Workshop, Norman, OK, Climatology Survey, CIMMS and the School of Meteorology, University of Oklahoma: 52-57.

Woxell, L.K., 1998, Prehistoric beach accretion rates and long-term response to sediment depletion in the Columbia River littoral system, USA: M.S., Portland State University, Portland, OR: 206.

APPENDIX A: 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 A1, and in an expanded form as the geometric model in Figure A2. 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).

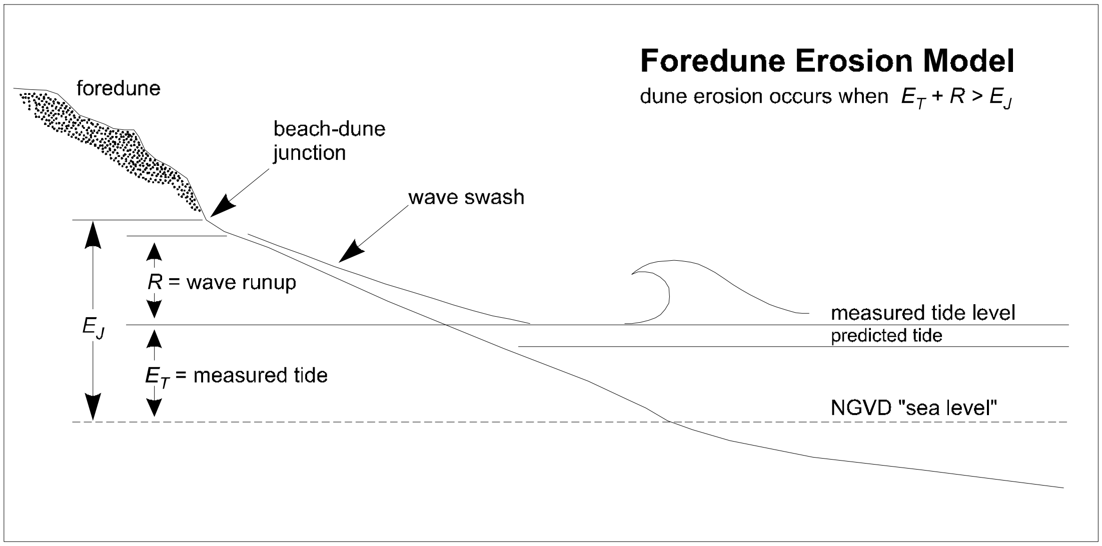


Figure A 1 The foredune erosion model (Komar and others, 1999).

As can be seen from Figure A2, estimating the maximum amount of dune erosion (DE_{max}) is dependant on identifying the total water level elevation, *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 the $WL > E_J$ the beach retreats landward by some distance, until a new beach-dune junction is established, whose elevation approximately equals the extreme water level. Since 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 the dunes are eroded landward until the dune face reaches point B in Figure A2. 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, 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 *?BL* shown in Figure A2, which causes the dune to retreat some additional distance landward until it reaches point C. As can be seen from Figure A2, the distance from point A to point C depicts the total retreat, DE_{max}, expected during a particularly severe 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).

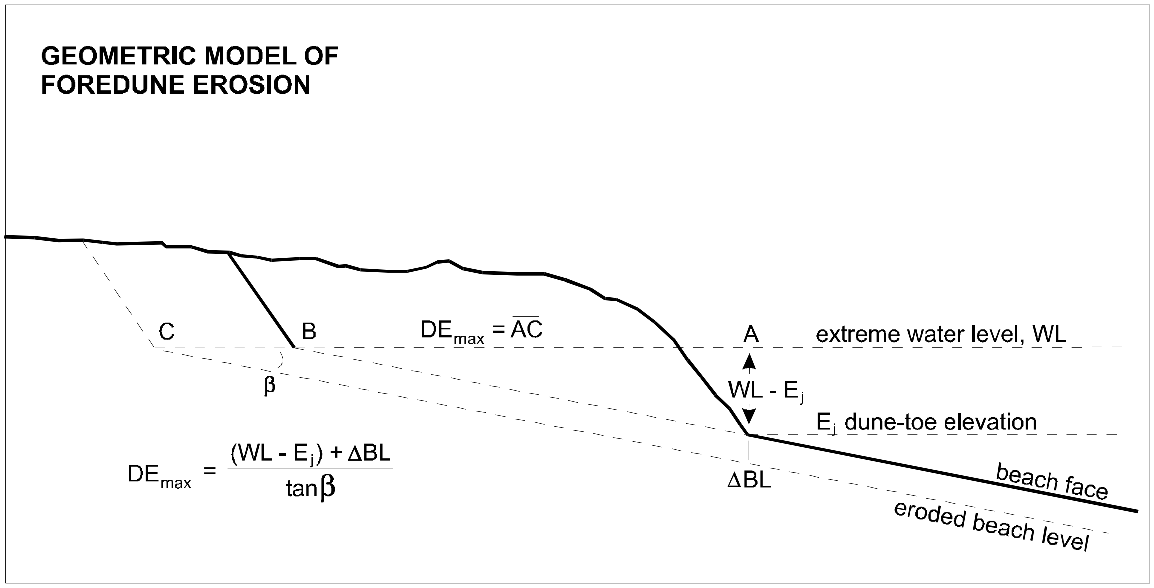


Figure A 2 The geometric model used to assess the maximum potential beach erosion in response to an extreme storm (Komar and others, 1999).

