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

STATE OF OREGON
DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES
Suite 965, 800 NE Oregon St., #28
Portland, Oregon 97232

OPEN-FILE REPORT O-01-03

EVALUATION OF COASTAL EROSION HAZARD ZONES ALONG DUNE AND BLUFF BACKED SHORELINES IN TILLAMOOK COUNTY, OREGON: CASCADE HEAD TO CAPE FALCON

PRELIMINARY
TECHNICAL REPORT TO TILLAMOOK COUNTY

2001

By
JONATHAN C. ALLAN AND GEORGE R. PRIEST
Oregon Department of Geology and Mineral Industries
Coastal Field Office, 313 SW 2nd St, Suite D
Newport, OR 97365

NOTICE
The results and conclusions of this report are necessarily based on limited geologic and geophysical data. At any given site in any map area, site-specific data could give results that differ from those shown in this report. **This report cannot replace site-specific investigations**. The hazards of an individual site should be assessed through geotechnical or engineering geology investigation by qualified practitioners.

Table of Contents

EXECUTIVE SUMMARY

This report describes and documents a range of coastal hazard zones distinguished for the Tillamook County coastline. In particular, the report focuses on identifying maximum potential erosion distances for bluffs and for dune backed shorelines using two quite different but complementary approaches. In both types of shorelines four zones were defined, an ***active hazard zone*** characterized by existing, active erosion processes, and three zones of potential future erosion, ***high, moderate, and low risk zones*** 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-risk 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-risk zone defines the outermost limit of expansion of the active hazard zone in a worst-case scenario. This scenario could be a catastrophic event such as a great earthquake on the Cascadia subduction zone, coupled with severe storms. For example, a Cascadia earthquake would directly cause widespread landsides on steep slopes, while remobilizing existing landslides. Near instantaneous subsidence of the coast by ~3 feet during a Cascadia event would lead to extensive coastwide retreat of dune and bluff backed beaches.

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) Analyses of historical shoreline changes along the Tillamook County coastline indicate that the dune-backed shorelines respond episodically to such processes as the El Niño/La Niña Southern Oscillation, and as a result of rip current embayments that cause "hotspot erosion" of the coast. Previous work suggests that such processes can cause up to 125 ft of beach erosion. Thus, the coastline undergoes periods of both localized and widespread erosion, with subsequent intervening periods in which the beaches and dunes rebuild. Nevertheless, because the record of such occurrences is relatively short, limited to 30 years at best, the effects of extremely large storms, or storms-in-series remain largely unknown, except for qualitative observations (e.g. sawed logs in dunes).

2) The most significant historical shoreline changes identified in Tillamook County has occurred in response to humans, particularly as a result of jetty construction during the early part of last century. In particular, jetty construction has had a dramatic influence on the morphology of Bayocean Spit. For example, erosion in the vicinity of the Cape Meares community has resulted in the coastline retreating by some 850 ft since 1927. However, erosion at Cape Meares appears to have stabilized since the construction of the south jetty. In contrast, erosion from jetty construction has been much less along the Rockaway-Manzanita beaches.

3) Coastal change adjacent to the unmodified bay mouths and spit ends has been dramatic in the past. These features are capable of migrating over large distances (up to 1500 feet) in response to changes in both the sediment supply and the predominant wave conditions.

4) Hazard zones on dune-backed beaches were determined from 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**). 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 width of the HIGH hazard zone was found to range from **250 to 280 ft**, and varies between the four littoral cells due to subtle differences in the beach morphologies (specifically the beach slope) among the littoral cells.

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

   - *Scenario 2* (**MODERATE-risk**). This scenario is based on an extremely severe storm event (waves ~52.5 ft high) coupled with a long-term rise in sea level of 1.3 ft. Maximum potential erosion distances (MPED) estimated for the Tillamook coastline under this particular scenario range from **415 to 460 ft**, varying between the four littoral cells.

   - *Scenario 3* (**LOW-risk**). 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 **460 to 510 ft**, varying between the four littoral cells.

5) Hazard zones on bluff-backed shorelines were mapped based on an understanding of several geological parameters including bluff erosion rates, potential for block failures, and empirically determined angles of repose for the bluff materials.

   - *Scenario 1 (***HIGH risk**) portrays the zone of bluff retreat that would occur if only gradual erosion at a relatively low mean rate were to occur after the slope reaches and maintains its ideal angle of repose (for talus of the bluff material). The time interval of erosion was assumed to be 60 years. The width of the high-risk hazard zone generally ranged from **20 to 30 ft** wide, depending on the type of geology. Where slopes were steeper than the angle of repose for talus of the bluff material, the zone width was increased by the lateral distance necessary to accommodate retreat to the angle of repose.

   - *Scenario 2* (**MODERATE risk**) portrays an average amount of bluff retreat that would occur from the combined processes of block failures, retreat to an angle of repose, and erosion for ~60-100 years. The moderate hazard zone boundary was placed halfway between the high and low risk boundaries, and resulted in bluff retreat that generally ranged from **40 to 250 ft,** depending on the type of geology. Width of the moderate hazard zone was locally increased to accommodate for the presence of inland landslides.

- Scenario 3 (**<u>LOW risk</u>**) illustrates a "worst case" for bluff retreat in ~60-100 years. This zone accommodates a maximum bluff slope failure, subsequent erosion back to its ideal angle of repose, and gradual bluff retreat for ~100 years. For bluffs composed of Holocene to Pleistocene dune sand, an additional retreat of the bluff top in response to short-term wave erosion events and potential subaerial erosion is achieved by adding a 100 percent safety factor to the erosion calculations, and making sure that the resulting bluff top retreat corresponds to at least a 50 percent factor safety for the ideal angle of repose (i.e. a 2:1slope). Low hazard zone widths ranged from **60 to 490 ft** wide, depending on the type of geology. Width of the low hazard zone was locally increased to accommodate for the presence of inland landslides.

6) An analysis of maximum single slide block failure width revealed that maximum width increases with bluff height but that above a threshold height width increases to hundreds of feet. This width is ~70-80 feet for seaward-dipping fine-grained Tertiary sedimentary rocks and ~150-160 feet for bluffs with clay-rich Pleistocene soil at the base. The observations for bluffs with clay-rich Pleistocene soil are tentative, because of the unknown effect of paleotopography developed on hard rock underlying the soil where the data was collected.

7) An active erosion hazard zone (AHZ) has also been identified for the Tillamook County coastline. For dune-backed shorelines, the AHZ encompasses the active beach to the top of the first vegetated foredune, and includes those areas subject to large morphological changes adjacent to the mouths of the bays due to inlet migration. On bluff-backed shorelines the AHZ includes actively eroding coastal bluff escarpments and active or potentially active coastal landslides.

8) Finally, the report identifies all landslides, slide blocks, and earth flow deposits located within about six miles of the coast, and classifies these features as active, potentially active, or prehistoric.

INTRODUCTION

The Oregon Department of Geology and Mineral Industries (DOGAMI) has been commissioned to carry out an assessment of existing and potential coastal erosion hazards along the Tillamook County shoreline, extending from Cascade Head in the south to Cape Falcon in the north. In particular, assessments of hazards have focused on those shorelines with sandy beaches that are populated. The purpose of this investigation is to assist County planners in effective decision-making adjacent to the shoreline. It should be stressed that this is a regional investigation and is not intended for use as a site-specific analysis tool. However, the investigation can be used to identify 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, near shore 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. Beaches and dunes therefore provide an essential buffering mechanism, protecting properties and infrastructure from wave attack. Notwithstanding this, because bluffs are also characteristic of much of the Oregon coast, erosion of these features is often accelerated by large storms during the winter months due to the removal of beach sediment from the base of the bluffs. This process enables waves to directly attack the bluff toe, causing it to be undercut. Eventually, the bluff begins to retreat, either gradually or in the form of major landslides that can cause catastrophic loss of property. These problems may be further enhanced due to the occurrence of extreme rainfall events and associated high groundwater levels.

Increasingly, the natural response of coastal shorelines to erode has come into conflict with the "built" environment due to the rapid growth in population and increased urbanization of coastal margins. Such development is characteristic of much of the Oregon coast, including significant sections of the Tillamook County shoreline (e.g. Neskowin, 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 provided to decision makers so they can make informed choices regarding shoreline management practices. That is the ultimate objective of this investigation. Specific tasks included:

1) Establish or work with local advisory groups to guide the investigation;

2) Purchase appropriate historical aerial photographs;

3) Search the literature for hazard data;

4) Compile a database of maximum block failure widths for bluff types in the area;

5) Map existing open coastal shoreline landslides, classifying them as prehistoric, potentially active, or active.

6) Collect shoreline topographic profiles and other data necessary to estimate the width of a zone of shoreline variability on dune-backed open coastal shorelines;

7) In collaboration with Tillamook County and technical advisors, establish a methodology for mapping erosion hazard areas.

8) Map the erosion hazard areas;

9) Digitize all line data, providing appropriate map labels and map explanations;

10) Transmit all digital data to Tillamook County in an appropriate file format;

11) Plot 2 copies of all maps, one to be transmitted to the County and one to be kept on file at DOGAMI.

12) Provide follow-up advice on use of the maps in policy development.

This report documents the methodologies and results associated with the broad objectives outlined in the above tasks.

SCALES OF COASTAL CHANGE

Coastal changes along the Pacific Northwest (PNW) span an extremely wide range of temporal and spatial scales, due to the diverse range of processes that influence the coastal environment (Shoreland Solutions, 1998a). Most obvious and simplest to appreciate in the PNW are those beach changes that occur between summer and winter. For example, during the summer months beaches accumulate sediments due to the predominance of low wave heights and long periods, while in winter the same beaches erode rapidly in response to an increase in the wave energy and changes in the directions of wave approach. Periodically these natural cycles of coastal change are further enhanced by the occurrence of infrequent high magnitude storm events that can account for some 100 ft of dune retreat along the coast (Komar and others, 1999). More recently, Ruggiero and Voigt (2000) presented measurements of beach change for six sites along the Clatsop Plains. They found that the Clatsop beaches eroded by as much as 125 ft during the 1998-99 La Niña winter. Nevertheless, as noted by Komar and others, the record of such occurrences is relatively short, limited to 30 years at best, so that the effects from extreme storm events, or from storms-in-series, remain largely qualitative. This absence of high-quality field data was made particularly apparent after the extreme 1998-99 La Niña winter storm that occurred on March 2-3, 1999. That event is one of the most severe storms to hit the PNW Coast since the 1962 Columbus Day storm and resulted in widespread erosion along the Oregon coast (Allan and Komar, 2002). However, apart from a few problem sites such as at Cape Lookout State Park and several study sites on the Clatsop Plains, measured data of coastal recession rates associated with the storm are virtually non-existent.

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 1). 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 1 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.

During an El Niño, the mean elevation of the sea is typically raised by tens of centimeters along the Oregon coast. As a result, waves superimposed on the tides are able to reach much higher elevations on beaches and bluffs 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 (Komar, 1986, 1997). Less well known is the coastal response associated with a La Niña, largely because of the relatively few La Niñas that have occurred over the past 20 years. 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). 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.

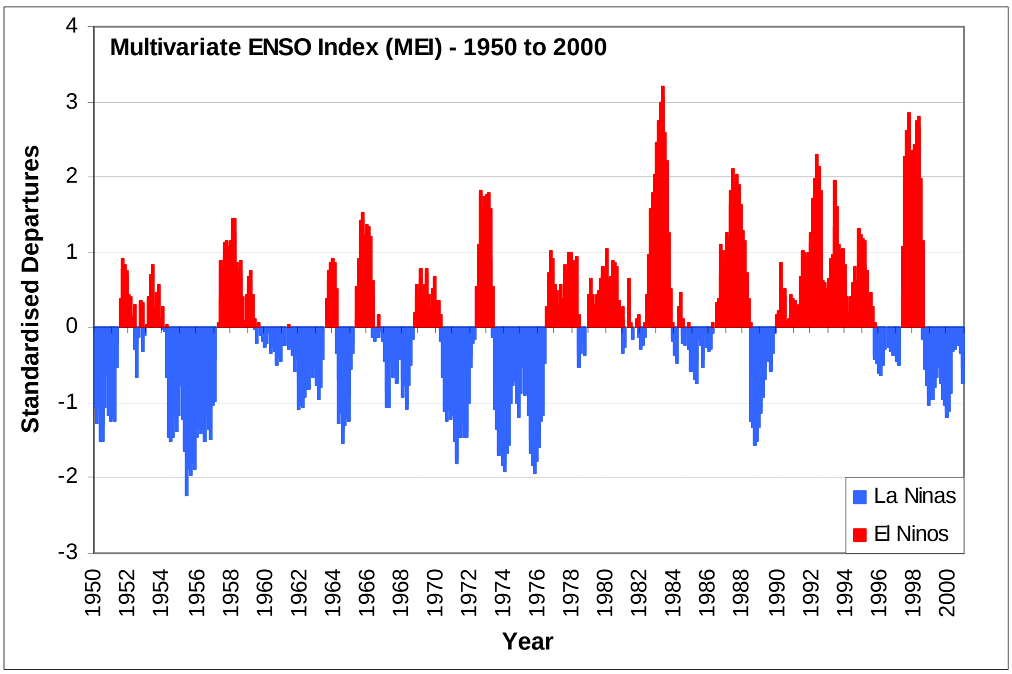


Figure 1 Multivariate ENSO index (MEI) showing the incidence of El Niños and La Niñas since 1950 (Data from Dr. K Wolter, http://www.cdc.noaa.gov/~kew/MEI/).

ENSO events are superimposed on much longer climate cycles that periodically change on a 20 to 30 year basis (Figure 2). 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 2). 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, 2000). 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.

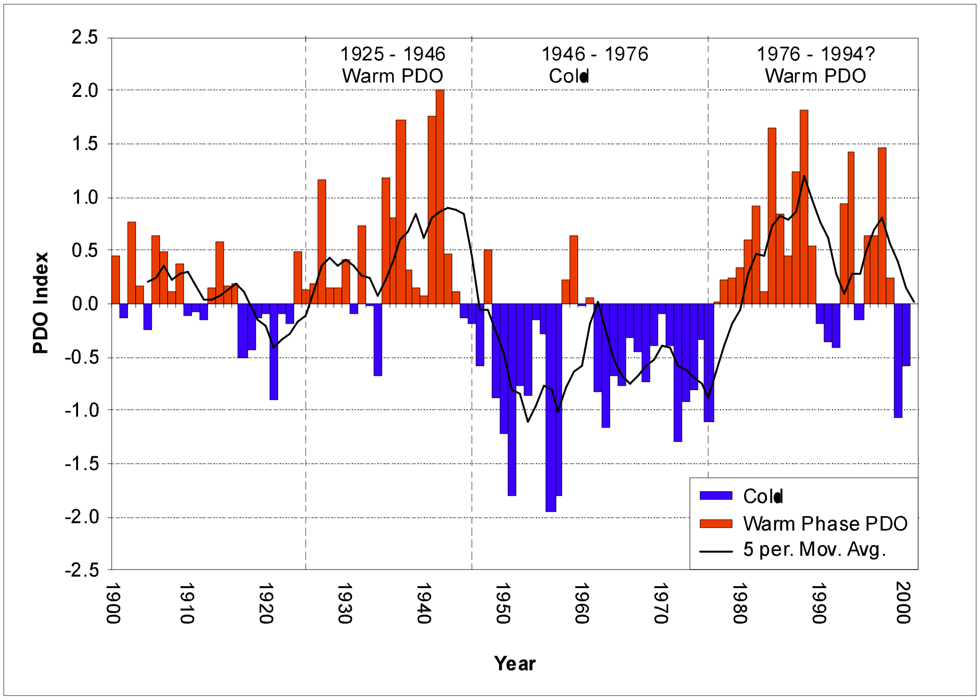


Figure 2 The Pacific Decadal Oscillation (PDO) climate index, 1900-1999 (Data from Dr. N. Mantua, http://jisao.washington.edu/pdo/).

Of further concern to coastal planners and managers are possible changes in the world's climate that may occur over the course of this century. It is likely that such climate changes will impact coastal systems, as variations in the incidence of storm frequency, storm tracks, or the heights of waves. For example, following efforts in the North Atlantic where long-term trends in the ocean wave heights have been identified (e.g., Carter and Draper, 1988; Bacon and Carter, 1991), Allan and Komar (2000a; 2000b; in review) have discovered similar upward long-term trends in the wave heights and periods (and therefore the wave energy) offshore from the PNW coast. This progressive increase in 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 however, Graham and Diaz (2001) provided a comprehensive examination of the North Pacific storm climatology. Their results substantiate the findings of Allan and Komar (2000a; 2000b; in review). In particular, Graham and Diaz revealed that the frequency and magnitude of storms in the North Pacific has in fact been increasing since the early 1940's. Furthermore, they identified increasing sea surface temperatures in the western tropical Pacific as a plausible cause of the observed changes in North Pacific storm frequency and intensity.

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

Unfortunately, there is little data available along the Oregon coast to make concise statements about the long-term character of the coastal system. This absence of information makes it equally difficult to project future trends in shoreline positions. However, what is known about the coast is that the beaches and bluffs mainly respond episodically (Komar and others, 1999; Peterson, 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. In the absence of high quality coastal data for Tillamook County, we have used the geometric model to estimate the MPED on the dune-backed beaches based on three scenarios, high, moderate, and low risk events. Each of the three scenarios is fully described below.

Additional information on coastal shoreline changes have been derived from an analysis of National Ocean Service (NOS) Topographic (T) sheets. These data provide a first-order understanding of historical shoreline variability that supplement the estimates of coastal change determined by the geometric model. For example, variations in the position of the shore, typically identified as the Mean High Water Line (MHWL) on the NOS T-sheets, can reveal details of:

- Long-term and short-term advance or retreat of the shore,
- Longshore movement of beach sediment,
- 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.

Bluffs in particular tend to erode in episodic slope failures dependent not only on wave erosion, but also in response to variations in ground water levels, and landward changes in the composition of rock and soil. However, unlike dune-backed beaches, defining coastal hazard zones on bluffs is complicated due to the wide range of mechanisms governing slope failure. Thus, there is no "one-size-fits-all" approach that can be applied coast wide. This report presents a variety of approaches for defining bluff-backed hazard zones, based on the geological conditions, slope failure types, and processes identified throughout Tillamook County and elsewhere on the Oregon coast. Based on this information, and the results of a technical workshop (convened in December 2000), which examined the process of erosion hazard mapping along coastal bluffs, a systematic methodology has been developed which allows for hazard zones to be established in a rigorously organized manner.

STUDY AREA

Tillamook County has approximately 61 miles of coastline, comprised of long sandy beaches interspersed with prominent headlands and steep bluffs (Schlicker and others, 1972). An additional 50 miles of coast exist along the bays and estuaries, which include from south to north, Nestucca, Netarts, Tillamook and Nehalem Bays. The entire shoreline can be broadly divided into four distinct littoral cells, with each cell separated by resistant headlands (Shoreland Solutions, 1994). Littoral cells are headland-bounded stretches of coast that trap beach sediment. Because the headlands extend into deep-water, wave processes are unable to transport sediment around the ends of the headlands and into the adjacent littoral cells. For the purposes of this investigation the four littoral cells include:

- Nestucca (Cascade Head to Cape Kiwanda);
- Sand lake (Cape Kiwanda to Cape Lookout);
- Netarts (Cape Lookout to Cape Meares), and;
- Rockaway (Cape Meares to Cape Falcon).

Each of these littoral cells is therefore more or less closed to sediment transport from the adjacent cells, depending on the efficiency of the bounding headland in preventing the along shore movement of sediment. As a result, each cell can be viewed as independent physical system.

METHODOLOGY

A variety of approaches have been used to define coastal hazard zones along the Tillamook County shoreline. In particular, significant time was spent during the summers of 1999 and 2000 “walking” the coast, classifying the many landslide features adjacent to the beach into one of three categories; active, potentially active, and prehistoric. Furthermore, from a review of the literature (Schlicker and others, 1972; Wells and others, 1994), a number of additional landslides were compiled for areas within approximately 6 miles of the coast. In most cases these inland landslides are listed simply as Quaternary landslides, without any interpretation about activity, especially if no field examination or other information could be found. The locations and classification of all landslides have subsequently been incorporated into MAPINFO, Geographic Information System (GIS) software, in which other data including the MPED estimated from the geometric model were added. Digital files of the same data but in ArcView and ArcInfo formats were also produced. The following sections present in more detail the approaches that have been used to establish erosion hazard zones on dune and bluff-backed shorelines.

Active Erosion Hazard Zone

An active erosion hazard zone (AHZ) (Figure 3) was mapped for dune and bluff-backed shorelines throughout the study area based on a combination of purely geomorphic observations, and from an analysis of historical shoreline positions. The AHZ is the least speculative of the designated coastal hazard zones since it depends on easily identifiable coastal features that may be seen on modern aerial photos supplemented with current field data. On dune-backed beaches, the AHZ 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. The landward boundary of the AHZ was drawn on 1994 digital orthophoto quadrangles (DOQ) at the top of the first continuously vegetated foredune. Furthermore, the landward boundary was adjusted to include 1998 Light Detection and Ranging (LIDAR) topographic data, indicative of shoreline recession that has occurred since 1994.

It is important to note that the AHZ 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).

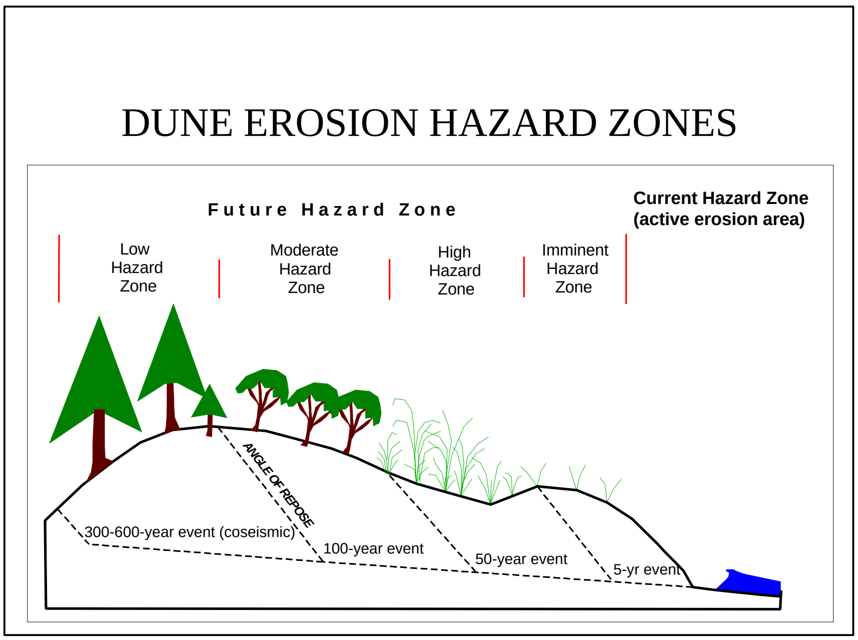


Figure 3 Schematic diagram showing possible dune erosion hazard zones.

On bluff-backed beaches the AHZ was mapped from the shoreline to the top edge of bluffs, sea cliffs, and the headwall of active, or potentially active shoreline landslides. Consistent with the view held for dune-backed shorelines, building within the active hazard zone along bluff-backed shorelines also reflects considerable risk from direct wave attack at the bluff toe or from slope instability.

The seaward boundary of the AHZ was established as the MHWL derived from an analysis of the NOS T-sheet shoreline positions and from the LIDAR data. This approach is discussed further below. These data were also used to identify the AHZ along the spit ends and around the mouths of the estuaries. Where those geomorphic features are uncontrolled (e.g. by the construction of jetties), the results clearly highlight the highly dynamic nature of both the spit ends and the mouths of the estuaries.

National Ocean Service T-sheets covering the period 1927, 1953 and 1955 were obtained from the Department of Land Conservation and Development. Additional shoreline positions were derived from 1985/1986 U.S. Geological Survey topographic maps in digital raster graphic format (DRG), 1994 digital orthophoto quadrangles (DOQ's), and from 1997 and 1998 LIDAR data. These latter datasets provide the most up-to-date assessments of the stability of the Tillamook coastline. The NOS T-sheets were originally mapped at 1:20,000 (1927), 1:10,000 (1953), and 1:5000 (1955) scales, respectively, by NOS surveyors and provide the most accurate representation of historical shoreline positions other than by direct field measurement.

Moore (2000) provides an excellent review of shoreline mapping techniques, including the use of NOS T-sheets, and their associated errors. She notes that post-1941 NOS T-sheets must meet or exceed National Map Accuracy Standards of ±10.2 m (33.5 ft) at a scale of 1:20,000, and ±8.5 m (27.9 ft) at a 1:10,000 scale, while older NOS T-sheets are likely to have an accuracy of no better than ±20 m (65.6 ft). Furthermore, she observed that post-1941 T-sheet maps are held to very strict standards since they are used to construct nautical charts. In contrast, older NOS T-sheets (pre-1941) were found to be less reliable and were largely dependant on the standards set forth by the chief surveyor at the time. Nevertheless, since the intention of the early NOS surveyors was to identify the location of the High Water Line (HWL), the surveys were taken seriously (Shalowitz, 1964 in Moore, 2000). Mapped shoreline accuracies associated with the 1985/1986 U.S. Geological Survey topographic maps are on the order of ±12.2 m (40 ft).

The NOS T-sheets were taken into MAPINFO, and re-projected to the Universal Transverse Mercator (UTM), North American Datum (NAD) 1927 coordinate system. To project the NOS T-sheets in MAPINFO, map control points need to be established, which are characterized by the most accurate and current geographic coordinates. These control points are used by the computer mapping program to calculate the transformations necessary to change a map's projection and scale (Gorman and others, 1998; Moore, 2000). As noted by Gorman and others (1998), the most suitable control points are triangulation stations whose current coordinates are available from the National Geodetic Survey. For the purposes of the present analyses, triangulation stations identified on the NOS T-sheets and from 1985/1986 U.S. Geological Survey topographic maps were used to project the NOS T-sheet images into the MAPINFO GIS environment. The MHWL shoreline position was subsequently digitized in MAPINFO. 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. Thus, the total shoreline mapping errors are likely to be on the order of ±15 m (49 ft) and ±11 m (36.1 ft) at 1:20,000 and 1:10,000 map scale respectively.

Besides the errors associated with digitizing a shoreline from historical NOS T-sheets, there are also problems with digitizing shoreline positions from the 1994 DOQ's. 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 4. 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.

The seasonal and short-term variations in the HWL can be minimized somewhat by confining the photographic flights to the summer months when wave conditions are much milder. More difficult is defining the magnitude of HWL variations caused by tidal fluctuations. Dolan and others (1980) carried out one such study and found that on a medium grained beach with a slope of 3 - 6 degrees, the HWL varied by about 3 - 6 ft over one tidal cycle. No such investigation however, has been carried out for the gently sloping beaches that characterize the coast of Oregon. Because of the flatter nature of the beaches of Oregon, the potential errors associated with tidal variations are likely to be much higher.

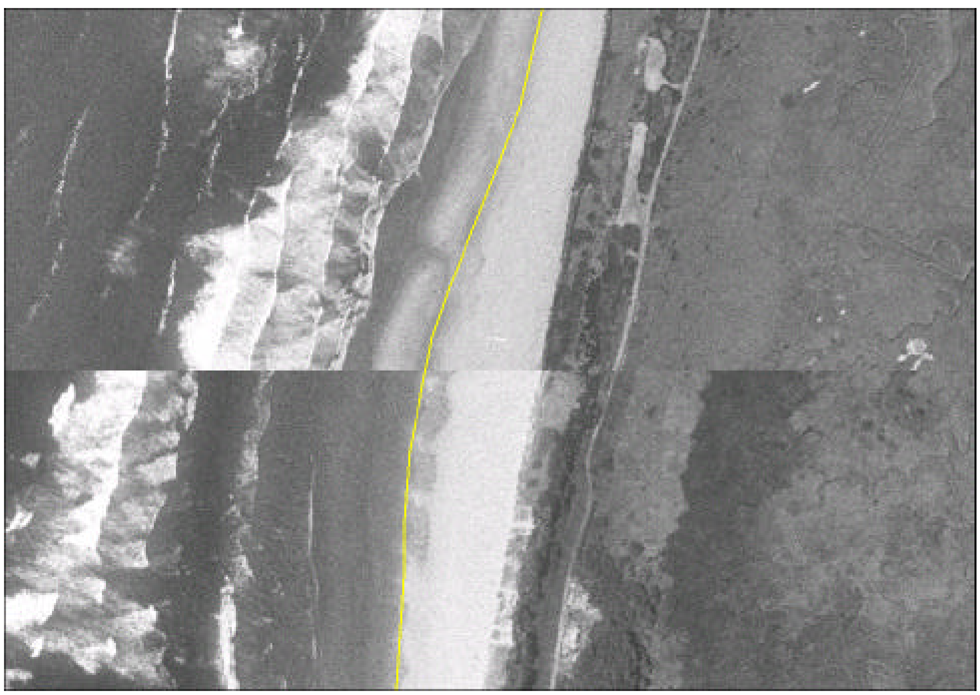


Figure 4 Shoreline position identified as the boundary between the wet/dry sand from a 1994 digital orthophoto quadrangle (scale is 1:500). The photo is taken just north of Cape Lookout State Park and comprises two aerial photographs that have been merged.

Figure 4 highlights the problem of delineating a shoreline, and some of the potential errors that may occur. The diagram represents a merged aerial photograph of Netarts spit. The northern half of the Figure represents an aerial photograph taken at low tide, while the southern portion of the photo was taken at high tide. Focusing first on the southern half of Figure 4, it can be seen that the wet/dry sand junction is for the most part easily distinguishable. However, some uncertainty exists around mid-photo where it is apparent that part of the beach landward of the identified shoreline has been saturated (characterized by the crescentic wet patches). This wetted area is not unique to this section of the coast and is the product of waves swashing up on the beach face. The widths of these semi-saturated areas are on the order of 20 to 120 ft wide. As a result, the potential error associated with defining the 1994 shoreline is likely to range from ±20 ft to ±120 ft, and will depend on both the beach slope and the local processes (e.g. the formation of rip cell embayments).

The northern half of Figure 4, which was flown at low tide, presents even greater problems for defining a shoreline, since there are two wet/dry lines separated by a dry sandy section. This type of morphology reflects a swash-bar system, in which a wide (~100 ft), sandy ridge (1 to 2 ft high) occurs around the low tide mark (Figure 5). Since the MHWL is clearly located landward of the low tide line shown in the top half of Figure 4, compared with the bottom half, we have delineated the shoreline as the landward wet/dry line for those 1994 aerial photographs taken at low tide. This approach covers only those aerial photos taken in the Netarts and Rockaway littoral cells, since the Sand Lake and Neskowin cells were flown at high tide. Thus, the likely maximum error associated with defining the 1994 shoreline position along the Netarts and Rockaway cell is likely to be on the order of ±100 ft. Finally, it is important to note that the errors reported here are gross estimates. Further work is therefore required to better define the magnitude of MHWL errors caused by variations in the tidal cycle, or from swash patterns on gently sloping beaches.

Figure 5 Example of a swash-bar system at Agate Beach, Newport, on March 21, 2001 (Photo is courtesy of the Coastal Imaging Lab, College of Oceanic & Atmospheric Sciences, Oregon State University).

Supplementary mapping of the AHZ was carried out through stereoscopic viewing of 1994 aerial photos and from field reconnaissance. All map data was then transferred by inspection to standard USGS DOQ's using MapInfo software. Some interpretation was needed when mapping the AHZ around the mouths of bays. In particular, where considerable accretion has occurred beside the jetties, we drew the landward boundary at the top of the first major foredune, even if only sparsely vegetated. An exception is the area immediately adjacent to a jetty where strong rip currents cause larger potential erosion. In those areas the zone was drawn at the point of first continuous grassy vegetation. The lateral extent of this rip current effect was judged by the extent of the associated embayment. For areas of highly active inlet migration, such as the end of Netarts Spit, even the grassy dunes were considered highly vulnerable to changing spit position. As a result, the landward boundary there was drawn at the first densely vegetated dune with trees and/or shrubs.

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. An example is sea level rise, which to some extent makes all past storm events and even coseismic subsidence events, somewhat less erosive than equivalent events in the future. The geometric model of Komar and others (1999) will be used in this investigation.

Dune-Backed Shorelines

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 6, and in an expanded form as the geometric model in Figure 7. 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).

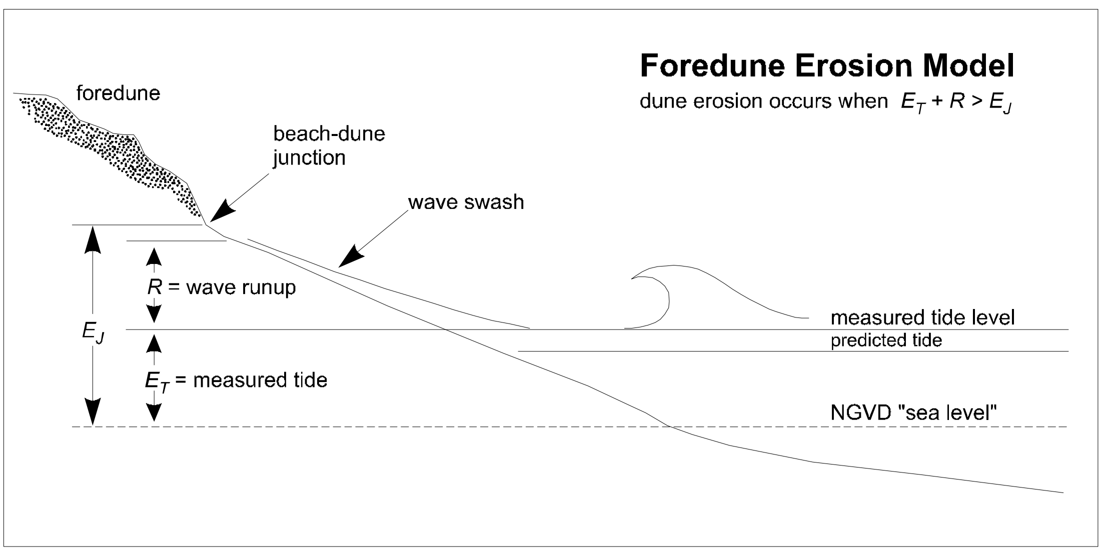


Figure 6 The foredune erosion model (Komar and others, 1999).

As can be seen from Figure 7, 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 7. 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 7, which causes the dune to retreat some additional distance landward until it reaches point C. As can be seen from Figure 7, 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).