<u>*Wave Runup*</u>

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

$$R_{2\%} = 0.27\left(S\, H_{SO}\, L_O\right)^{1/2} \qquad \text{(Equation 1)}$$

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 $L_O = (g/2p)T^2$ where T is the wave period, and g is acceleration due to gravity (9.81 m.s^{-1}). Therefore, estimates of the wave runup elevation depend on knowledge of the wave heights and periods. Since 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 A2), it is important to examine the probabilities of extreme wave occurrence offshore from the PNW coast.

Wave data (wave heights and periods) have been measured in the North Pacific using wave buoys and sensor arrays for almost 30 years. 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. Previous analyses of these data up through 1996 by Ruggiero and others (1996; 2001) indicated that the projected 100-year extreme storm would generate a deep-water significant wave height on the order of 33 ft. However, during the 1997-98 El Niño that height was exceeded by one storm, and by four 100-year storms during the 1998-99 La Niña winter, with the March 2-3, 1999 storm having generated deepwater significant wave heights of 46 ft (Table A1). Finally, a sixth 100-year storm occurred during the winter of January 2000.

Table A 1 Peak storm wave statistics for the Newport wave buoy for the major 1997-98 El Niño and 1998-99 La Niña (Allan and Komar, In Press).

Buoy #46050	*Date*	*Significant wave height (feet)*	*Wave Period (s)*	*Wave Breaker height (feet)*
El Niño (1997-98)	19-20 Nov, 1997	34.5	14.3	38.4
La Niña (1998-99)	25-26 Nov, 1998	35.4	12.5	37.1
	6-7 Feb, 1999	33.1	12.5	35.4
	16-17 Feb, 1999	32.8	20.0	42.3
	2-3 Mar, 1999	46.3	16.7	51.8
La Niña (1999-00)	16-17 Jan, 2000	39.7	14.2	43.0

In response to the large wave events that occurred during the latter half of the 1990s, the wave climate of the eastern North Pacific has been re-examined to determine the probabilities of extreme wave occurrence offshore from the PNW coast (Komar and Allan, 2000; Allan and Komar, In review). 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 U.S. These analyses yield 100-year storm wave heights that ranged from 46 to 55.1 ft, 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. To accommodate this type of variation in our analyses and for input into Equation 1, the extreme wave height estimates were averaged, so that mean 10- through 100-year extreme value significant wave heights could be determined for the Oregon coast. These values are presented in Table A2.

Analyses have also been undertaken of the range of wave periods that are experienced in the eastern North Pacific (Komar and Allan, 2000; Allan and Komar, in review). These data have been examined using joint-frequency graphs of the significant wave heights versus the spectral-peak periods, the latter being the region where most of the wave energy occurs. The analyses have revealed that the largest wave heights tend to correspond to spectral-peak periods that range from 15 to 17 seconds, with some storm events producing periods up to 20 seconds. Since Equation 1 is particularly sensitive to the magnitude of the wave period, we have focused on the longer period wave events in our modeling of wave runup elevations.

Table A 2 Average extreme-wave projections based on data from four NDBC wave buoys located offshore the Pacific Northwest coast.

Projection (years)	*Extreme wave heights (feet)*
10	39.7
25	44.3
50	47.6
75	49.2
100	52.5

<u>*Tides*</u>

The elevation of the sea, 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 top of 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.

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, 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. 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 of the order of 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 1.3 to 2.0 ft, which suggest that much larger storm surge heights can be experienced along the PNW coast (Allan and Komar, In Press). As a result, any analysis of future coastal change should include a storm surge component.

Much longer-term processes that depend on offshore water temperatures and ocean currents can also influence the monthly-averaged water levels observed along the coast (Komar and Allan, 2000). In particular, analyses of the South Beach, Yaquina Bay tide gauge located in Newport, reveal a seasonal increase in mean water levels along the Oregon coast that occurs between summer and winter. This seasonal rise in mean water levels is on the order of 0.7 to 1.3 ft, and is a function of changes in the water temperature and effects from ocean currents (Komar and others, 2000). Additional analyses of water levels were carried out using the Astoria tide gauge, located within the Columbia River estuary. The analyses revealed a pattern of seasonal variability in mean water levels that are analogous to the Newport tide gauge. Because of these similarities, we have used the Newport tidal data in our modeling of MPED along the Clatsop Plains. As noted earlier, major climate events such as El Niños can also have a dramatic impact on water level elevations along the U.S. West Coast. For example, during the 1982-83 El Niño, water levels along the Oregon coast were raised by about 1.6 ft, and remained elevated for several months (Huyer and others, 1983). These findings were reinforced in a subsequent investigation of water levels during the 1997-98 El Niño by Komar and others (2000).

Long-term trends in the level of the sea can also be identified along the Oregon coast, which relate to the global (eustatic) rise in mean sea level that has been occurring over the past several thousand years. However, these changes in mean sea level are complicated due to on-going changes in the level of the land that are also occurring along the Oregon coast (Vincent, 1989). For example, Vincent demonstrated that the southern Oregon coast is rising at a faster rate than the global rise in mean sea level, while the northern Oregon coast is being slowly submerged by the rise in mean sea level (Figure A3). Analyses of long-term sea level changes at the Astoria tide gauge by Flick and others (1999) indicated that mean sea level at Astoria has remained relatively static. This compares with a rise in mean sea level of 3.7 mm/yr identified at the South Beach, Yaquina Bay tide gauge on the central Oregon coast (Flick and others, 1999). Thus, for modeling the MPED along the Clatsop Plains, we have <u>not</u> included a term to account for a long-term rise in mean sea level.