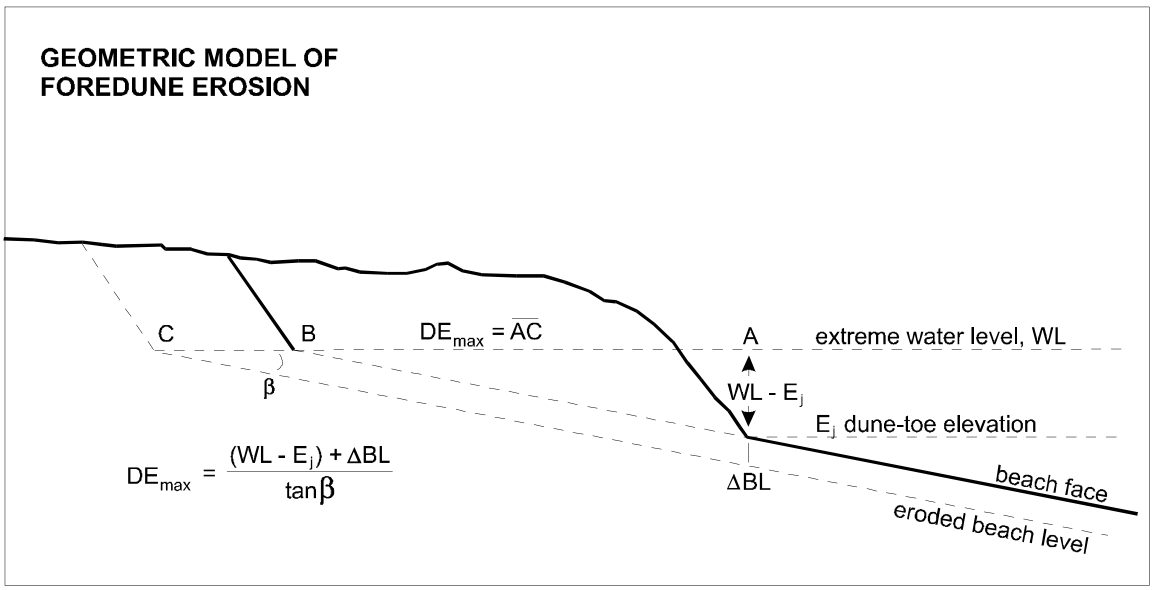


Figure 7 The geometric model used to assess the maximum potential beach erosion in response to an extreme storm (After Komar and others, 1999).

<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; 2001), have yielded the following relationship

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

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 7), 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 1). Finally, a sixth 100-year storm occurred during the winter of January 2000.

Table 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, 2002).

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

Table 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

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.

<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, 2002). 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). 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. For example, Vincent (1989) has 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, including Tillamook County, is being slowly submerged by the rise in mean sea level (Figure 8). Recent analyses of the Newport tide gauge by Flick and others (1999), has indicated that mean sea level is rising at a rate of 3.7 mm per year. Assuming this rate of sea level rise continues, we can expect a further increase in mean sea level of about 1.3 ft along the Tillamook coastline over the next 100 years, which is likely to influence the long-term stability of shorelines in the PNW.

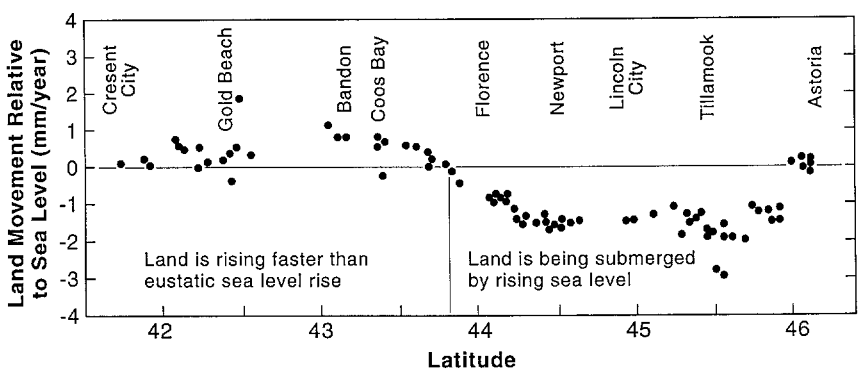


Figure 8 Elevation changes along the Oregon coast, measured by geodetic surveys (Vincent, 1989). The elevation changes are relative to the global increase in sea level, with positive values representing a rise in the land at a higher rate than the increase in sea level, while negative values represent the progressive submergence of the land. [*from* 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; 2001). Table 3 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 3, 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 3 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).

In the absence of surveyed beach morphology data along the Tillamook County coast, 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).

Table 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

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 Tillamook coastline. 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. This report also provides a brief examination of the 1997 LIDAR data that was flown prior to the 1997-98 EL Niño winter. This is covered in the section on Tillamook County Historical Shoreline Positions (p.38), which examines the changes in shoreline positions between the 1997 and 1998 LIDAR flights. The section compares shoreline changes from other years as well.

Scenarios of Coastal Change in Tillamook County

The previous sections have described the ranges of variables required for input into the geometric model. This section discusses the three scenarios used for modeling MPED on dune-backed beaches in Tillamook County.

Figures 6 and 7 reveal that the measured tides (E_T) and the wave runup levels (R) calculated from Equation 1 are combined to yield a total water level (*WL*) elevation, which is then input into the geometric model. When *WL* exceeds the elevation of the beach-dune toe, erosion occurs and the dune retreats landward until a new beach-dune toe is established, which approximately equals the total water elevation caused by the storm. However, the addition of the measured tides and wave runup components together, e.g. the 50-year runup level combined with the 50-year tide, is not as straightforward as it seems, due to the fact that these processes have been found to operate independently from each other (Komar and others, 1999; Ruggiero and others, 2001). In other words, the occurrence of an extreme storm does not necessarily mean that it will occur concurrently with an extreme tide. As a result, because both variables are occurring independently, it is necessary to consider their joint probabilities of occurrence, which is the product of the two individual probabilities. Thus, a 50-year runup level combined with a 50-year tide would yield a joint return period of about 2,500 years (50*50 = 2500 years). To some degree, one can get around this problem by applying various combinations of the extreme tides plus the wave runup elevations. For example, a 50-year storm runup event may be combined with a 2-year extreme tide to yield a 100-year total water level. A better approach might be to evaluate the total water levels associated with particular storms, the combined mean-water level (tides + surge + El Niño effects) and the wave runup, and then analyze the probabilities of these levels (Komar and others, 1999). Analyses of this type however, have yielded values that closely approximate those derived using the approach that sums the individual values, suggesting that either technique is useful. Finally, it should be noted that the analyses of extreme water levels undertaken previously (Shih and others, 1994; Ruggiero and others, 1996; 2001), excludes the most recent high water levels generated during the 1997-98 El Niño and 1998-99 La Niña winter. As a result, future efforts are planned to better establish the total water levels that may be experienced along the Oregon coast.

In developing the three scenarios below, 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, which respectively indicate decreasing probability levels of occurrence, with the high risk scenario having the greatest chance of occurrence during 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. This is consistent with the approach taken by Komar and Allan (2000) in developing their scenarios of high waves and water levels. Along the central Oregon coast, the Mean Higher High Tide averages about 8.38 ft (2.55 m) relative to Mean Lower Low Water. When converted to the NAVD'88 datum, this amounts to an elevation of 7.55 ft (2.3 m). 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:

- 47.6 ft (14.5 m) significant wave height,
- 17 second peak spectral wave period,
- 7.55 ft (2.3 m) Mean Higher High Tide,
- 1.31 ft (0.4 m) monthly mean water level,
- 3.28 ft (1.0 m) storm surge.

This particular scenario is similar to the 2-3 March 1999 La Niña storm, which caused widespread damage along the Oregon coast. 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 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 3.28 ft storm surge component as part of this scenario. When combined, these data yield a water elevation of 12.14 ft relative to the NAVD'88 datum.

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

- 52.5 ft (16.0 m) significant wave height,
- 20 second peak wave period,
- 7.55 ft (2.3 m) Mean Higher High Tide,
- 1.31 ft (0.4 m) monthly mean water level,
- 5.58 ft (1.7 m) storm surge,
- 1.31 ft (0.4 m) sea level rise.

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 52.5 ft significant wave height used in this scenario is similar to the predicted 100-year storm wave shown in Table 2. 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 (5.58 ft). Furthermore, this scenario includes a 1.31 ft rise in mean sea level expected to occur over the next 100 years. This rise in mean sea level is an estimate based on existing trends determined for the South Beach, Yaquina Bay tide gauge (Flick and others, 1999). 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 a particularly severe storm.

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

- 52.5 ft (16.0 m) significant wave height,
- 20 second peak wave period,
- 7.55 ft (2.3 m) Mean Higher High Tide,
- 1.31 ft (0.4 m) monthly mean water level,
- 5.58 ft (1.7 m) storm surge,
- 1.31 ft (0.4 m) sea level rise.
- 3.28 ft (1.0 m) 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 (Darienzo and Peterson, 1995; Geomatrix, 1995; Atwater and Hemphill-Haley, 1996). These types of events can cause some parts of the PNW coast to be abruptly lowered by 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 3.28 ft coseismic subsidence for the Tillamook County coast, which is “typical” for this part of the northern Oregon coast based on paleoseismic analyses of previous subduction events (Peterson and others, 1997; 2000).

Bluff-Backed Shorelines

Introduction

This section describes a methodology whereby four coastal erosion hazard zones can be drawn for bluffs of Tillamook County. The zones are as follows:

1) ***Active hazard zone***: The zone of currently active mass movement and wave erosion.
2) The other three zones define HIGH, MODERATE, and LOW risk scenarios for expansion of the active hazard zone by bluff top retreat. Similar to the dune-backed shorelines, the three hazard zones depict decreasing levels of risk that they will become active in the future, but an increase in the magnitude of erosion. These hazard zone boundaries are mapped as follows:
    a. ***High hazard zo****ne*: The boundary of the high hazard zone will represent a best case for erosion. It will be assumed that erosion proceeds gradually at a mean erosion rate for 60 years, maintaining a slope at the angle of repose for talus of the bluff materials.
    b. ***Moderate hazard zone***: The boundary of the moderate hazard zone will be drawn at the mean distance between the high and low hazard zone boundaries.
    c. ***Low hazard zone***: The low hazard zone boundary represents a “worst case” for bluff erosion. The worst case is for a bluff to erode gradually at a maximum erosion rate for 100 years, maintaining its slope at the angle of repose for talus of the bluff materials. The bluff will then be assumed to suffer a maximum slope failure (slough or landslide). For bluffs composed of poorly consolidated or unconsolidated sand, another worst case scenario will be mapped that assumes that the bluff face will reach a 2:1 slope as rain washes over it and sand creeps downward under the forces of gravity. For these sand bluffs, whichever method produces the most retreat will be adopted.

In order to understand how these zones are defined, it is useful to examine what variables are generally used for erosion hazard zone calculations and how they relate to the way bluffs actually erode.

The Bluff Retreat Model

Table 4 summarizes those variables that are generally used for calculating bluff erosion hazard zones (see Komar (1997), and Komar and others (1999) for further discussion), while Figure 9 illustrates those parameters, and one approach (of many) that may be used to map bluff hazard zones. Note that the major policy decisions used for delineating the hazard zones are:

1) Which hazard zones will be useful for planning, and;

2) What planning horizons (projected number of years in the future) should be used for erosion rate calculations.

Table 4 Summary of bluff erosion data that can be used to calculate bluff hazard zones. Only maximum observed (empirical) block failure width is listed (versus most probable or average width), because this is generally the only empirical data that can be easily obtained in most areas. Quantitative slope modeling or regional empirical analyses would be required to establish a mean or most probable block failure width. Angle of repose refers to the ideal slope angle for unconsolidated talus of the bluff material.

Erosion Data	*Planning Horizon*	*Safety Factor*
Average Erosion Rate (ft/year)	x 60-100 years	+ error (1-2σ or some %)
Stable Slope Angle or Angle of Repose (Projected from the bluff toe to top)	Not applicable	+ error (generally 10-50%)
Maximum Block Failure Width (ft)	x number of blocks per 60-100 years	+ error (generally 10-50 %)

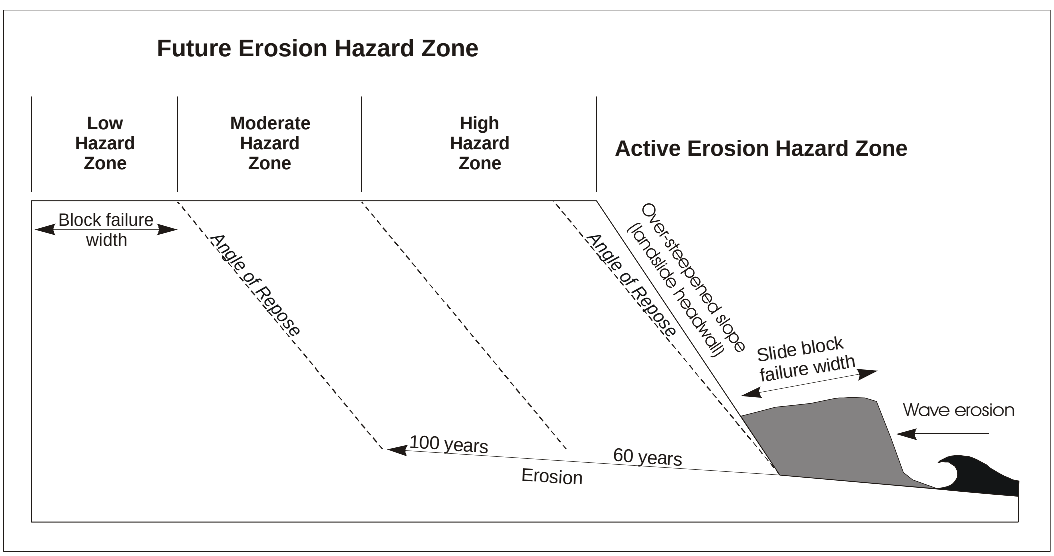


Figure 9 Schematic illustration of block failure on a bluff, angle of repose, and erosion rate in relation to possible hazard zones. These factors can be combined in a variety of different ways to produce hazard zones.

To understand how to apply these factors, it is useful to first discuss how bluffs actually erode.

Bluff erosion generally occurs in the following steps:

1. Erosion of the bluff toe occurs in response to waves, and sub-aerial weathering of the bluff slope.
2. Slope failure occurs and blocks of various sizes may slide, fall, or topple. The final forcing event for failure may be a function of:

    - The critical slope stability angle is exceeded;
    - Exposure of weak rock layers in the bluff face;
    - Unusually high ground water pressure (i.e. pore pressure);
    - Severe wave erosion event;
    - An earthquake, or;
    - Combination of any or all of the above factors.

3. The size of blocks that fall or slide is a function of the strength and the type of material, its structure (bedding, jointing, etc.), and bluff height. If only small sloughs, topples, and falls of material occur, then the bluff will erode back gradually, maintaining a stable slope angle. Wave erosion generally keeps the slope steep enough so the forces tending to cause the bluff to suffer a slope failure are just balanced by the forces opposing failure; in other words, the ratio of these forces, or *factor of safety*, is equal to ~1.0. On the other hand, some bluffs subject to deep bedrock landslides retreat in a highly episodic fashion, resisting erosion for long periods and then failing in large slide blocks, once the factor safety decreases below 1.0 (Figure 10).

4. After a slope failure, debris is subsequently removed by waves and the cycle repeats. Depending on how much debris accumulates, it can temporarily protect the bluff from wave erosion. Where landslide debris continues moving seaward, additional block failures at the headwall of the landslide can occur. These failures may occur virtually in lock step with slide movement.

Normally, wave attack keeps bluff slopes close to the angle of repose of the bluff talus or steeper, but in some cases dune sand, cobble berms, or other debris accumulates to protect the bluff from further wave erosion. However, if the toe of the bluff does get protected for an extended period of time, the steep face of the slope may erode to lower angles through subaerial weathering (soil creep and slope wash) without erosion of the toe by waves. This process is especially rapid on bluffs composed of poorly consolidated sand. In drawing erosion hazard zones, we will endeavor to emulate these various modes of bluff retreat. For a more detailed discussion of episodic versus gradual erosion see Appendix A.

Predicting whether a particular part of a bluff will erode away over the life of a proposed development depends on understanding the influence of several parameters. These include:

- Bluff slope;
- Bluff height;
- Bluff material properties;
- Groundwater level and resulting pore pressures;
- Surface water runoff;
- Wave climate;

- How much material is present at the toe of the bluff (e.g. slide debris, dune sand, logs, etc.) that can both buttress and protect the bluff from wave erosion;
- Whether any buttressing material is moving seaward (active slide blocks), and;
- Vegetative cover.

In a very real sense, each bluff must be judged based on the local geology, likely future climate (rainfall and storms), and its current state of instability in the erosion cycle. Owing to limitations of this regional county investigation, we will only be able to take into account parameters such as the bluff slope, height, material properties (rock or soil composition), and the historical response of broad classes of bluff to coastal erosion. As a result, detailed, site-specific investigations are necessary to provide projections of the erosion hazard for a particular development on coastal bluffs.

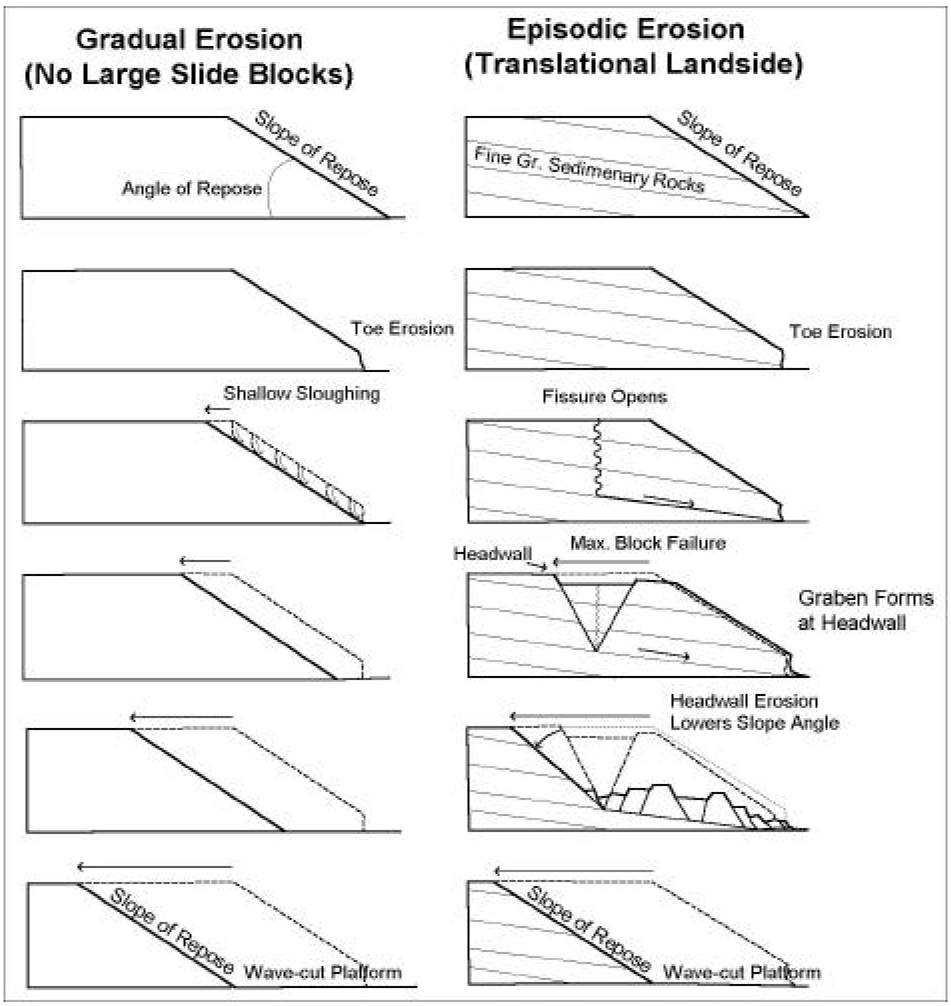


Figure 10 Gradual versus episodic bluff erosion. Note how the landslide toe position remains stable as the headwall retreats; hence erosion rate for bluffs with landslides is better measured at the headwall. Also note that the dangerous part of the bluff is much wider for the landslide-prone bluff, since another maximum block failure could occur at any point in the erosion cycle.

Data Used for Drawing Erosion Hazard Zones in Tillamook County

<u>*Angle of Repose*</u>

Numerous measurements of slope angles in the study area have revealed that the majority of coastal bluffs have slope angles ~34°' ± 2º (1.5 horizontal: 1 vertical) or ~45° ± 2º (1:1). The former slope is for Quaternary or Tertiary sedimentary material, while the latter is for basalt bluffs. The angle of repose for loose clean sand is 33° 41', while 45° is the angle for hard rotten rock (Merriman and Wiggin, 1947), so these values make sense for slopes composed of talus of these bluff materials. For example, detailed geotechnical measurements at The Capes area near Oceanside reveal an angle of repose for undisturbed Holocene dune sand of 45° with an apparent stable angle of repose at 32° to 35° (Rinne, 2000), matching the loose clean sand value.

Some basalt and sandstone cliffs are near vertical and appear to have persisted nearly unchanged by erosion for many decades; hence, 1:1 or 1.5:1 slopes probably overestimate the slope of repose[1] somewhat for these rock types in many areas. On the other hand, a 1.5:1 slope for unconsolidated or poorly consolidated Pleistocene or Holocene sand is at the theoretical angle of repose for this material so that few sand slopes will persist for long at steeper slopes unless cemented by clays or other minerals.

Slope angle must therefore be used in conjunction with a thorough understanding of the tendency toward slide block failures (Figure 10). Thus, the bluff edge could retreat much further than might be predicted from the simple angle of repose approach, should the bluff be subject to large block failures. Nevertheless, in spite of some uncertainty about how large a block might fail, and the slight over estimation of the slope of repose for hard rock bluffs, the slope angle approach is a relatively straight forward way to get a quick assessment of the likelihood of slope failure and where the bluff edge might eventually be located. Table 5 summarizes slopes of repose that are used to estimate bluff retreat in this study.

Table 5 Slopes of repose by material type.

Bluff Material	*Slope of Repose (horizontal:vertical)*
Basalt	1:1
Tertiary sedimentary rocks	1.5:1
Pleistocene soil, colluvial, and alluvial deposits	1.5:1
Pleistocene to Holocene dune sand	1.5:1

On bluffs with an existing landslide, the slope of repose was projected from the inferred base of the headwall landward to the bluff top using the techniques of Appendix D.

Coastal bluffs composed of Pleistocene to Holocene dune sand that are protected from constant wave attack by fronting dunes and wide beaches develop stable slopes at lower angles than 1.5:1, owing to bluff top retreat from slope wash and soil creep. Angles of about 2:1 are common on such protected bluffs. Because of the responsiveness of these bluffs to this type of erosion, the projected position of a 2:1 slope (factor of safety of 50 percent) should be mapped in addition to

[1] Slope of repose is synonymous with the cotangent of the angle of repose (ratio of the run to the rise); this usage is from Merriman and Wiggen (1947).

the 1.5:1 slope. For many high sand bluffs the boundary so mapped will provide a worst-case scenario for bluff top recession in these materials.

Erosion rate data

Time and funding for this project were insufficient to carry out a detailed analysis of rates of bluff erosion. This type of analysis requires intensive measurement of local bluff retreat on historical photos, either through detailed field measurements tied to geographic markers, or by rectification of historical photography.

In some cases there are features on historical photos that may be scaled to the same features on standard 1994 DOQ's of the US Geological Survey. These spot erosion rates are subject to minimum absolute spatial errors on the order of 33 feet. Nevertheless, it is possible to estimate relative (rather than absolute) changes in the position of the bluff toe or bluff top from photo to photo that belie this absolute error. In many cases, it is apparent that a distinctive feature is unchanged on photos of differing ages; hence the erosion rate is zero for that particular time interval. Likewise, a house built on or close to the bluff edge on a 1939 photo, if still present when a later photo is taken, places a definite limit on how much erosion may have occurred. Where available, locally derived erosion rates were calculated for selected bluffs along the Tillamook County coastline. All spot erosion rates are summarized in the accompanying digital database, including a detailed explanation of how each erosion rate was derived. Discussion and interpretation of the data is given in Appendix B.

According to Benumof and Griggs (1999) the most important control on the rate of bluff erosion are the material properties, if the bluff is not protected from open wave attack. Hence, spot erosion rates were correlated to rock and soil type in the lower bluff face based on field observations, and from the earlier mapping work of Schlicker and others (1972), Niem and Niem (1985), and Wells and others (1994). Appendix D discusses the correlation in detail. Table 6 summarizes the bluff erosion rate data that will be used in this investigation. Judging from the amounts of erosion and the geology in each area, all of the rates represent gradual bluff retreat rather than episodic failure of large (= ~40 feet) blocks. The most uncertain rates are those for Quaternary deposits. Rates for Quaternary deposits were adjusted to a 100 percent safety factor by multiplying the values by 2. This factor was added, because (1) Quaternary deposits, owing to the weakness of the material, are the most responsive to variations in wave attack from even short-term changes in the beach; and (2) significant accretion of many beaches occurred during the time of observation for rate measurements, biasing rates toward lower values.

Table 6 Erosion rates assumed for calculations of coastal erosion hazard zones in Tillamook County for bluffs exposed to open coastal wave erosion. The conservative rate is the mean rate plus the estimated error, either mean measurement error, or the one sigma error for the variance of the measurements from the mean, whichever is greater. The values in parentheses have an additional safety factor of 100 percent to cover uncertainties in estimation of erosion rate for soft soil and sand bluffs. The values in parentheses will be used for Quaternary deposits. See Appendix B for explanation of how the rates were determined.

Rock Type	Estimated Mean Erosion rate (ft/yr)	Conservative Erosion Rate (ft/yr)
Basalt	0.1	0.2
Resistant sandstone	0.1	0.2
Interbedded sandstone/siltstone/claystone	0.2	0.4
Quaternary deposits	0.25 (0.5)	0.5 (1.0)

Block failures

The rate (and thus the probability) of block failures of various sizes, especially large ones, is unknown, since hundreds of years of detailed observations are not available. This limitation is typical for bluffs along the entire U.S. West coast (probably the world for that matter). On the other hand, some maximum block failure widths can be derived from existing landslides, based on field measurements, and from an analysis of aerial photographs. The location and degree of historic activity of the existing landslides is an essential starting point for establishing the likelihood, extent, and rate of propagation of bluff slope failures. These data are discussed in Appendix C, while Table 7 summarizes the maximum slide block widths determined for the Tillamook County coastline.

Table 7 Recommended maximum block failure widths for coastal bluffs of Tillamook.

Bluff Material Causing Block Failure	*Maximum Block Failure Width (ft)*
Basalt subject mostly to rock falls and topples in bluffs < 100 feet high	8
Basalt subject mostly to rock falls and topples in bluffs = 100 feet high	47
Basalt at pocket beach south of Cape Meares	471
Resistant sandstone bluffs 80-160 feet high	39
Seaward-dipping Tertiary sedimentary rock with fine grained interbeds on bluffs <60 feet high	bluff height/1.25
Seaward-dipping Tertiary sedimentary rock with fine grained interbeds on bluffs 60-200 feet high	340
Seaward-dipping Tertiary sedimentary rock with fine grained interbeds on bluffs >200 feet <300 feet high	(bluff height + 200)/1.1765
Seaward-dipping Tertiary sedimentary rocks with fine grained interbeds on bluffs 300-400 ft high	442
Holocene to Pleistocene soil in bluffs ≤150 ft high	bluff height/1.25
Holocene to Pleistocene soil in bluffs >150 ft high	(bluff height – 124)/0.2174
Holocene to Pleistocene dune sand bluffs	24

In order to establish empirical block failure widths, data was gathered from Tillamook and Lincoln County, but it was clear that some blocks might actually represent fragments of earlier larger blocks, whereas other large intact slide blocks may have undergone unknown amounts of wave erosion. Both factors tended to bias the data to smaller block failures. For the purpose of this report, the largest identified block failure width was used to predict the "worst case" extent of bluff retreat. Empirical equations and locally derived maximum block failure widths were derived (Appendix C, Table 7). While block width did increase with bluff height, it did so in complex ways, apparently increasing to hundreds of feet at some threshold bluff height that varied from about 150-160 feet for bluffs with Pleistocene soil at the base, to ~70-80 feet for bluffs with seaward-dipping Tertiary sedimentary rocks. The observations for bluffs with clay-rich Pleistocene soil are tentative, because of the unknown effect of paleotopography on hard rock underlying the soil where the data was collected.

Despite a lack of knowledge concerning the frequency of maximum block failures, the data from Table 7 provide a measure for determining the potential worst-case bluff failure scenarios for Tillamook County. The most that a bluff is likely to retreat during a particular time interval is the amount of gradual erosion (from Table 6), plus the amount that would occur if at the end of the interval the bluff experienced a maximum block failure (Table 7) after reaching the angle of repose for talus of the bluff material (Table 5). While this may not be a very likely scenario, it does constitute a worst case.

Active Erosion Hazard Zone

The bluff top or active landslide headwall top is an important feature, since it separates an area of currently active erosion and mass movement from an area that may become that way some unknown time in the future. All areas seaward of this feature were mapped as an active coastal erosion hazard zone. To be conservative, all areas seaward of the headwall of potentially active landslides were also mapped in the active hazard zone. If there was some question about whether the landslide was potentially active, as defined below (i.e. it was shown as queried), then it was not placed in the active hazard zone.

Mapping the active hazard zone required delineation of the top edge of the bluff and top edge of active and potentially active landslides. Mapping the landslides was therefore essential to the project.

Landslide Mapping (Mass Movements)

Introduction

Mass movement is the natural down slope displacement of the land surface. It occurs by a process called mass wasting, which refers to the down slope transport of soil or rock by gravity. Rock falls, landslides, flows of soil or rock, and displacement of large blocks (slide blocks or slumps) are all forms of mass wasting. The system of geologic symbols used for this investigation is taken in part from Priest and others (1994) and is summarized in Table 8.

Prehistoric Mass Movements (PHls, PHb, PHf)

Many of the largest landslides and slide blocks appear to be prehistoric (older than about 150 years for historical observations on the Oregon coast). They are deeply eroded and have no evidence of recent activity. Many sea cliffs with active landslides and slide blocks are surrounded by larger prehistoric slide blocks and slumps. Prehistoric slide blocks surrounding the Jumpoff Joe landslide in Newport (Priest and others, 1997a and 1997b) is a particularly good example. Prehistoric landslide terrain upslope of the Three Capes Loop landslide south of Tierra del Mar is a Tillamook County example. These areas illustrate that in the prehistoric past slide blocks and slumps larger than the modern ones have become unstable. Unusual amounts of rainfall, a large earthquake, removal of material supporting the base of the slope, or some combination of these factors may have caused these mass movements.

Potentially Active Mass Movements (PAls, PAb, PAf)

A number of areas have mass movements that are currently stable (no bowed trees or cracked soil and pavement) but with evidence of recurrent movement in the last 150 years. Unlike the prehistoric slides, these features are generally not extensively eroded and have well preserved topography indicative of recent movement. Many show no evidence of movement since 1939 or 1967 aerial photography but are probably more likely to have movements than the prehistoric slide areas.

Active Mass Movements (Als, Ab, Af)

These areas have evidence such as bowed trees and cracked soil or pavement that indicate ongoing down slope movement of large masses of soil or rock.

Table 8 Landslide map units; "*Present?*" refers to presence on the Tillamook County coast.

Map Symbol and Label	*Description*	*Present?*
Als (Active Complex Landslide)	Typical complex landslide that is active.	Yes
Ab (Active Slide Block or Slump)	Block of rock that is actively moving down slope.	Yes
Af (Active Soil or Rock Flow)	Flow of soil and rock that is currently or recently active	No
PAls (Potentially Active Complex Landslide)	Complex landslide that is currently stable but probably had recurrent movement in the last 150 years.	Yes
Pab (Potentially Active Slide Block)	Block of rock that is currently stable but probably had recurrent down slope movement in the last ~150 years.	Yes
PAf (Potentially Active Soil or Rock Flow)	Flow of soil and rock that is currently stable but probably had recurrent down slope movement in the last ~150 years.	No
PHls (Prehistoric Complex Landslide)	Complex landslide that is currently stable but probably formed in prehistoric times (>~150 years ago).	Yes
PHb (Prehistoric Slide Block or Slump)	Block of rock that has moved down slope in prehistoric times but is currently stable.	Yes
PHf (Prehistoric Rock or Soil Flow)	Flow of soil and rock down slope in prehistoric times that is currently stable.	Yes
Qls (Quaternary Landslide)	Quaternary (<1.6 m.y. before present) landslide not examined in field, so activity unknown.	Yes

Extent and Quality of Landslide Mapping

Landslides were examined in the field primarily within a kilometer or less of the coastline. Inland landslides, within about 6 miles of the coast, were compiled mainly from literature sources (e.g. Schlicker and others, 1972; Wells and others, 1994), supplemented by photo and topographic map interpretation and limited field mapping. Field-mapped landslide boundaries were transferred by inspection from stereographic photos to standard 1994 DOQ's of the US Geological Survey (USGS) using MAPINFO software. Field-mapped boundaries are located no better than the inherent error of the DOQ's, ± 33 feet horizontal. Where tonal contrast on the photos was small (e.g. areas of featureless gray), the difficulty of information transferal increases, so that the error in these locations is likely to be somewhat higher. In some cases topographic contours and other features from 1985/1986 USGS DRG's were utilized to aid the transferal of the landslide data.

Mapping Technique for Bluff Erosion Hazard Zones

Description of the zones
Four bluff erosion hazard zones will be specified on the Tillamook County coastline:

1. **Active Erosion Hazard Zone:** Currently active erosion area (rapid soil creep on steep bluff or headwall slopes plus active or potentially active landslides).

2. **High Hazard Zone:** High probability that the area could be affected by active erosion in the next ~60-100 years. This zone boundary will, in effect, be the minimum distance that the bluff top (or landslide headwall) might retreat in the next 60-100 years.

3. **Moderate Hazard Zone:** Moderate probability that the area could be affected by active erosion in the next ~100 years. This zone boundary will, in effect, be the mean distance that the bluff top (or landslide headwall) is likely to retreat in the next 60-100 years. In general, this distance was approximately halfway between the high and low hazard zones.

4. **Low Hazard Zone:** Low but significant probability that the area could be affected by active erosion in the next ~60-100 years. This includes; bluff tops that may retreat by maximum block failure at the end of an interval of gradual erosion, including some sub-aerial erosion, slope failures induced by Cascadia subduction zone earthquakes, or unusually high groundwater conditions. This zone boundary will, in effect, be the maximum distance that the bluff top (or landslide headwall) is likely to retreat in the next 60-100 years.

Uncertainty in spatial location of the zones
Owing to limitations of available base maps, none of the mapped bluff hazard zones are located closer than plus or minus ~33 feet horizontal and ~20 feet vertical (40 foot elevation contours).

General procedure for drawing hazard zones
Detailed explanations of how each of the hazard zones were established for specific geological situations encountered in Tillamook County are given in Appendix A. The north-south extent of shoreline segments mapped with specific methods is given in the geographic information database that accompanies this report. Hazard zones are drawn in transitions between segments utilizing professional judgment. Professional judgment is really the basis for drawing any geological hazard zone, but the procedure described below has been uniformly applied to make the hazard zones reasonably reproducible by multiple workers.

1. Determine bluff composition, structure, and extent of all landslides, including ancient (prehistoric) slides.
2. Map the bluff top or top edge of the active or potentially active landslide headwall. Exclude all mass movement hazard areas that are prehistoric (e.g. unit PHls) or potentially active but queried (e.g. Pals?). Everything seaward of this line is the **active hazard zone**.
3. Determine the projected bluff top (or projected landslide headwall position) at the slope of repose for the bluff material, making sure that each soil or rock unit in the bluff has the appropriate slope of repose (Table 5). On active or potentially active landslides, project

the slope of repose from the toe of the headwall at its subsurface intersection with the slide plane. Use local geotechnical data to find this intersection if available; if no data is available, use the procedure of Appendix D.