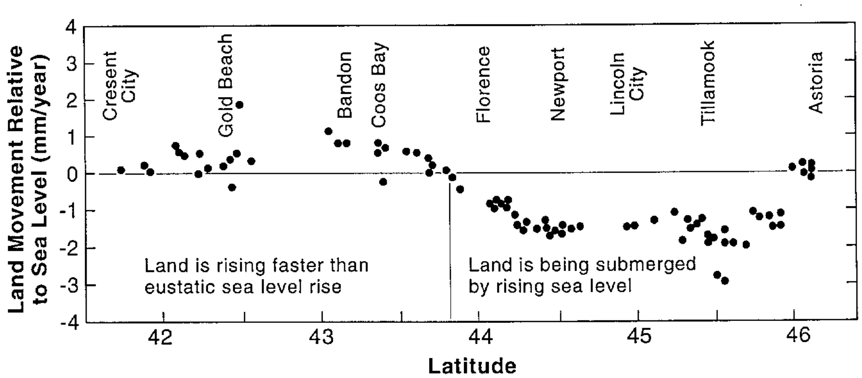


Figure A 3 Elevation changes along the Oregon coast, measured by geodetic surveys (Vincent, 1989). The elevation changes are relative to the global increase in sea level, with positive values representing a rise in the land at a higher rate than the increase in sea level, while negative values represent the progressive submergence of the land (Komar, 1997)

It is therefore apparent that the Oregon coast experiences highly variable mean-water levels, with the occurrence of extreme high tides being a contributing factor to the development of erosion problems (Komar and others, 1999). To accommodate the huge variability in tidal elevations experienced along the Oregon coast, an extreme value analysis (similar to that used to estimate the probabilities of the extreme wave heights) has been used to analyze the tidal elevations for the South Beach, Yaquina Bay tide gauge (Shih and others, 1994; Ruggiero and others, 1996; Ruggiero and others, 2001). Table A3 presents the 5- through 100-year expected extreme tide levels (E_T) determined for the South Beach, Yaquina Bay tide gauge. These data are referenced to the National Geodetic Vertical Datum of 1929 (NGVD'29) datum. As can be seen from Table A3, the expected 50- and 100-year tide is on the order of 8.2 ft, and likely includes the effects of an El Niño. Furthermore, it is apparent from Table A3 that there is in effect little difference in the extreme tidal elevations estimated for the 5- through 100-year expected tides, with the difference amounting to only about 1.0 ft.

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).

A remote sensing technology, LIDAR, was used to assess the morphology of beaches at the end of the 1998 El Niño winter. These data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center website (http://www.csc.noaa.gov/crs/tcm/index.html), operated in tandem with the United States Geological Survey (USGS) and NASA. The LIDAR data consists of x, y, and z values of land topography that are derived using a laser ranging system mounted on board a De Havilland Twin Otter aircraft. To measure the coastal topography, the aircraft flies at an altitude of approximately 700 meters at a rate of about 60 $m.s^{-1}$, and surveys a several hundred meter wide swath of the shoreline, acquiring a value of the surface elevation every few square meters (USGS, 2000). Subsequent analyses of the LIDAR data by NOAA staff have revealed that the data has a vertical accuracy within ±0.5 ft, while the horizontal accuracy of these measurements are within ± 2.6 ft. As noted by the USGS, use of LIDAR enables hundreds of kilometers of coastline to be mapped in a single day, with data densities that are unsurpassed using traditional survey technologies. Furthermore, subsequent survey runs using the same system can provide unprecedented data, which may be used to investigate the magnitude, spatial variability, and causes of coastal changes that occur during severe storms. All LIDAR data obtained from the NOAA/USGS/NASA website were in the 1983 Oregon State Plane Coordinate system, while the elevations were relative to the North American Vertical Datum of 1988 (NAVD' 88).

Once the LIDAR data was obtained from NOAA, the data were subsequently pruned (e.g. data points located in the surf zone were removed), and then analyzed using a triangulation approach to generate a grid data set. This process was accomplished using Vertical Mapper (contour modeling and display software), which operates seamlessly within MapInfo's GIS software. Having generated the grid data, cross-sections of the beach morphology could then be constructed along the Clatsop Plains. These were established at 100 m interval along the coast. Identification of the beach-dune junction (E_J) was accomplished in an EXCEL spreadsheet. Features used to distinguish the beach-dune junction included erosion scarps, major breaks in slope, or some combination. Beach slopes were estimated using standard linear regression techniques and included those data seawards from the beach-dune junction out to about the 3.3-ft contour elevation relative to the NAVD'88 datum.

Table A 3 Extreme annual tides (Shih and others, 1994). Note all elevations are relative to the NGVD'29 datum.

Projection (years)	*Mean water elevation (feet)*
5	7.2
10	7.5
25	7.9
50	8.2
100	8.2

APPENDIX B: ACTIVE HAZARD ZONE

An AEZ was mapped throughout the study area based on an analysis of historical shoreline positions, geomorphic features identified from aerial photographs (e.g. erosion scarps), and from an analysis of the total wave runup elevation (tides + wave runup) at the shore. The landward boundary of the AEZ was established by analyzing the total wave runup elevation (tides + wave runup) at the shore using Equation 1 (Appendix A) and the parameters outlined in Scenario 1. This produced an average elevation of 10 m relative to the NAVD'88 vertical datum. The 10 m contour elevation line was identified from Gearhart to Clatsop Spit, using the 1998 LIDAR topographic grid data. Some adjustments of the 10 m contour line were necessary along the northern end of Clatsop Spit due to the significant erosion that is being experienced there. These data were subsequently drawn on 1999 digital orthophotos in MapInfo obtained from the SWCES.

The seaward boundary of the AEZ was established as the most seaward contemporary Mean High Water Line (MHWL) identified from National Ocean Service (NOS) Topographic (T) sheets, 1995 and 1999 aerial photographs, and from the LIDAR data. The methodology for deriving the MHWL is discussed below. These data were especially useful for identifying coastal changes along Clatsop Spit, and around the mouth of the Necanicum estuary. The results clearly highlight the highly dynamic nature of both the spit ends and the mouths of the estuaries.

Approaches used to derive historical and contemporary shoreline positions

Historical and contemporary shoreline positions were derived from National Ocean Service (NOS) Topographic (T) sheets, 1995 and 1999 aerial photographs, and from the 1997 and 1998 LIDAR data. These data provide an understanding of the variability of previous shoreline locations 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 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,
- The impact of storms, including spit breaches, overwash, and changes in inlet mouth position, and
- Human impacts caused by construction (e.g. the jetties) or dredging.

National Ocean Service T-sheets covering the period 1870s era, 1926, and 1950s era were obtained from the SWCES. The images were georeferenced and orthorectified[2] using the ERDAS Imagine™ and Orthomax™ software to correct for various distortions (Kaminsky and others, 1999b). The historical shoreline positions were subsequently derived using visual cues to determine the MHWL (Daniels and others, 1998; Huxford,

[2] Ortho-rectification means removing distortions from the photo, so it can be used as an accurate map of the features that it depicts. These distortions include distortion around the photo edges caused by the camera lens, distortion due to elevation variation throughout the photograph, and changes in the altitude and attitude (pitch, roll, yaw) of the airplane (Kaminsky and others, 1999b).

1998). Errors associated with the identified shorelines (vector data) were analyzed, Table B1, and found to meet the published NOS accuracy standards for the original data source (e.g. ±3 m for 1:10,000 T-sheet and ±6 m for 1:20,000 T-sheets) (Daniels and others, 2000). Great care was taken to account for the variability of the various shoreline positions. However, it is recognized that some error may occur during the digitizing process that is largely a function of the ability of the operator to accurately follow the position of the shoreline. Estimates by Anders and Byrnes (1991 in Moore, 2000) indicate that such operator errors are on the order of ± 5.0 m at 1:20,000 map scale, while analyses by Daniels and others (1998) indicated an operator error of ± 6.0 m for the NOS T-sheets and ± 2.0 m for the aerial photographs (Table B1).

Additional shoreline positions were derived from photography flown in August and September of 1995 (Daniels and others, 1998), 1997 and 1998 LIDAR data, and from 1999 digital orthophotos. These latter datasets provide the most up-to-date assessments of the character of the Clatsop coastline.

Besides the errors associated with digitizing a shoreline from historical NOS T-sheets, there are also problems with digitizing shoreline positions from the digital orthophotos. The line between the wet and dry sand, which can be clearly identified on aerial photographs as a tonal change, is the most commonly used proxy for defining a shoreline position (Moore, 2000). This line closely approximates the HWL, which in turn approximates the MHWL. An example of this is shown in Figure B1. According to Moore (2000), there are a number of potential errors that may arise from using the wet/dry line to represent a shoreline. These include:

1) Variations in the HWL over the short-term as a result of storm events, or as a result of seasonal variations in the wave climate;
2) The HWL may also fluctuate in response to the tidal stage, beach slope, or wave conditions;
3) Interpretation of the HWL from an aerial photograph, or;
4) Measurements that are derived from HWL that are used to define rates of coastal change.

Of the errors listed above, those associated with seasonal and daily changes in the tidal cycle present the greatest problem for scientists attempting to define a shoreline. As part of the SWCES, Daniels and others (2000) carried out detailed analyses of the MHWL position over five months, using different techniques (e.g. beach surveys, interpretation of aerial photos, and GPS). They found that the MHWL varied on a monthly basis from as little as ± 13.0 m to ± 17.6 m. These variations are purely a function of monthly differences in the tidal elevations and the wave conditions. Based on their analyses, Daniels and others (2000) identified an average seasonal variability in the position of the MHWL of ± 15.0 m (Table B1).

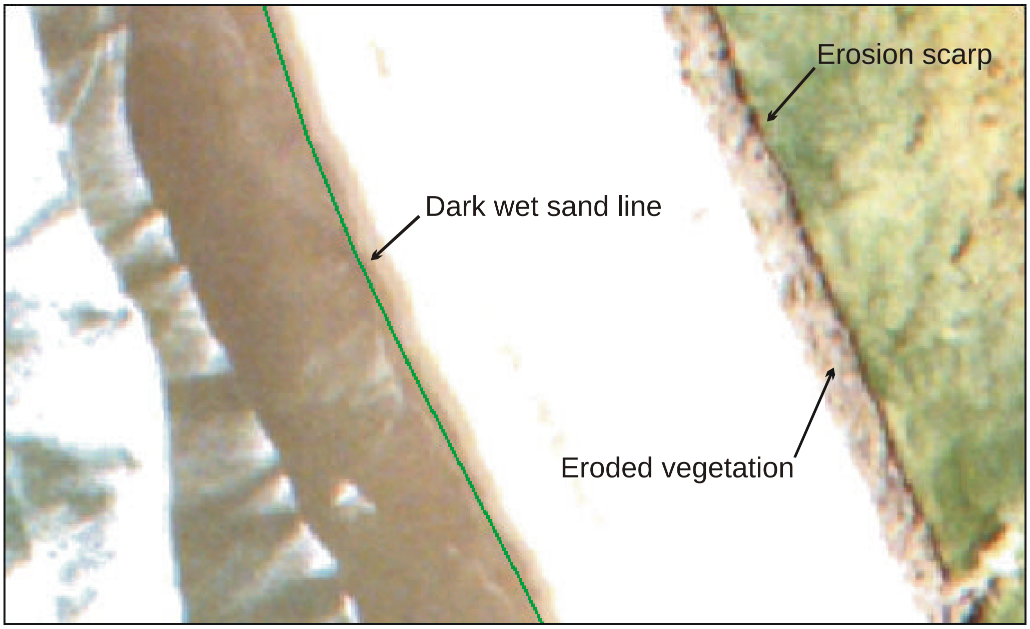


Figure B 1 The dark wet sand line used to identify the MHWL along Clatsop Spit. Note the erosion scarp clearly identified to the right of the white sand. This indicates further evidence of continued erosion along Clatsop Spit.