4. For Pleistocene or Holocene sand or soil bluffs, map the projected bluff top position for a slope of 2:1 from the current slope toe (factor of safety of 50 percent relative to a 1.5:1 slope).
5. Using Table 6, determine an estimated minimum expansion of the active hazard zone (or projected position at the slope of repose from Table 5, whichever is the most landward) by multiplying the mean erosion rate of the basal soil or rock unit by 60 years. This is the landward boundary of the **high hazard zone**.
6. Using Tables 6 and 7, determine the maximum expansion of the active hazard zone (or projected position at the slope of repose from Table 5, whichever is most landward) by multiplying the maximum erosion rate by 100 years. Add to this the maximum block failure width from Table 7. This represents the landward boundary of the **low hazard zone** for most bluffs.
7. For bluffs composed of Pleistocene or Holocene sand, move the **low hazard zone** boundary to the projected position of the previously mapped 2:1 slope, if the drawn boundary is not already landward of the 2:1 slope.
8. Draw the **moderate hazard zone** boundary at the mean position between the high and low hazard zone boundaries (i.e. sum the lateral distances of the high and low hazard zones and divide by 2).
9. Adjust the **low and moderate hazard zone** boundaries for any inland landslides that are intersected by the projected expansion of the active coastal erosion hazard zone. Use geologic judgment and endeavor to:
    a. Encompass the parts of inland landslides that may be further destabilized by future coastal erosion.
    b. Match the general risk levels implied by the hazard zone designations (i.e. inland prehistoric or queried potentially active landslides in the "low" zone; and active or potentially active landslides in the "high" or "moderate" zones).
    c. Predict the probable future expansion of these inland landslides should coastal erosion reach them.

Example of a large inland landslide at Cape Meares

At the Cape Meares landslide, the headwall of the landslide is so far inland from the coast that the landward recession of the headwall is for all practical purposes decoupled from coastal processes in the considered time frame. The headwall is 7,000 feet inland, above a large area of potentially active landslide that lies above an equally large area of currently active landslide. Thus, while coastal erosion may cause some landward expansion of the active portion of the landslide, it is unlikely to cause expansion of the potentially active portion of the slide, at least not over reasonable (~100-year) time spans. The upper portions of this landslide probably respond more to local fluctuations in groundwater than to coastal erosion. To complicate things further, in the vicinity of the Cape Meares water supply tank, the northern part of the landslide toe is actually overriding ancient landslide deposits and does not reach the coast at all! In any case, to be on the conservative side, we will map the hazard zones around the active landslide based on the most conservative assumptions possible, that the headwall does retreat with coastal erosion and that the headwall materials have the maximum possible block failures from Table 7. The entire active and potentially active landslide was therefore placed in the **active hazard zone**. The **low hazard zone** is placed at the perimeter of ancient landslide and paleosol deposits, except at the headwall, where the slide is in contact with Tertiary basalt and sedimentary rocks. At the headwall and steep slopes to the north and south, the low hazard boundary is placed at a lateral distance of 490 feet, which is the maximum single block failure distance identified for basalt and Tertiary sedimentary rock. The moderate hazard zone is mapped halfway between these two boundaries. This complex landslide deserves a detailed geotechnical investigation to determine:

1. The slide mechanisms in various portions of the landslide.
2. How quickly the active landslide might expand in the future, particularly around the water supply tank. In that area the landslide is thrusting up and over more stable soil and is apparently spilling around the ridge where the tank is constructed.

Example of modifications for detailed geotechnical data at The Capes development

At The Capes development south of Oceanside, all of the hazard zones were drawn essentially using the recommended procedure but with slight modifications because of a wealth of detailed geotechnical information available from Rinne (2000). Rinne (2000) mapped the projection of a 1.5:1 and 2:1 slope from the headwall toe to the top of the bluff, taking into account subsurface geological contacts with the underlying basalt. An erosion rate of 0.41 ft/year was calculated from the Rinne (2000) cross section D-D' which shows lateral displacement of the headwall between 1939 and 1998. The hazard zones were drawn using the detailed projection of the 1.5:1 and 2:1 slopes of Rinne (2000) and the regular technique outlined above. We do not use the local bluff retreat rate of 0.41 ft/yr, because the foot of the headwall of the landslide is basalt up to an elevation of ~60 feet, hence the long-term erosion rate is near zero (Table 6). Local bluff retreat is caused by the sand adjusting to its angle of repose. Thus, when it reaches a slope of 1.5:1, retreat will cease, other than through processes of slope wash and soil creep, which will gradually lower the slope angle (Rinne, 2000). If the slide debris is someday removed by wave erosion, then bluff retreat will be at the negligible erosion rate of the underlying basalt. Lateral extent of the basalt will be assumed to be from the outcrop on the northern margin of the slide to the southern-most drill hole that encountered the basalt at ~60 elevation. A "worst case" scenario is mapped whereby a 350-foot wide slide block fails, plus an additional 20 feet. This width is the maximum width of the existing slide mass (see Appendix D for map and cross sections).

Geological relations allow for the slope failure to occur either in the ~30 feet of clay-rich Pleistocene soil and colluvium overlying the basalt at the headwall, or in the basalt itself. Both units show similar ~90-foot vertical offsets in the drill hole data (Rinne, 2000; Appendix D). Smaller maximum block failure widths are possible. Additional detailed investigations (drilling, trenching, sampling, etc.) might reveal that the ~90 foot vertical offset in the basalt is tectonic (i.e. a fault) or from original topography (e.g. a wave-cut terrace). In either case it might be argued that the 350-foot slope failure is not a realistic scenario.

RESULTS AND DISCUSSION

Summary compilations of the active hazard zone, historical shoreline changes, projected beach-dune erosion hazard zones using the geometric method, projected bluff erosion hazard zones, and landslide hazard areas are shown graphically in Appendix E. More useful are the digital geographic information files that are on the attached CD ROM. These files contain not only the graphic information but, in many cases, explanatory descriptions for each of the graphic objects. These descriptions list such things as data sources and uncertainties.

Active Hazard Zone

The active hazard zone identified for the Tillamook County coastline varies in width from a few tens of feet on cliffy headlands to hundreds of feet on low-sloping beaches (Appendix E). Furthermore, in the Cape Meares area, a large bedrock landslide reaching 1.3 miles inland has also been included as part of this zone. It is recalled that on dune-backed beaches, the active hazard zone distinguishes the zone of beach variability. This is the area of beach that has undergone considerable change up through April 1998, and can therefore be expected to experience further changes in the immediate future. Thus, there can be no doubt that building within the active hazard zone can represent considerable risk to property and lives.

As noted previously, the landward extent of the active hazard zone has been delineated according to vegetation and topographic patterns that could be identified on 1994 aerial photos, with the inclusion of some local adjustments that were derived from the 1998 LIDAR dataset. It is recalled that the 1998 LIDAR data essentially characterizes those beach changes that occurred in response to the 1997-98 El Niño. Therefore, the 1998 LIDAR data provides the most recent assessment available to us, of the shoreline position along the Tillamook County coastline. Unfortunately, due to the absence of subsequent LIDAR flights, especially after the particularly severe 1998-99 La Niña winter storms, we are not able to quantify those more recent shoreline changes, and therefore provide the most current assessment of the active hazard zone. For example, severe coastal erosion is known to have occurred at Rockaway Beach, the southern end of Cape Lookout State Park, the north side of the entrance to Netarts Bay, particularly at The Capes area, and at Neskowin on the north side of the estuary, all of which was exacerbated by the 1998-99 La Niña winter storms. As a result of the erosion, a number of these sites (e.g. at Neskowin and Rockaway) have subsequently been stabilized with shore protection structures, generally basaltic rip rap. Accordingly, at these locations, the rip rap has “fixed” the shoreline, so that these sites are unlikely to continue to retreat in the immediate future. Nevertheless, these structures are likely to require ongoing maintenance as they become damaged by future winter storms, and continued long-term changes in mean sea level along the coast.

In addition to the recent “hot spot” erosion, sawed logs located *in situ* in the contemporary foredunes at Neskowin, Daley Lake, Tierra del Mar, Rockaway, and at Nedonna beach (Figure 11), demonstrate that the shoreline has been highly variable since European settlement. Similar observations have been made in Lincoln County (e.g. Komar, 1997). One may infer from this line of evidence, that the coast has been subjected to extremely severe storms in the past (probably more extreme than those storms observed over the last 55 years), which probably contributed to widespread coastal erosion. It follows, that similar types of storms are equally likely to be experienced in the future, especially if climate change persists. For example, climate modeling by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) Climate Impacts Group (1999) has revealed that large-scale climate changes are predicted to occur over the Pacific Ocean during the next 50 to 100 years. In particular, their models suggest that the

Aleutian Low is likely to deepen and move progressively southward, resulting in an increase in wind speeds and hence larger waves along the PNW coast. These changes are likely to result in a higher incidence of situations similar to the 1982-83 and 1997-98 El Niño events (JISAO/SMA Climate Impacts Group, 1999). As a result, it is possible that the ensuing decades could be characterized by stormier conditions, further increases in North Pacific wave energies, and therefore an increase in coastal erosion problems.

Figure 11 Example of a sawed log located *in situ* in the foredune at Nedonna Beach. The log was exposed due to the presence of a large rip embayment that had formed, enabling wave processes to erode the beach.

Aside from possible changes in climate, tectonic subsidence from great subduction zone earthquakes will likely cause severe countywide erosion some time in the future. Application of the geometric model to dune-backed shorelines is one way of estimating the degree of shoreline variability when historical photos and surveys of proper vintage are not available to do an empirical analysis.

Tillamook County Historical Shoreline Positions

This section presents a qualitative discussion of large-scale morphological changes derived from an analysis of NOS T-sheets for the entire Tillamook County coastline. Due to the inherent problems associated with deriving erosion rate information from NOS T-sheets, no attempt has been made to quantify rates of coastal change for the dune-backed beaches of Tillamook County. The exception to this is the community of Cape Meares (located at the southern end of the Rockaway littoral cell), which experienced massive erosion between 1917 and the mid 1970s, due to the construction of the north Tillamook jetty.

National Ocean Service T-sheet shoreline positions covering the period 1927, 1953 and 1955 are shown in Appendix E, and on the attached CD-ROM. Additional shoreline position information has been derived from 1985/1986 U.S. Geological Survey topographic maps, 1994 DOQ's, and from the 1997 and 1998 LIDAR data. These latter datasets provide the most up-to-date assessments of the stability of the Tillamook coastline. Furthermore, comparisons between the 1997 and 1998 LIDAR shorelines highlight the seasonal variability in shoreline positions, a function of variations between the summer and winter wave heights. The approach adopted here is to describe the broad morphological changes identified along the coast, beginning in the south at Neskowin, and progressing northward towards Cape Falcon.

Neskowin Cell

At Neskowin, the plotted historical shoreline positions reveal little systematic pattern, with all of the identified shorelines falling within a few hundred feet of each other (Appendix E). Furthermore, a number of the shorelines reveal the presence of large embayments along the coast coincident with the formation of rip currents. Along the southern half of the cell, the 1927 shoreline tends to track landward of the other shorelines. This suggests that beach conditions in 1927 were characterized by widespread erosion following a period of large storm events. In contrast, the 1985/1986 and 1994 shoreline positions represent the most seaward extent of the MHWL, implying that significant accretion had occurred adjacent to Neskowin during those years. What is surprising about these latter findings is that the 1985/1986 shoreline position follows the major 1982-83 El Niño winter, which resulted in extensive erosion along the Oregon coast (e.g. Komar, 1986; Komar and others, 1989). However, discussions with Department of Land Conservation and Development (DLCD) staff indicated that the Neskowin area did not begin to experience significant erosion until the latter part of the 1980s and 1990s (Dr. John Marra, *personal communication 2001*). In contrast, the 1997-98 El Niño and 1998-99 La Niña winters caused considerable coastal erosion along Neskowin beach. As a result, property owners responded by installing rip rap revetments along much of the shore north of Proposal Rock. Of interest, the 1998 shoreline still indicates substantial beach width following the 1997-98 El Niño, suggesting that much of the erosion that took place occurred over the subsequent 1998-99 La Niña winter. With progress north along the coast, the 1994 shoreline tends to track well seaward of the other shorelines. This suggests a period of accretion (probably occurred during the early part of last decade), and was most noticeable adjacent to Porter Point near the mouth of Nestucca Bay. Furthermore, the accretion appears to be consistent with a general decline in wave energy and storm incidence observed during the early part of last decade (Allan and Komar, 2000a).

Along Nestucca spit (Figure 12) the spit tip and bay mouth has remained predominantly in the south, with some evidence of a northward migration in 1998. Based on the few shorelines available to us, the Nestucca spit tip has ranged over a distance of about 640 ft between 1927 and 1998, and was at its most southerly position in 1997. Following the 1997-98 El Niño, the spit tip migrated northwards, probably in response to a change in wave direction that is typical of El Niño events (e.g. Komar, 1986). Of interest also is the presence of a large bulge identified by the 1985/1986 shoreline on the eastern side of the spit (Figure 12). This feature is probably remnant from when the spit was breached during a major storm in February 1978 (*see Figure 6.15 in* Komar, 1997).

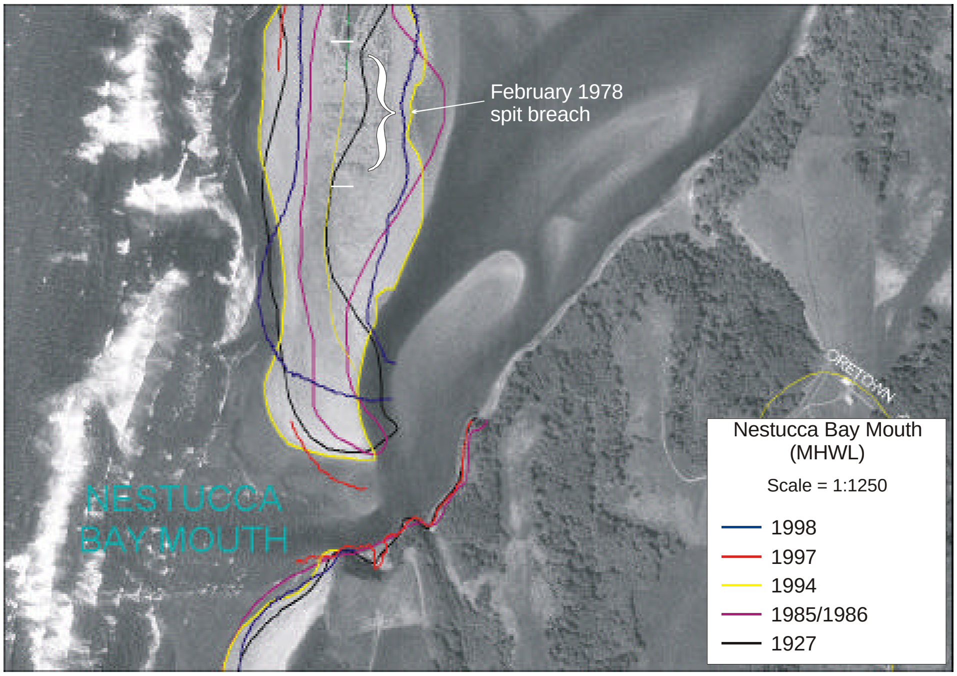


Figure 12 Historical shoreline positions identified adjacent to the Nestucca bay mouth (scale is 1:1250).

North of Nestucca spit, the 1985/1986 shoreline tracks landward of the other shoreline positions, and extends all the way to Pacific City at the north end of the cell. This finding is likely to be a function of erosion that occurred during the 1982-83 El Niño event (Prof. P. Komar, *personal communication 2001*). However, much of the erosion tended to be localized due to the presence of rip embayments that enable localized scour of the beach (Shoreland Solutions, 1998b). In contrast, the 1994 and 1997 shoreline positions represent the most seaward extent of the MHWL (located some 150 to 250 ft seaward of the 1985/1986 shoreline). This indicates that large volumes of sediment had accumulated along much of the northern half of the cell, the product of a persistent net drift of beach sediments to the north. It is highly likely that this pattern is a function of the persistent El Niño conditions that have characterized the PNW during the past two decades. Similar observations of net accretion around Pacific City since about 1981 were also noted in a report by Shoreland Solutions (1998b). For example, considerable quantities of sand accumulated along much of the Pacific City shoreline, burying a large rip rap revetment that was installed in 1978. Furthermore, the continued accumulation of sand at the north end of the Neskowin cell has presented major problems for homeowners since at least 1984. Of particular concern has been the inundation of homes and property by sand (Komar 1997; Shoreland Solutions, 1998b). Recently, the pattern of net accumulation of sand at the north end of the Neskowin cell may have ceased. For example, storm waves during the 2000-2001 winter resulted in the formation of 15-foot-high dune scarps along parts (e.g. north of Pacific Avenue) of the northern Pacific City shoreline, suggesting a possible reversal in the dominant direction of sediment drift.

Sand lake Cell

Along the Sand Lake cell, the 1985/1986 and 1927 shoreline positions represent the most landward extent of the MHWL (i.e. eroded state), while the 1994 shoreline again characterizes the accreted state. For the most part, this pattern is broadly similar to that identified above at Neskowin. However, unlike the Neskowin cell, the 1985/1986 shoreline at Sand Lake indicates cell-wide coastal erosion. While the 1982-83 El Niño event is likely to have been a major factor causing the erosion, the typical pattern of coastal recession along the southern ends of littoral cells, accompanied by sediment accumulation at the northern cell ends clearly did not eventuate in the Sand Lake littoral cell. This is somewhat surprising and it is unclear from the data why the erosion was so widespread. While it is possible that such a pattern may be a function of some form of interpretation problem by the U.S. Geological Survey when the topographic maps were constructed, the absence of a similar northward sand migration following the 1997-98 El Niño suggests that the pattern is more likely to be a function of variations in wave approach angles in the Sand Lake cell.

Some of the most interesting shoreline changes identified in the Sand Lake cell can be found adjacent to the mouth of the estuary. As shown in Figure 13, the location of the estuary mouth has varied considerably, particularly during the last two decades. The 1927 shoreline characterizes the most southerly extent of the estuary mouth (implying a period of net southerly sand transport), while the 1994 shoreline identifies its most northerly position. As a result, the estuary mouth has migrated some 1400 to 1500 ft during this period. These results clearly highlight the dynamic and unstable nature of spit ends. An examination of aerial photographs flown in 1939 also reveals a southerly bay-mouth position, while the spit ends were much wider. These latter characteristics are broadly similar to the 1927 shoreline identified in Figure 13. In contrast, the 1985/1986 shoreline indicates an extremely wide bay mouth (~ 1800 ft wide), so that much of the inner bay was fully exposed to the sea (Figure 13). However, between 1985/1986 and 1994 the spit ends reformed. Of interest, the southern spit tip grew northwards some 1200 ft, while the northern spit tip migrated southward by 500 ft. This suggests that for the period 1985-86 to 1994, the net sediment transport was to the north. However, by 1998, the bay mouth had migrated an additional 200 ft further south so that the bay mouth was located approximately midway along the estuary (Figure 13).