The range of potential errors associated with determining the historical shoreline positions from the NOS T-sheets, and from aerial photographs is summarized in Table B1. As indicated in the table, total errors range from ± 41 m (134.5 ft) for the 1880 era T-sheets to ± 20 m (65.6 ft) for the aerial photographs.

Table B 1 Total error and uncertainty budget for MHWL estimates (Daniels and others, 2000).

	Shoreline Derivation Error *m (ft)*	*Shoreline Interpretation Uncertainty* *m (ft)*	*Seasonal Variability* *m (ft)*	*Total Error and Uncertainty* *m (ft)*
1880 era T-sheets	± 20 (65.6)	± 6 (19.7)	± 15 (49.2)	± 41 (134.5)
1920 and 1950 era T-sheets	± 6 (19.7)	± 6 (19.7)	± 15 (49.2)	± 27 (88.6)
Aerial Photography	± 3 (9.8)	± 3 (9.8)	± 15 (49.2)	± 20 (65.6)

For further information on the analysis procedures used to identify historical shoreline positions in the Columbia littoral cell, refer to Daniels and others (1998), Huxford (1998), and Kaminsky and others (1999b).

APPENDIX C: COASTAL HAZARD ZONES OF THE CLATSOP PLAINS

Coastal erosion hazard zones drawn on 1999 digital orthophotos for the Clatsop Plains (digital images were provided by the Southwest Washington Coastal Erosion Study). North is at the top of the page.

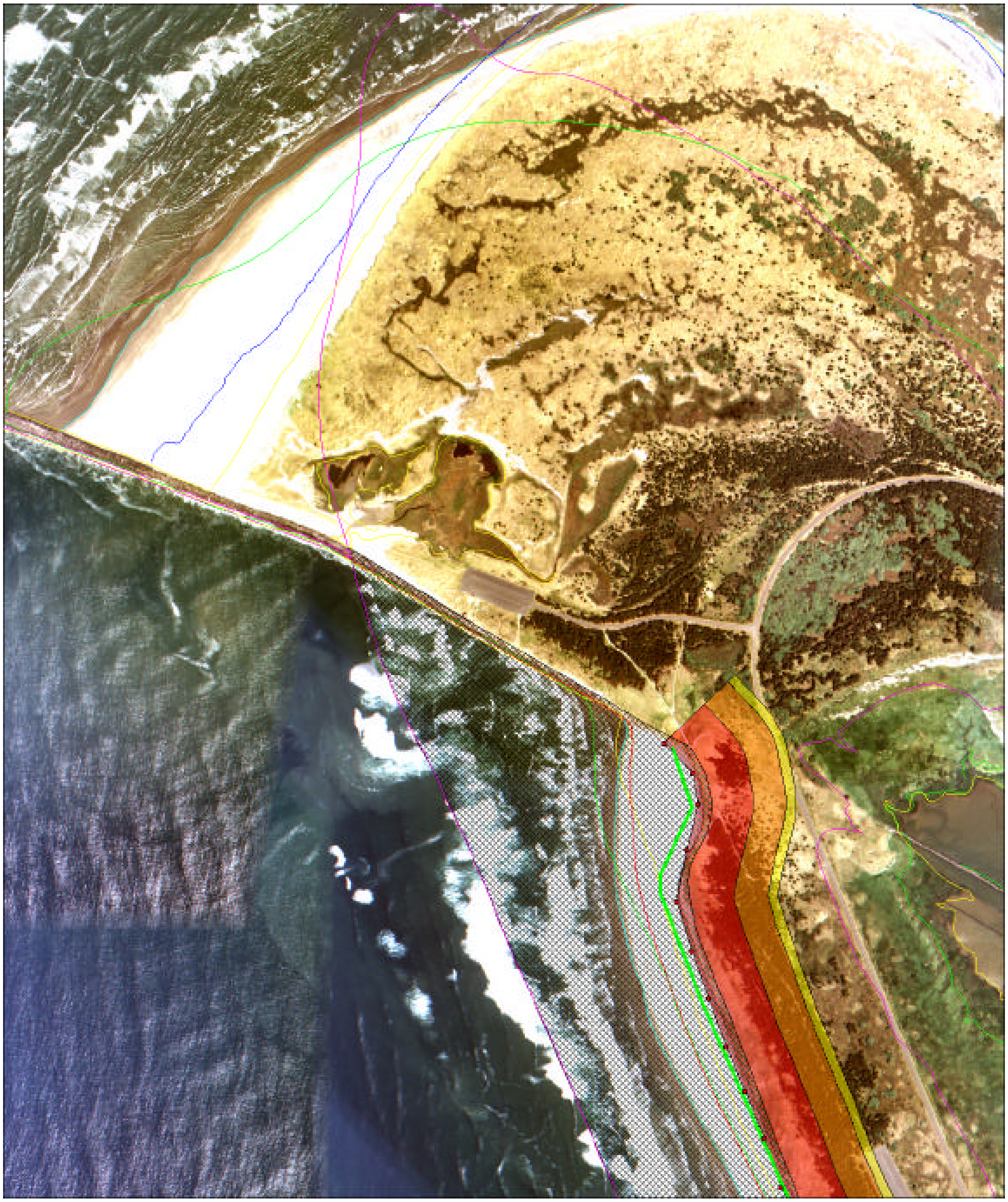
Maps progress sequentially from Clatsop Spit in the north to Gearhart in the south. Map scales are indicated with each figure.