Netarts Cell

The Netarts littoral cell is one of the smallest cells on the Oregon coast. It is therefore especially susceptible to variations in wave approach caused by the El Niño/La Niña Southern Oscillation. According to Komar and others (1989), El Niño events have produced large spatial changes in the configuration of the Netarts coastline and the morphology of the beaches, especially during the past two decades.

The shoreline analyses presented here demonstrate a number of morphological changes that are less apparent in the other littoral cells. At Cape Lookout State Park (CLSP) located at the southern end of the cell (Figure 14), the shorelines track closely to each other. The exceptions to this are the 1994 and 1998 shorelines. The former shoreline identifies the accreted state (consistent with the other littoral cells in Tillamook County), while the 1998 shoreline reveals the most eroded state. In fact, subsequent storms over the 1998-99 La Niña winter caused extensive erosion of the park. In particular, the March 2-3, 1999 storm eventually resulted in the foredune being breached, jeopardizing the campground facilities.

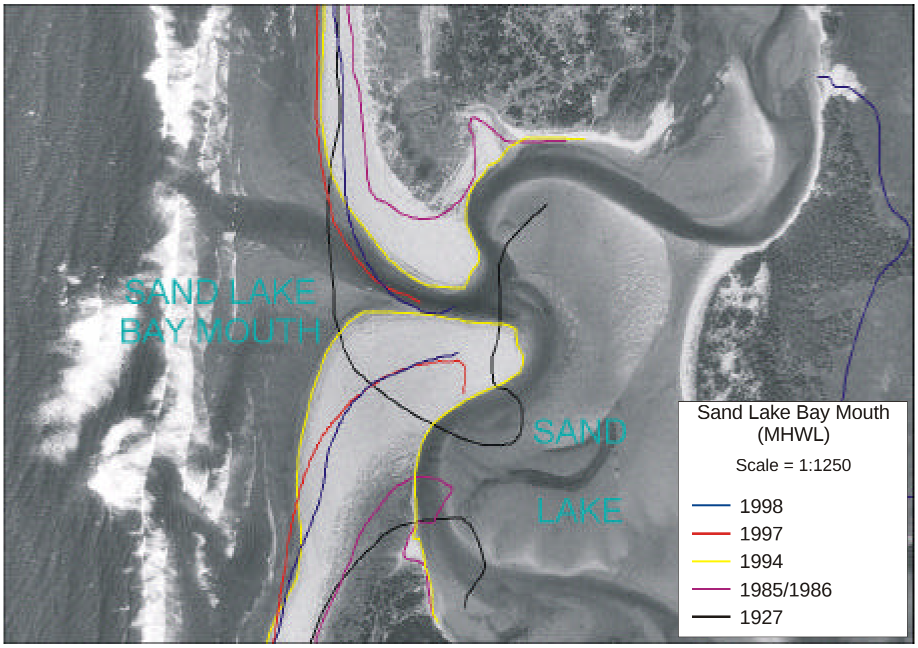


Figure 13 Historical shoreline positions identified adjacent to the Sand Lake bay mouth (scale is 1:1250).

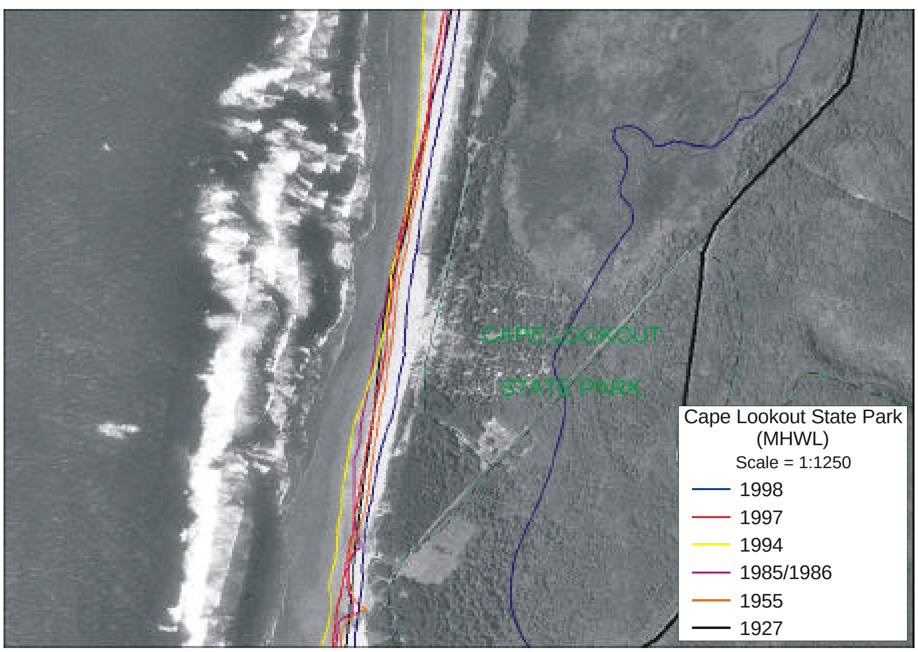


Figure 14 Historical shoreline positions identified at Cape Lookout State Park in the Netarts littoral cell (scale is 1:1250).

Prior to the 1982-83 El Niño, erosion on Netarts Spit had been minimal (Komar and others, 1989). As a result, significant erosion of CLSP did not begin to occur until the 1982-83 El Niño, and was very significantly advanced by the 1987-88 El Niño erosion event. Interestingly, the

1985/1986 shoreline presented in Figure 14, indicates a relatively broad beach in front of the park, suggesting that the beach had reformed somewhat after the 1982-83 El Niño. This is consistent with observations reported by Komar and others (1989). However, they noted further that although some of the sand had returned, the volume of sand contained on the beach was still depleted when compared with the period prior to the 1982-83 El Niño. Evidence for this was indicated by the extensive areas of gravel exposed on the beach and the presence of rock outcrops in the shallow offshore. Because the beach was in such a depleted state, its capacity to act as a buffer against storm waves during subsequent winter seasons was severely reduced. This was especially the case during the 1987-88 El Niño event, which eventually caused the destruction of a bulkhead emplaced along the beach foredune during the late 1960's. By April 1998, the width of the beach in front of CLSP had narrowed significantly, from about 170 to 300 ft wide in 1994, to around 40 to 80 ft wide in 1998 (Figure 14). Furthermore, the area affected by the erosion extended about 0.9 miles north and 0.7 miles south of the campground. In an effort to mitigate the erosion problems, the Oregon Parks and Recreation Department responded by installing a dynamic revetment structure in the area most affected (Figure 15). Such structures are a "soft" form of engineering (when compared with basaltic rip rap revetments) since they are less intrusive on the coastal system, and are designed to respond dynamically to wave attack.

Figure 15 A dynamic revetment structure constructed at Cape Lookout State Park, utilizing materials found at the site.

Further north along Netarts Spit (about 1.8 miles north of CLSP), the shoreline data converge. Beyond this point, the 1985/1986 and 1955 shorelines migrate landward and track close to the vegetation line, indicating erosion along much of the northern end of Netarts Spit, while the 1994, 1997, and 1998 shorelines migrate seawards and track about 200 to 250 ft seaward of the 1985/1986 and 1955 shorelines. Such a transformation is analogous to a pivot point in which one set of processes (erosion), gives way to another (accretion). In other words, the coastal response along Netarts Spit reflects a reorientation of the entire coastline towards the direction of wave attack, with erosion occurring along the southern end of the cell and accretion in the north (Komar and others, 1989; Revell and Komar, in press).

Figure 16 distinguishes the historical shoreline positions adjacent to the end of Netarts spit. Apart from the 1955 shoreline, which shows the spit end having re-curved into the bay and a much narrower mouth, the morphology of Netarts spit has remained broadly the same. In keeping with the Nestucca and Sand Lake bay mouths, the spit tip migrated northwards some 400 ft between 1985/1986 and 1994. However, by 1998 the spit tip had returned to the south. These changes again highlight the dynamic nature of spit ends.

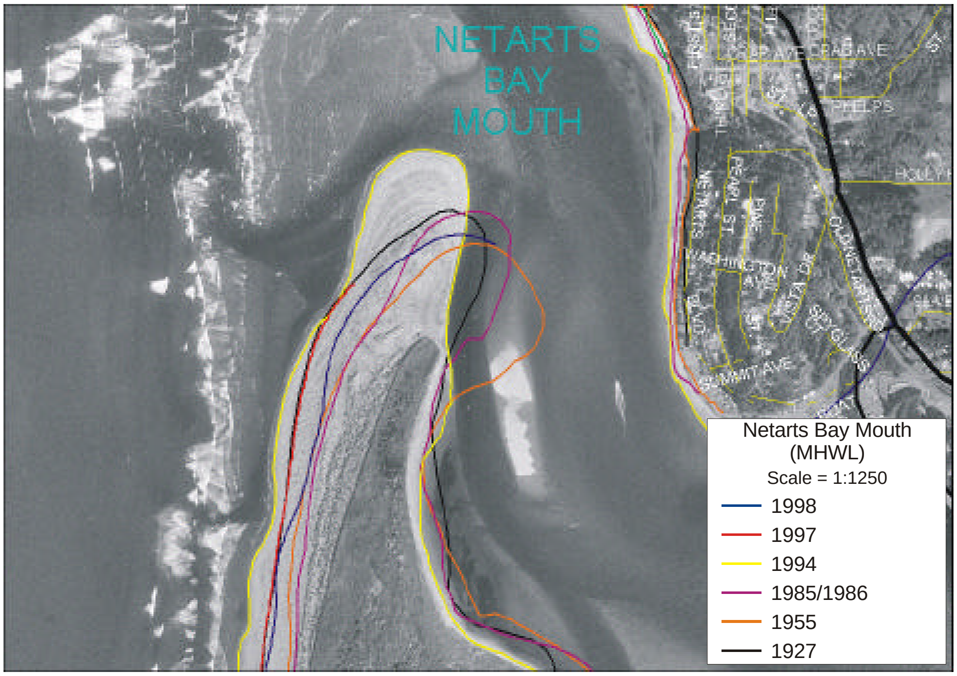


Figure 16 Historical shoreline positions identified at the end of Netarts spit (scale is 1:1250).

Along the Capes, the shoreline data reveals that the width of the beach in front of the Capes has varied considerably in the past (Figure 17). In 1994, the beach width at the toe of the slide was some 350 ft wide. Furthermore, the 1994 photos reveal the formation of small dune features along a 3500 ft section of the beach. This implies that a significant volume of sand had accumulated in the area. However, following the 1997-98 El Niño, the beach eroded back about 320 ft, cutting into the base of the slide.

The erosion that occurred at the Capes was likely triggered by the northward migration of the bay mouth, a typical El Niño response. This produced a deeper section of water adjacent to the slide, enabling storm waves to break close to the beach, enhancing the erosion process (Prof. P. Komar, *personal communication 2001*). Additional beach erosion occurred over the 1998-99 winter, eventually resulting in several houses having to be abandoned. The recent phase of Capes erosion is clearly not unique, having probably occurred over a number of occasions in the past. For example, Figure 17 shows that the shoreline position has been located close to the toe of the slide on at least three previous occasions in the past, 1927, 1953, and to a lesser extent in 1985/1986. Examination of 1939 aerial photos clearly shows numerous areas of sloughing of the bluffs in and around The Capes areas in response to yet another erosion event.

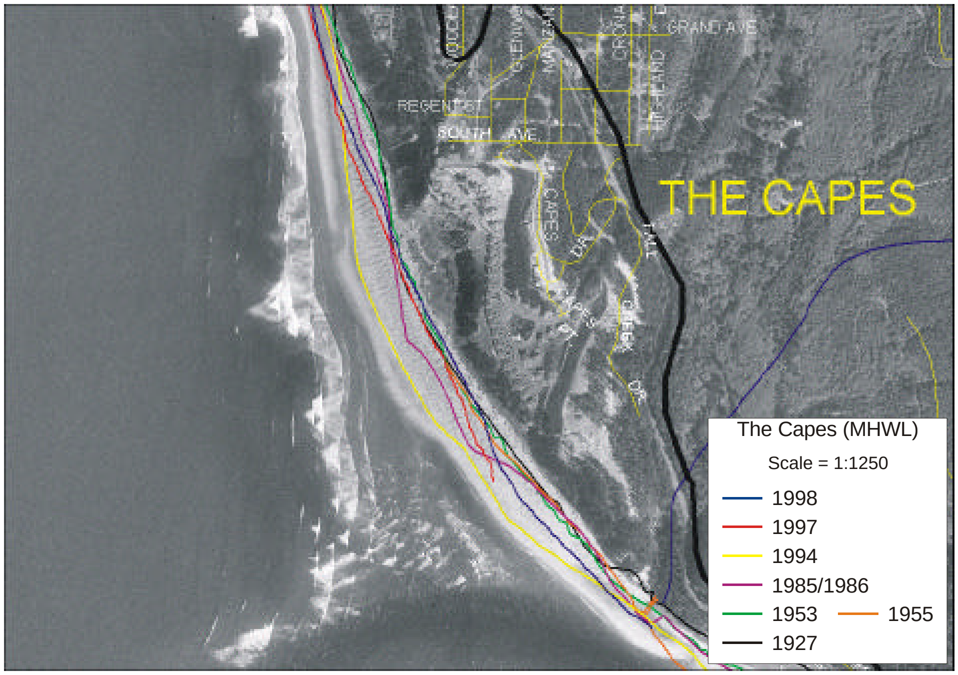


Figure 17 Historical shoreline positions identified adjacent to the Capes in the Netarts littoral cell (scale is 1:1250).

Finally, Figure 18 reveals the historical spread of shorelines adjacent to Oceanside. The 1927 and 1953 shorelines reveal the presence of an extremely narrow beach in the vicinity of Oceanside. This suggests a period of extensive erosion during those years. Of interest also is the 1985/1986 shoreline, which shows significant differences between Oceanside and the two pocket beaches to the north. At Oceanside, the 1985/1986 shoreline is located in the approximate same location as the 1994, 1997 and 1998 shorelines and indicates a relatively broad beach (Figure 18). In the two pocket beaches to the north, the 1985/1986 shoreline tracks close to the base of the bluff, indicating a very narrow beach. These variations in shoreline positions probably reflect a lag in the transport of sediment around the bluff headlands that bound the smaller pocket beaches. Furthermore, erosion events similar to what occurred at the Capes (Figure 17) likely contribute large slugs of sediment that progressively move northwards along the coast, producing the apparent shoreline variations seen at Oceanside and in the smaller pocket beaches in the north. These findings clearly highlight a very dynamic and complex coastal environment, in which a wide range of different processes are operating over a broad range of spatial and temporal scales.

Rockaway Cell

Some of the most dramatic shoreline changes identified on the Oregon coast have occurred in the Rockaway littoral cell, particularly in response to the construction of the north jetty at the mouth of Tillamook Bay (Figures 19 and 20). Previous descriptions of the response of Tillamook Bay mouth to jetty construction can be found in Terich and Komar (1974), while Komar (1997) provides a historical summary of the destruction of Bayocean spit.

Construction of Tillamook's north jetty was completed in October 1917. During the construction phase, changes in the inlet channel and the adjacent shorelines soon became evident (Figure 19). North of the jetty, sand began to accumulate rapidly and the shoreline advanced seawards at a rate almost equal to the speed at which the jetty was being constructed (Komar 1997). Between 1914 and 1927, the coastline just north of the jetty advanced seaward some 3,200 ft. However, by 1920 the rate of sand accumulation on the north side of the jetty had slowed dramatically, so that the position of the shoreline was much the same as it is today (Figure 20). According to Komar and others (1976), the volume of sand that accumulated north of the jetty caused some to speculate that the predominant net sand transport was to the south. However, Komar and others argued that this was not the case. They observed that if a net southward drift of sediment was occurring, why was there no evidence of an accumulation of sand adjacent to Cape Meares, located at the southern end of the Rockaway littoral cell. Instead, the Cape Meares beach is narrow and is composed mainly of cobbles and gravels.

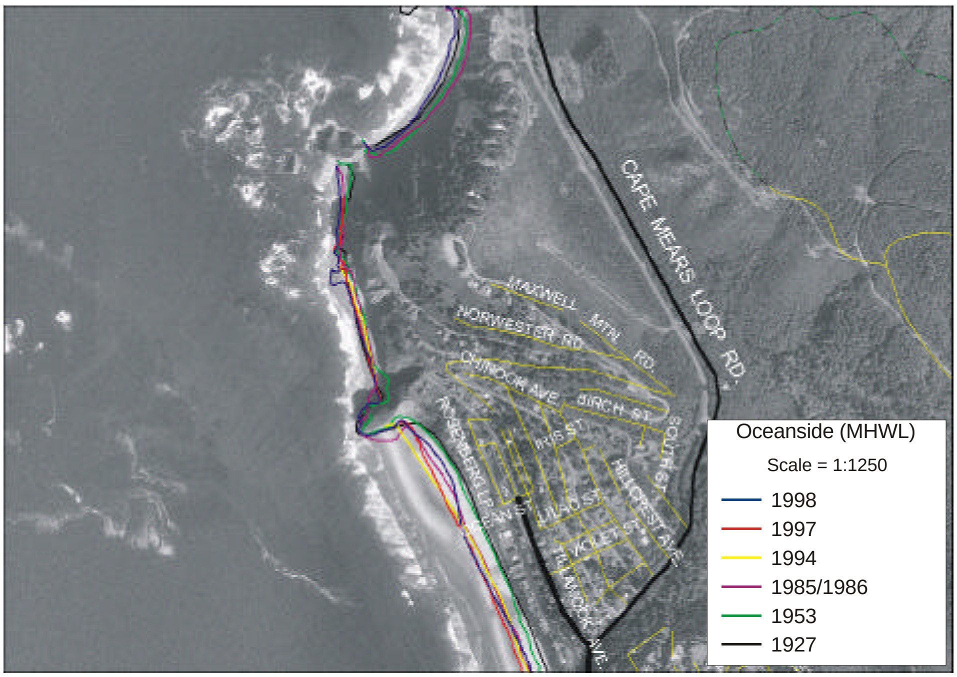


Figure 18 Historical shoreline positions identified adjacent to Oceanside in the Netarts littoral cell (scale is 1:1250).

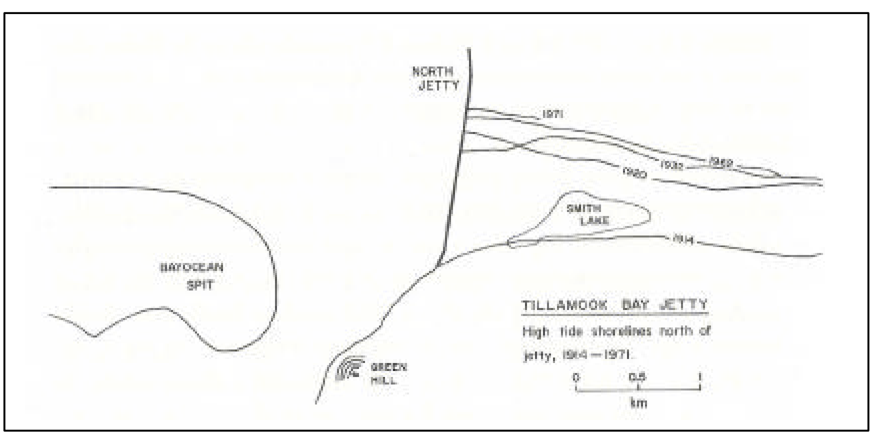


Figure 19 Shoreline positions north of Tillamook Bay jetty, 1914-1972 (From Terich 1973 in Komar 1997).

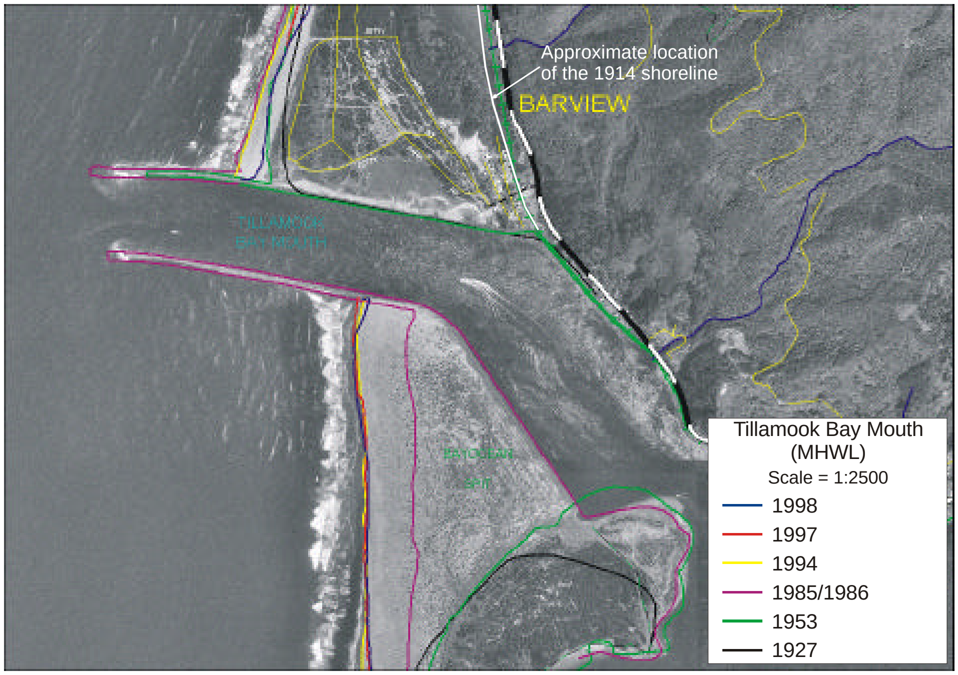


Figure 20 Historical shoreline positions identified adjacent to the mouth of Tillamook Bay in the Rockaway littoral cell (scale is 1:2500).

Although the coastline from Rockaway-Manzanita experienced some erosion (discussed below) due to jetty construction, the most dramatic changes were in fact observed further south along Bayocean Spit. In particular, significant coastal recession occurred at the southern end of the Rockaway cell in the vicinity of Cape Meares (Figure 21). As shown in the figure, the 1927 shoreline previously extended well seaward (up to 850 ft) of the present-day shoreline. Over time the shoreline has progressively retreated landward to its present position in 1998. Between 1927 and 1953, the shoreline retreated by about 220 to 280 ft (an average erosion rate of 8 to 10 ft/yr). In particular, significant coastal erosion occurred in the vicinity of the Cape Meares community as a result of a major storm during January 3-6, 1939 (Komar, 1997). Additional large storm wave events during the winter of 1940 continued to erode the spit. This process continued to be repeated throughout the 1940s, and culminated with the cutting away of a 4,000 ft section of Bayocean spit on November 13, 1952, breaching the spit (Figure 22).

The above erosion rate estimated for the area around Cape Meares appears to have been maintained between 1953 and the early 1980's, since the shoreline continued to retreat landward by some 300 ft (Figure 21). Since then however, the contemporary shoreline data suggests that the coastline may have stabilized since it appears to be oscillating around its present location. Undoubtedly, the absence of a south jetty at Tillamook Bay prior to 1974 probably enhanced the erosion of Bayocean spit, since a lot of sediment accumulated as shoals at the spit end, or was washed into the bay (Komar, 1997). However, with the completion of the south jetty in November 1974, sand quickly began to accumulate at the north end of the spit causing the shoreline to prograde seaward by some 1,000 to 2,500 ft (Figure 20). Since then, the shoreline along Bayocean Spit has stabilized, so that it now responds in a manner similar to other littoral cells on the Oregon coast (Komar, 1997). Nevertheless, due to the low nature of the foredunes just south of the Bayocean Spit breach (Figure 22), this area remains particularly susceptible to wave erosion.

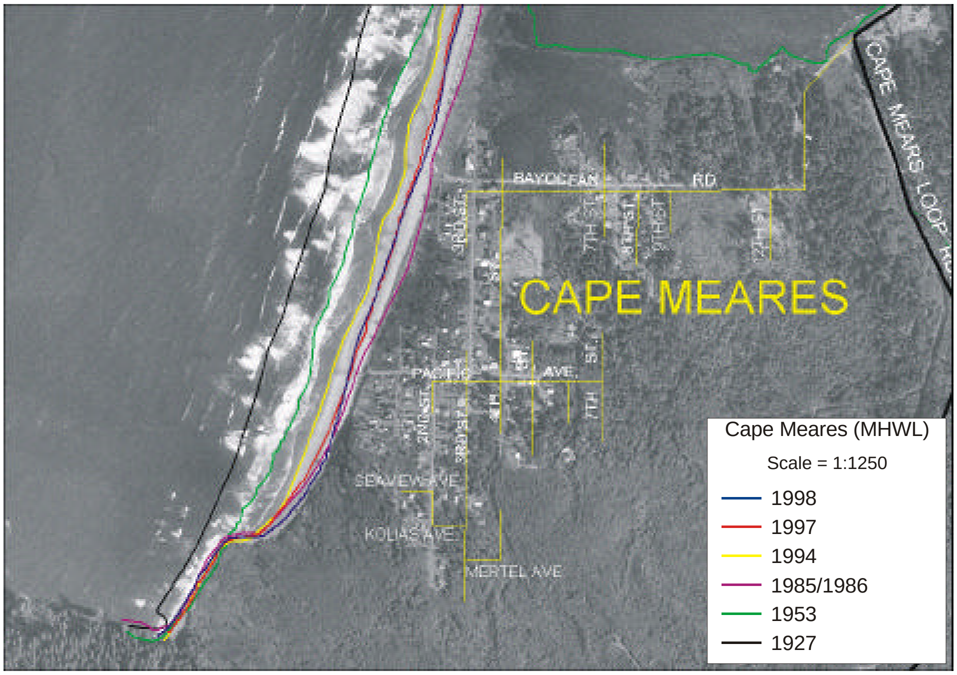


Figure 21 Historical shoreline positions identified at the southern end of the Rockaway littoral cell in the vicinity of the Cape Meares community (scale is 1:1250).

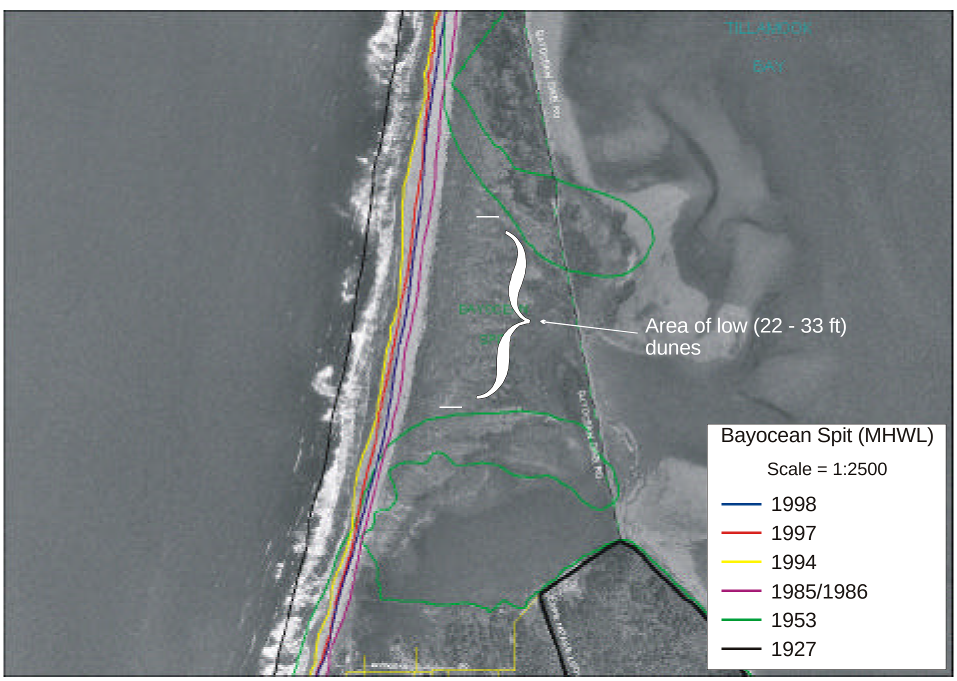


Figure 22 The breach of Bayocean Spit on November 13, 1952 (scale 1:2500).

Further north along the Rockaway-Manzanita coastline, the 1927, 1953 and 1955 shorelines track well landward of the contemporary shorelines (Figures 23 and 24). This type of pattern is a direct response to construction of the north Tillamook jetty. However, the erosion that occurred along the Rockaway-Manzanita beaches was generally much less then on Bayocean Spit (Komar, 1997). This is because the length of shoreline along the Rockaway-Manzanita coastline is much greater than along Bayocean spit. As a result, only a small amount of sand had to be eroded from those beaches, per unit length of shoreline, to supply sand to the accreting area around the north jetty. Erosion along the Rockaway-Manzanita coastline probably stabilized some time after the 1950's, enabling the coastline to enter an accretionary phase (Figures 23 and 24). As shown in Figures 23 and 24, the 1994 and 1997 shorelines characterize the seaward extent of this rebuilding phase. This view is also supported from observations of dune growth around Manzanita, culminating with the initiation of a dune management program to control the growth of the foredunes (Dr. J. Marra, *personal communication 2001*). Nevertheless, El Niño/La Niña type processes have also resulted in periods of significant erosion along the Rockaway-Manzanita coastline during the past two decades. For example, significant erosion occurred in response to the 1982-83 El Niño. Much of this erosion was still evident in 1985/1986 (Figures 23 and 24). More recently, Rockaway beach experienced extensive erosion as a result of the 1997-98 El Niño. The erosion was further enhanced during the extremely severe 1998-99 La Niña winter, so that the coast experienced a "one-two punch", with little time to recover.

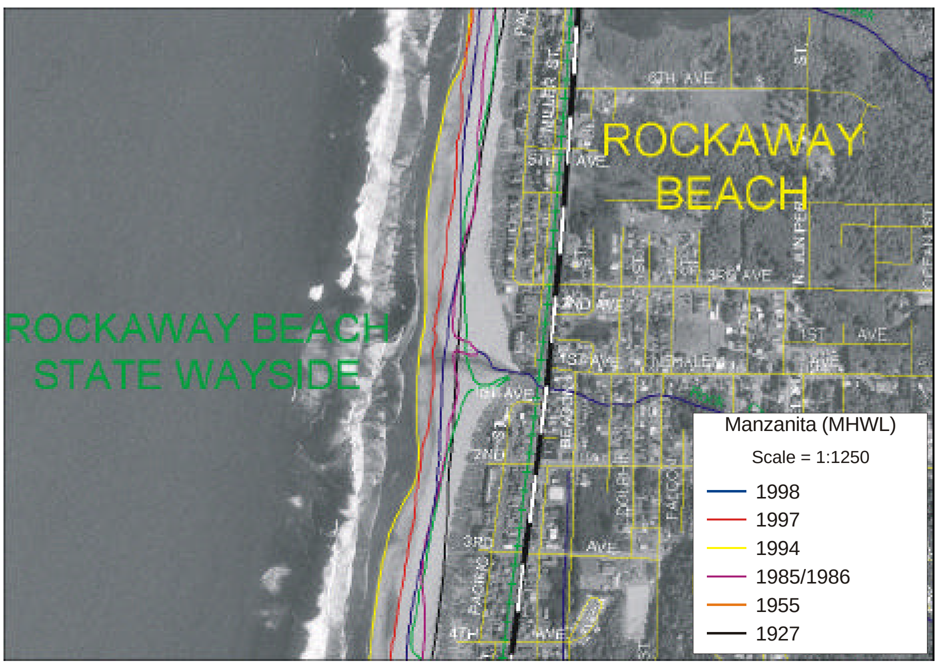


Figure 23 Historical shoreline positions identified along the Twin Rocks and Rockaway beach (scale is 1:1250).

This section has presented information on the historical shoreline changes that have occurred along the Tillamook County coastline. The analyses indicate that for the most part the dune-backed shorelines respond episodically to such processes as the El Niño/La Niña Southern Oscillation, and as a result of rip current embayments that cause highly localized "hotspot erosion" of the coast. Thus, the coastline undergoes periods of both localized and widespread erosion, with subsequent intervening periods in which the beaches and dunes rebuild. Perhaps the most significant coastal changes identified in Tillamook County have in fact occurred in response to humans, particularly as a result of jetty construction during the early part of last century. In particular, jetty construction has had a dramatic influence on the morphology of Bayocean Spit, and to a lesser extent between the north Tillamook jetty, and the Rockaway-Manzanita beaches to the north. Finally, the present analyses have shown that the mouths of the estuaries and the spit ends are extremely dynamic features, migrating over large distances in response to changes in both the sediment supply and the predominant wave conditions.

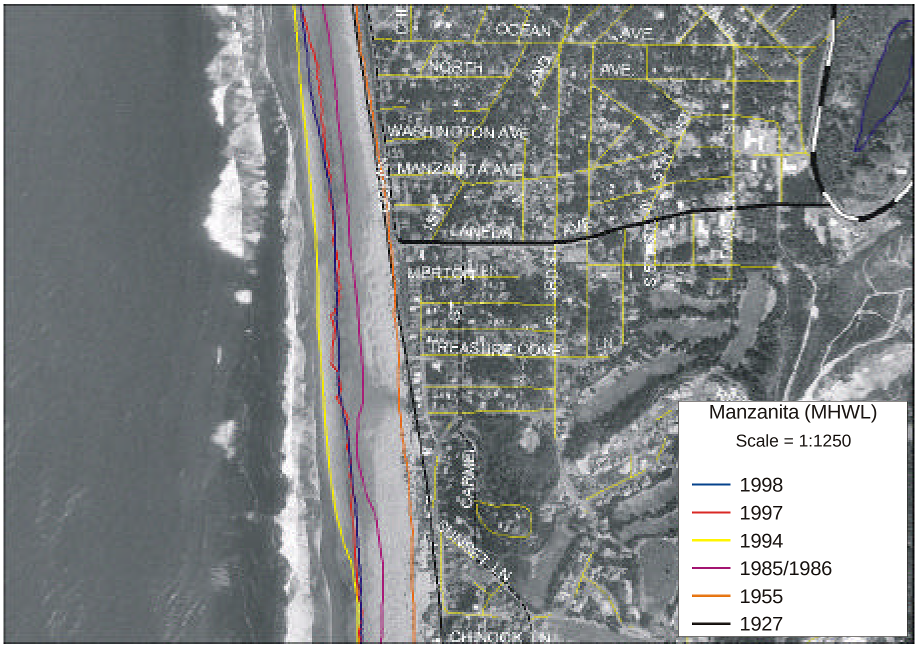


Figure 24 Historical shoreline positions at Manzanita (scale is 1:1250).

Beach-Dune Coastal Hazard Zones

Having described the historical shoreline changes that have occurred along Tillamook County, this section examines the possible future coastal response that may occur under a variety of extreme scenarios. Estimates of maximum potential erosion distances (MPED) for the dune-backed beaches have been determined by the geometric model (Figure 7) 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 considerable variability in the morphology of the beach environment along the Tillamook coastline, 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 E.