<u>Key to Appendix C</u>

	Beach/dune toe junction as at April 1998
	Digital shorelines
	1999
	1998
	1997
	1995
	1950s era
	1926
	1870s era
	Active erosion hazard zone
	High-risk coastal erosion hazard zone
	Moderate-risk coastal erosion hazard zone
	Low-risk coastal erosion hazard zone

APPENDIX C (cont.)

(scale = 1:12,000 or 1 inch = 1,000 ft)



APPENDIX C (cont.)

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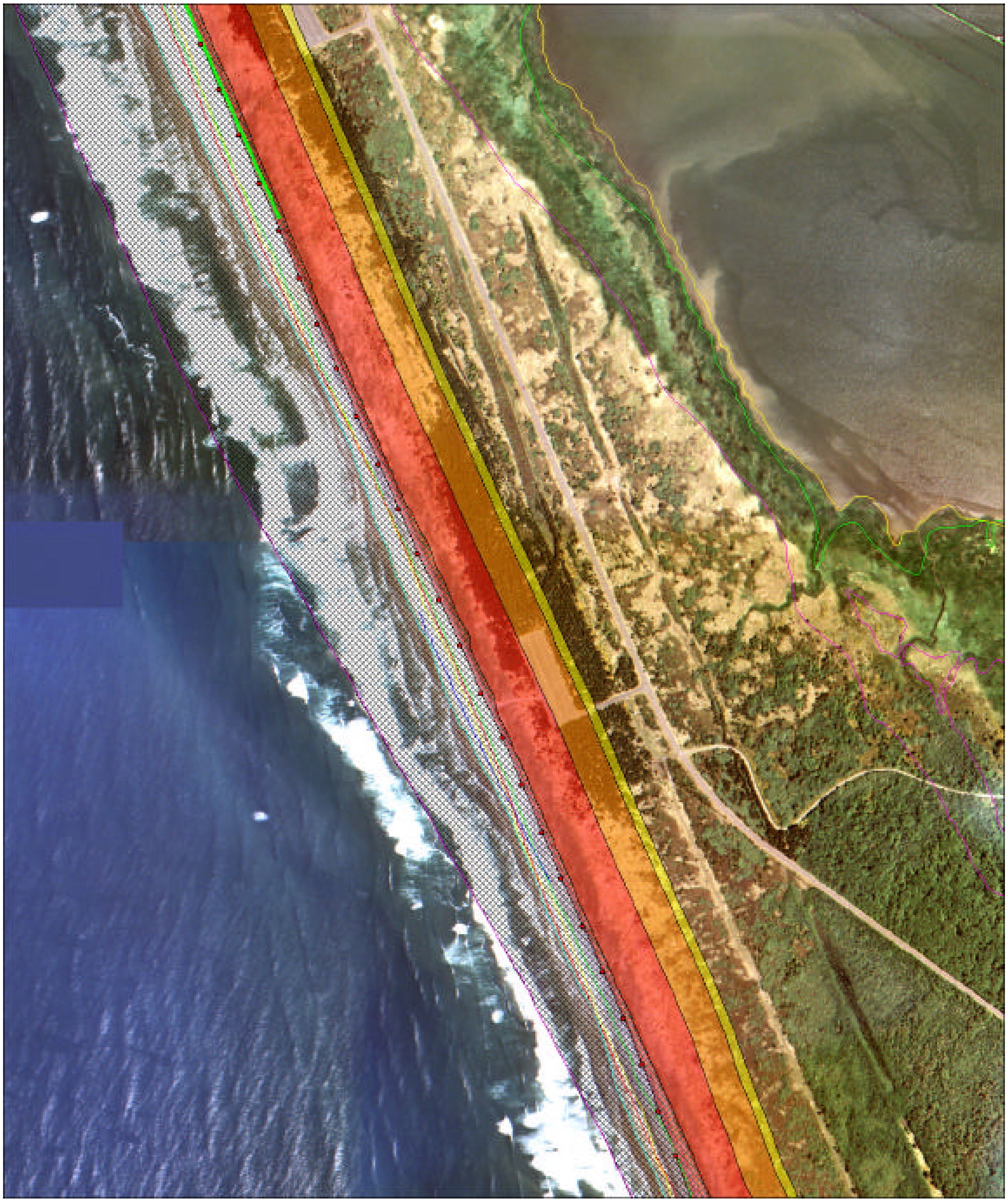

APPENDIX C (cont.)
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APPENDIX C (cont.)

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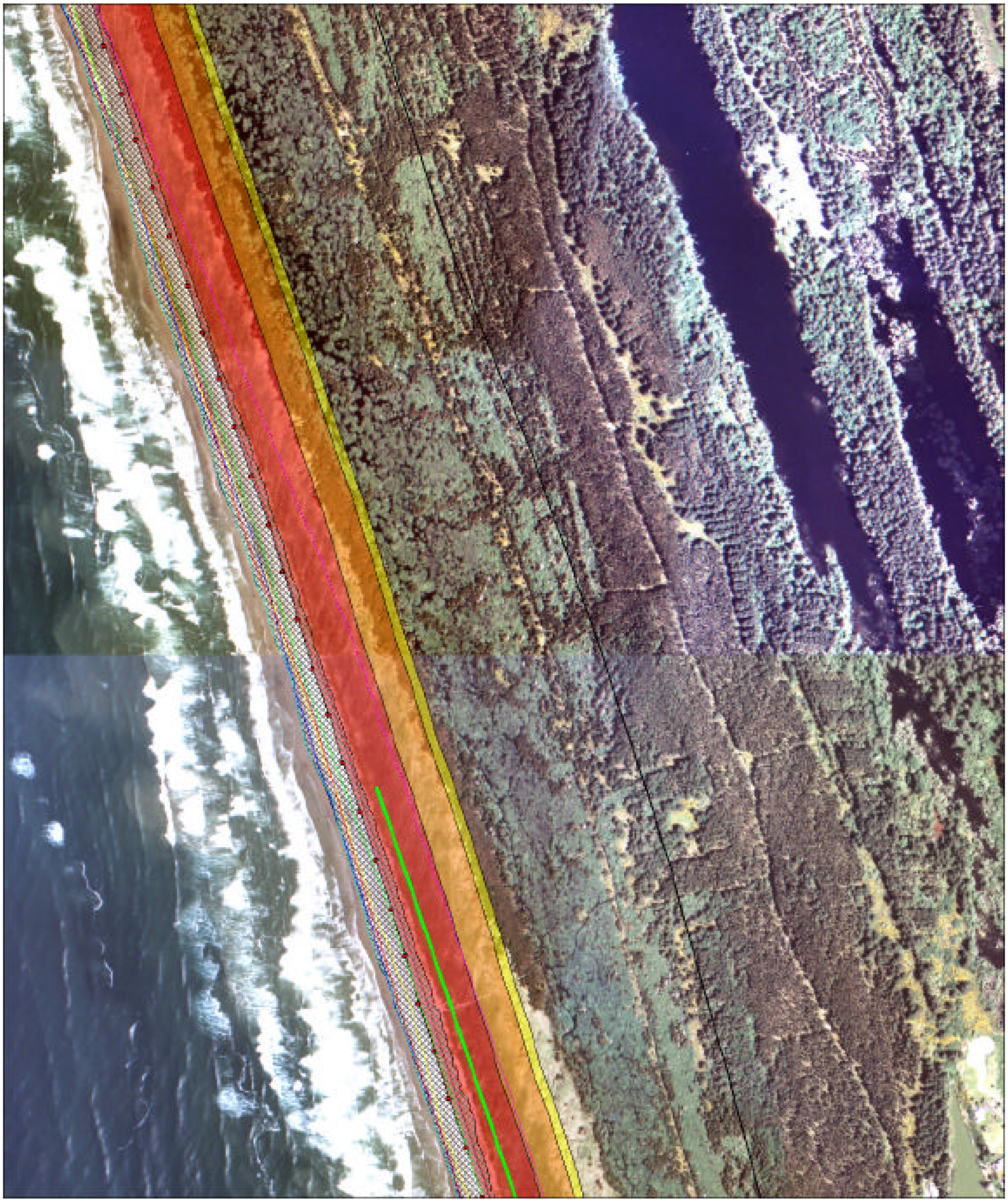

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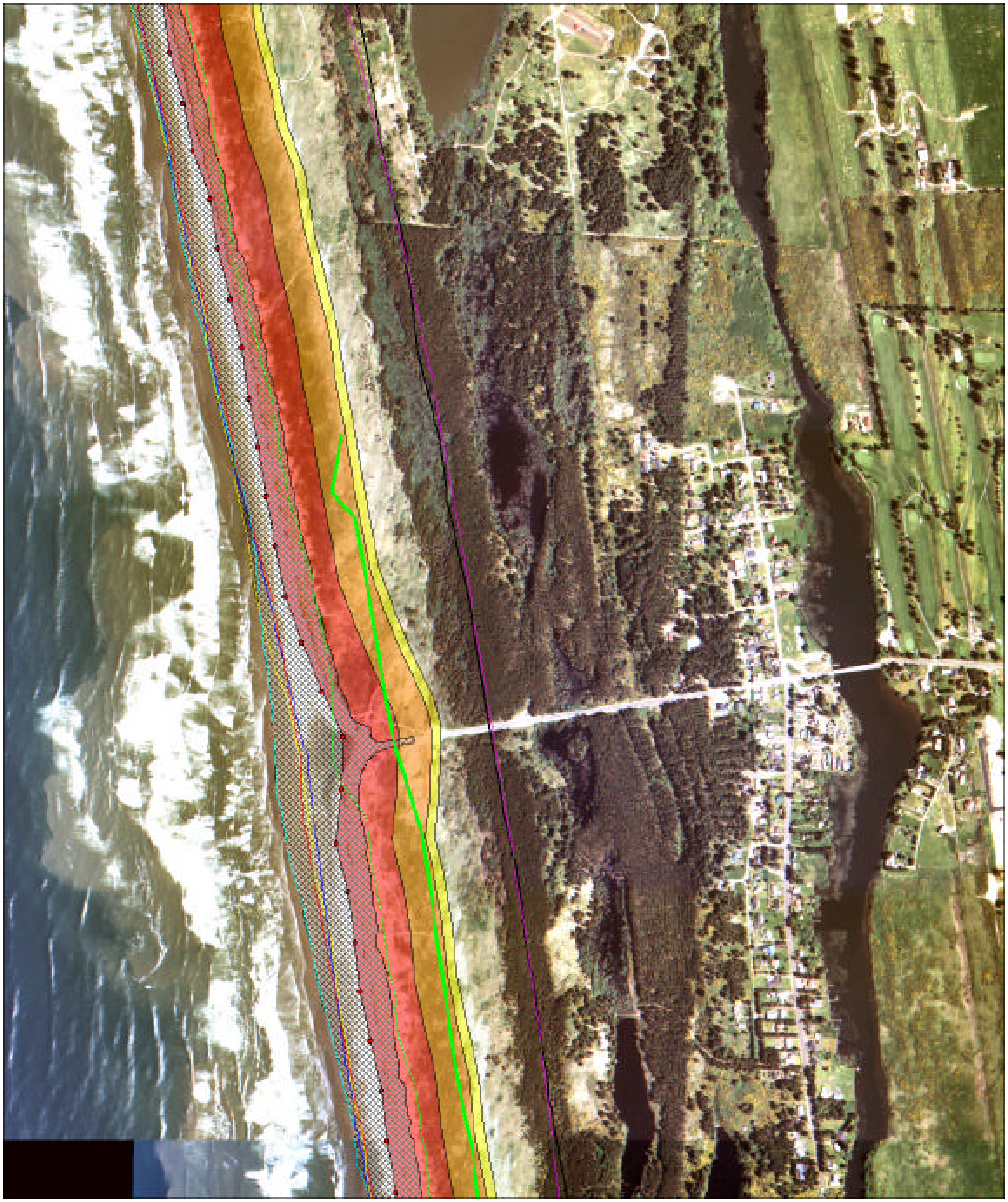

APPENDIX C (cont.)

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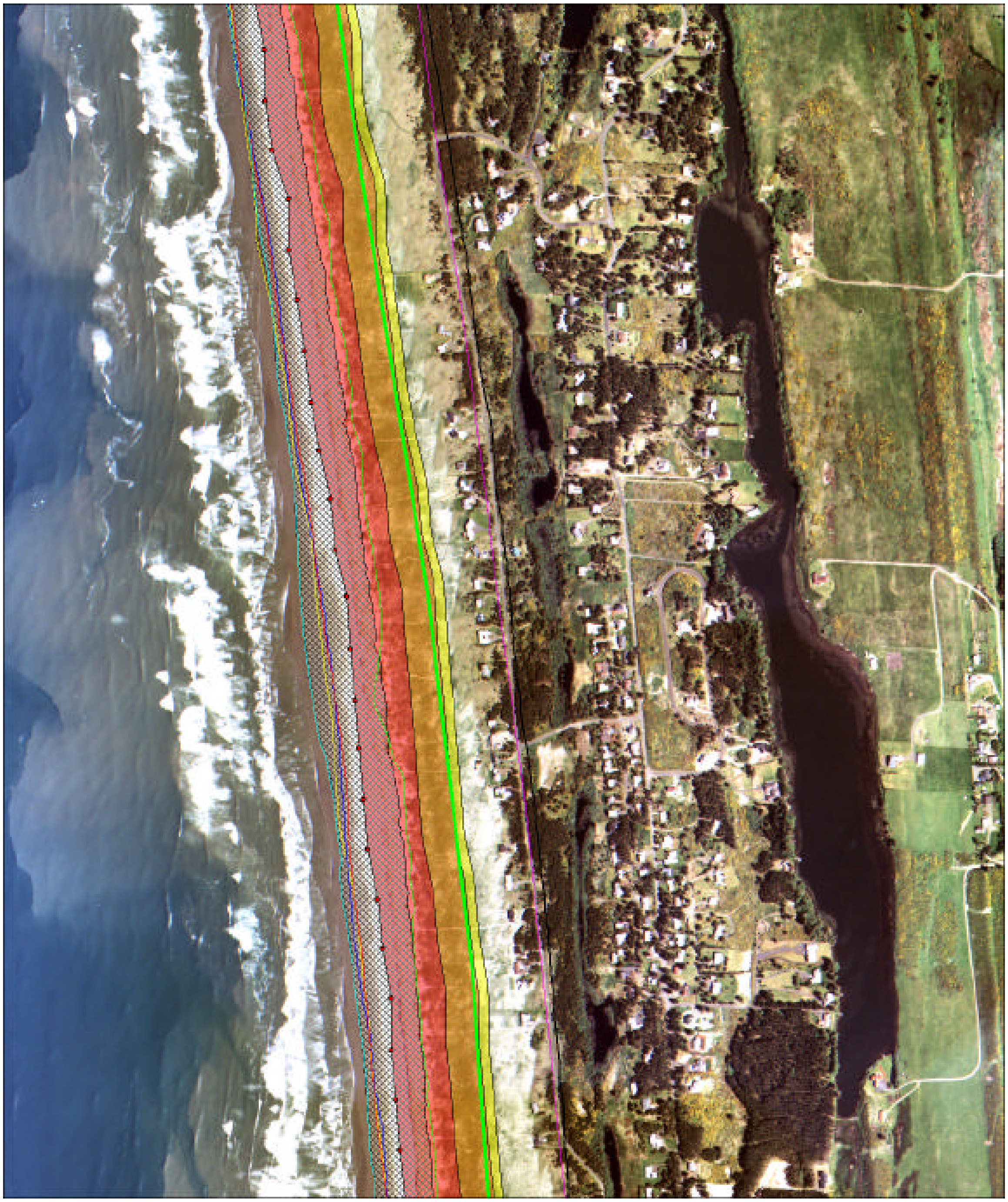

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