Table 9 presents values of the MPED identified for the Neskowin littoral cell. As can be seen for the HIGH-risk hazard zone, estimated erosion distances range from 150 to 560 feet, with an average MPED of 250 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 for the Neskowin littoral cell in

Appendix E. As expected, a much broader range of values characterize the MODERATE and LOW risk scenarios (Table 9), with some potential erosion distances that extend up to 1000 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. Conversely, the widest MPED estimates were found along sections of beach that were in a degraded state. These areas included regions of dune blowouts typical of much of the coast between Neskowin and Porter Point, localized areas where rip currents had been located, or sites where streams cross the beach. Average maximum potential erosion distance estimates for the MODERATE and LOW risk hazard zones were determined to be 415 ft and 460 ft respectively (Table 9, Appendix E). These zones are shown graphically in Appendix E.

Table 9 Maximum potential erosion distances determined for the Neskowin littoral cell.

Hazard zone scenarios	*Min (ft)*	*Max (ft)*	*Average MPED (ft)*
HIGH	151.5	564.0	**250**
MODERATE	277.3	905.7	**415**
LOW	301.4	1021.4	**460**

Maximum potential erosion distances are presented for the Sand Lake littoral cell in Table 10, and are shown graphically in Appendix E. Under the HIGH-risk scenario, estimated erosion distances again range widely (182 to 569 ft), with a mean MPED of 280 ft (Table 10, Appendix E). This value is somewhat greater than the same zone delineated for the Neskowin littoral cell, and is largely due to the generally lower beach-dune toe elevations that typified much of this shoreline in 1998. Of note, are high MPED values estimated for the beaches close to the mouth of Sand Lake (up to 400 ft wide). These large estimates are probably a function of the northward migration of the Sand Lake channel. Analyses of the 1998 LIDAR dataset revealed the presence of a prominent scour channel immediately north of the mouth of Sand Lake. As a result of the deeper channel, waves were able to erode this section of coast causing "hotspot" type erosion, with lower beach slopes and beach elevations. For the MODERATE risk scenario the average MPED is 455 ft, while the LOW risk scenario is characterized with an MPED of 505 ft (Table 10).

Table 10 Maximum potential erosion distances determined for the Sand Lake littoral cell.

Hazard zone scenarios	*Min (ft)*	*Max (ft)*	*Average MPED (ft)*
HIGH	182.4	569.3	**280**
MODERATE	286.9	851.4	**455**
LOW	310.9	942.5	**505**

Table 11 presents values of the MPED identified for the Netarts littoral cell. Under the HIGH-risk scenario, our analyses suggest an MPED of about 275 ft, while the MPED for the MODERATE-risk and HIGH-risk hazard scenarios are 430 ft and 460 ft respectively. These results are shown graphically in Appendix E. Based on these results, it can be seen from Appendix E that much of Cape Lookout State Park is located within the HIGH-risk hazard zone. In particular, most of the campground facilities are located within the HIGH-risk zone. Given the current degraded state of the beach system in this area, and especially the absence of a frontal foredune adjacent to the campground, it is likely that this part of the coast will experience further significant erosion in the immediate future.

Table 11 Maximum potential erosion distances determined for the Netarts littoral cell.

Hazard zone scenarios	*Min (ft)*	*Max (ft)*	*MPED (ft)*
HIGH	123.0	515.6	**275**
MODERATE	173.1	755.3	**430**
LOW	181.4	829.5	**460**

The Rockaway littoral cell is the largest stretch of sandy beach in Tillamook County with approximately 27 km of shore. Furthermore, this section of coast has been extensively modified, with the construction of jetties at the mouths of Nehalem and Tillamook Bays, and due to the establishment of coastal engineering structures in places such as at Rockaway. Maximum potential erosion distances again reveal a wide range of values for each of the scenarios (Table 12). Under the HIGH-risk scenario (Table 12) the potential erosion distances ranged from 138 to 674 ft, with a mean MPED of about 280 ft. For the MODERATE and LOW-risk scenarios, we have derived MPED values of 460 ft and 510 ft respectively. These hazard zones are shown graphically in Appendix E, for the region between Cape Meares and Cape Falcon.

Table 12 Maximum potential erosion distances determined for the Rockaway littoral cell.

Hazard zone scenarios	*Min (ft)*	*Max (ft)*	*Average MPED (ft)*
HIGH	137.9	673.7	**280**
MODERATE	245.5	1228.9	**460**
LOW	265.9	1436.9	**510**

The above calculations provide an estimate of the average maximum potential erosion distance for sandy beaches located along the coastline of Tillamook County. 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 rise in mean sea level, 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 Tables 9 to 12, the MPED varies from 250 to 280 ft due to subtle differences in the beach morphologies along each of the four littoral cells. However, even under the HIGH-risk scenario some beach sites have predicted coastal retreat of up to 670 ft. This is especially the case in areas where streams cross the existing beach such as at Rockaway or Twin Rocks, or sites where dune blowouts have occurred (e.g. north of Neskowin). Because of the lower beach elevations and slopes that characterize these areas, very large potential erosion distances are always going to be predicted by the geometric model. Having said this, analyses of the 1998 LIDAR dataset has revealed that significant "hotspot" erosion (up to 165 ft since 1994) has occurred in the vicinity of Spring Lake (Twin Rocks), largely due to the northward migration of a stream channel up against the dunes. At this stage, the geometric model does not account for this type of "hotspot" erosion that typifies parts of the Oregon coast, such as at the southern ends of littoral cells, and around the mouths of the bays. As a result, further efforts are required to better define maximum potential erosion distances in these regions.

The reality is, that it is unlikely that coast-wide erosion of the magnitudes shown in Tables 9 to 12 would take place along the shoreline of Tillamook County, because of certain assumptions that are characteristic of the geometric model. For example, as noted by Komar and others (1999), in the first instance the geometric model projects a mean linear beach slope. As a result, if the beach is more concave, it is probable that the amount of erosion would be less, though not by much. Perhaps of greater significance is that the geometric model assumes an instantaneous erosional response, with the dunes retreating landward as a result of direct wave attack. However, the reality of coastal change is that it is far more complex than this so that there is in fact a lag in the erosional response behind the forcing mechanism. As noted by Komar and others, the extreme high runup elevations calculated from Equation 1 occur for only a very short period of time, i.e. the period of time in which the high wave runup elevations coincide with high tides. 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 such widespread coastal retreat in Tillamook County. Finally, as beaches erode, the sediment is removed offshore (or further along the shore) into the surf zone where it accumulates as near shore sand bars. This process helps to mitigate the incoming wave energy by causing the waves to break further offshore, dissipating much of the wave energy, and forming the wide surf zones that are characteristic of the Oregon coast. In turn, this process helps to reduce the rate of beach erosion that occurs. In the absence of high quality coastal data required to run sophisticated models of coastal change, the geometric model remains a useful approach for estimating maximum potential erosion distances along dune-backed beaches.

Bluff and Landslide Hazard Zones

Bluff Hazards

Table 13 illustrates the lateral distances of bluff top or headwall retreat that are calculated using the step-wise procedure outlined above but without steps 4 (2:1 slope for Pleistocene to Holocene dune bluffs) and 9 (adjustments for inland landslides). The effect of step 4 is illustrated in Table 14.

The results illustrate the uncertainty in estimating future bluff retreat in Tillamook County. This uncertainty is highest for bluffs with the potential for large single slide block failures. What is most immediately apparent is the small bluff retreat that is predicted for the high hazard zone. The predicted retreat for 60 years of erosion, for all bluff material was only 6-15 feet. By adjusting this value to the minimum width of ~20 feet that could be mapped at the map scale, this effectively added a safety factor of 33-233 percent to all of the high hazard zone widths. Doubling the estimated erosion rates for Pleistocene to Holocene sand and soil bluffs added a 100 percent safety factor. These conservative adjustments are fully justified by the inherent uncertainties in the data and mapping technique.

Table 13 Table lists for generic types of bluff the minimum, mean, and maximum lateral distances of bluff top retreat should erosion continue for 60-100 years.[2] These distances would define the landward boundaries of the high, moderate, and low hazard zones, respectively, when added to the lateral distance of the projected angle of repose for talus-of each bluff. Table illustrates the uncertainty of predicting future bluff retreat from erosion rate and maximum block failure width. Values in parentheses are actual mapped widths, taking into account the limitations of the digital base maps and drawing accuracy.

Bluff Rock Type and Height	*High Hazard* Zone *(ft)*	*Moderate Hazard* *Zone (ft)*	*Low Hazard* *Zone (ft)*
Basalt subject mostly to rock falls and topples in bluffs < 100 feet high	6 (20)	19 (40)	28 (60)
Basalt subject mostly to rock falls and topples in bluffs = 100 feet high	6 (20)	38 (40)	69 (70)
Basalt in Pocket Beach South of Cape Meares	6 (20)	247 (250)	488 (490)
Resistant sandstone bluffs 80-160 feet high	6 (20)	34 (40)	62 (60)
Seaward-dipping Tertiary sedimentary rock with fine grained interbeds on bluffs <60 feet high (5-59 feet bluffs)	12 (20)	28-50 (40-50)	44-87 (60-90)
Seaward-dipping Tertiary sedimentary rock with fine grained interbeds on bluffs with interbedded fine-grained sedimentary rock 60-200 feet high	12 (20)	198 (200)	384 (390)
Seaward-dipping Tertiary sedimentary rock with fine grained interbeds bluffs 60-200 feet high with mainly resistant sandstone beds	6 (20)	183 (180)	360 (360)
Seaward-dipping Tertiary sedimentary rock with fine grained interbeds on bluffs >200 feet <300 feet high (range 201 to 299 feet)	12 (20)	198-240 (200-240)	385-468 (390-470)
Seaward-dipping Tertiary sedimentary rocks with fine grained interbeds on bluffs 300-400 ft high	12 (20)	249 (250)	486 (490)
Holocene to Pleistocene soil in bluffs ≤150 ft high (range 5-150 feet)	30 (30)	55-105 (60-105)	100-220 (100-220)
Holocene to Pleistocene soil in bluffs >150 ft high (range 151-200 feet)	30 (30)	95-208 (100-210)	196-425 (200-425)
Holocene to Pleistocene dune sand bluffs	30 (30)	77 (75)	124 (120)

An important implication of the resulting 20-30 foot width of the high hazard zone on the bluffs is the inferred high level of stability of the bluffs on 27-55-year time spans, the intervals between the 1939, 1967, and 1994 air photos. This stability is reflected in the low calculated erosion rates

[2] The distances do not take into account (1) the possibility of pre-existing structures like ancient landslides (step 6 in the procedure); (2) the possibility that the bluff top might erode gradually from the top by subaerial weathering that might lower the slope angle below the angle of repose (e.g. the 2:1 slope mapped in step 3 of the procedure for dune sand bluffs); or (3) bluffs composed of hard rock at the base and softer soils above (composite bluffs). For these composite bluffs (as with all bluffs) the basal unit determines the gradual erosion rate (Table 6). The only difference is that angles of repose must be projected for each unit in a composite bluff using the values of Table 5.

of Appendix B, and the overall lack of significant bluff changes that could be identified on the bluffs since 1939. This presents problems with predicting future bluff retreat since the period of observation may have not been representative of the future erosion rates. For example, the historical shoreline analysis showed that most of these bluffs had at least some exposure to wave attack during the observation interval, particularly in 1955. Nevertheless, the wide beaches indicated by the 1985/1986 and 1994 shorelines may have biased the erosion rate data to unrepresentative low values. Much of the bluff erosion rate data was dependent on comparison of 1967 to 1994 photos, since features like houses were easier to find for reference on these more modern photos. Thus, it may be that considerably more bluff retreat occurred during the landward shoreline excursion noted for the 1927 shoreline, and, if that information were available, the calculated erosion rates, particularly for bluffs composed of Pleistocene or Holocene soil or dune sand, would likely have been much higher.

Table 14 Table lists lateral distance from the bluff top to the low hazard zone boundary, assuming that the bluff is already at the ideal slope of repose for sand, 1.5:1. Comparing to the last row of Table 13, it is clear that for most dune sand bluffs =150 feet in height, the 2:1 slope of repose will determine the low hazard zone boundary.

Holocene to Pleistocene Dune Sand Bluff Height (ft)	*Distance to Low Hazard Zone Boundary (difference between a 1.5:1 and 2:1 slope, ft)*
100	50
150	75
200	100
250	125

Our conclusion is that the sparseness of the quantitative rate data (only 72 localities), the potential error inherent in such short (= 55 years) observation periods, and the observation that much of the County coastline experienced beach accretion during the time interval used to estimate erosion rates make the bluff hazard zones specified primarily by erosion rate calculations the least certain of the zones. This problem justified (1) adding a large safety factor to bluff retreat predicted from erosion rate, and (2) providing an additional estimate of retreat independent of the erosion rate. Independent estimates include (1) the degree that the slope varied from the ideal angle of repose for talus of the same material and (2) the potential retreat that could occur should the slope suffer a maximum slide block failure. In particular, the high uncertainty of the response of soft soil bluffs to erosion justified doubling the estimated erosion rates for Quaternary deposits. Additional conservatism was added to the high hazard zone width by first projecting all bluffs to their empirically derived angle of repose before calculating bluff top retreat by gradual wave erosion. This step added additional width that was, in many cases, as wide or wider than the calculated retreat from gradual wave erosion. Requiring that the low hazard zone for Pleistocene to Holocene sand and soil bluffs be at least as far landward as a projected 2:1 slope added an additional degree of conservatism independent of the erosion rate data. Likewise, adding a maximum block failure width to specify low hazard zone boundaries for bluffs prone to block failures added a substantial safety factor entirely independent of the erosion rates.

For bluffs with clay-rich Pleistocene soil at the base, the addition of a maximum block failure always resulted in more bluff retreat than would be predicted for a 2:1 slope, because the maximum block width was approximately the bluff height divided by 1.25, and this distance was added landward of the bluff top already projected to a 1.5:1 slope. This technique is consistent with general observations of bluffs prone to deeply penetrating landslides in both Tillamook and Lincoln County. In most cases, the predicted retreat of the bluff from maximum block failures in these landslide-prone bluffs exceeded estimated retreat from gradual erosion and slope of repose calculations by factors of 2 to 8 (see Priest, 1999, for a summary of the Lincoln County data).

Hazard zones on resistant sandstone and basalt bluffs were highly dependent on erosion rate calculations where the slopes were already at the empirically derived angle of repose. Owing to the hardness of these rocks, they should, in fact, have extremely low erosion rates, even under severe wave attack. Rounding off the calculated hazard zone widths for these bluffs to minimum distances of 20 feet produced a de facto safety factor of about 100 to 300 percent. The resulting narrow band of erosion hazard zones is appropriate for these resistant bluffs.

Hard rock bluffs subject to large deeply penetrating landslides had worst-case erosion hazard zones essentially independent of the erosion rate data. Seaward dipping Tertiary sedimentary rock and landslide-prone portions of the basalt bluff south of Cape Meares had maximum block failures on the order of 300-450 feet. Adding these distances to the modest bluff retreat from gradual erosion produced worst-case erosion scenarios with up to 490 feet of bluff retreat (Table 13).

Additional conservatism was added to the worst-case erosion hazard zone in areas with inland landslides. At the large landslide north of Cape Meares the boundary was moved about 7500 feet inland to encompass this massive landslide and potential maximum block failures that could occur at the margins. In other areas like Oceanside and the north end of Manzanita, worst-case erosion hazard zones were widened hundreds of feet to encompass prehistoric or potentially active inland landslides.

Landslide Hazards

Potentially active and active landslides were mapped chiefly along the shoreline, although a few inland landslides with recent activity have also been identified. Active and potentially active landslides are particularly concentrated on bluffs at the south ends of littoral cells, or at the mouths of natural inlets like the mouth of Netarts Bay. As previously noted, south-to-north sand transport in winter and resultant north migration of inlets tends to focus wave and tidal current erosion on the north side of inlets as the channel impinges against the shore. The resulting erosion can remove buttressing sand dunes and cut the toes out of formerly stable slopes and ancient landslides. The Capes landslide is the prime example of a landslide reactivated by inlet migration.

The largest active landslide on the Tillamook coastline is on the north side of Cape Meares where slide movement has repeatedly closed the local highway. Large active landslides also occur at the pocket beach immediately south of Cape Meares, The Capes development near Oceanside (see Appendix D), and the Three Capes Loop area on the south side of Tierra del Mar. All but the pocket beach landslide south of Cape Meares are in moderately consolidated Pleistocene soil or seaward dipping Tertiary sedimentary rocks with fine-grained interbeds. The landslide in the pocket beach is in a basaltic sequence, but it is likely that weaker sedimentary or hyaloclastic (palagonite tuff) interbeds have caused the slope failure. Whereas weak rock and soil is the primary cause of these slides, all are also exposed to vigorous wave attack, which in combination with high groundwater in the less permeable slides, is the ultimate cause of slope failure.

Size of individual slide block failures for bluffs with Pleistocene soil at the base tends to increase more ore less regularly with bluff height; whereas there is less correlation to bluff height for landslides in seaward-dipping Tertiary sedimentary rocks (Appendix C). When bluff height exceeds about 70 feet, the Tertiary sedimentary rocks can form single slide blocks up to 300-400 feet wide and hundreds or thousands of feet long. These large slides are generally translational failures at relatively low angles, sometimes lower than the dip of the strata.

The most numerous active slope failures in Tillamook County are shallow landslides and rock falls. Shallow slides are most common on 150-400 ft high bluffs of Pleistocene or Holocene dune sand. Individual failures in these active landslides are shallow sloughs with maximum width of ~24 feet. Individual slope failure on the basalt headlands is mostly from rock toppling and rock falls that cause 8-14 ft deep scallops in the cliff face.

Active and potentially active slide areas are very hazardous to development unless some form of geotechnical remediation is pursued. In some cases remediation is not economically feasible.

Also common in Tillamook County are prehistoric landslides that are presently inactive but capable of activity should they become destabilized. Prehistoric slides may become reactivated if slope buttressing or groundwater conditions are altered. Cutting the toe out of these slopes or allowing storm water runoff from housing developments to raise the water table can cause reactivation.

Prehistoric landslides are located principally in Tertiary sedimentary rocks. The slides cover large areas but may not have experienced movements in hundreds or thousands of years. These landslides show less spatial correlation with the littoral cell geometry, many being on the north ends of cells, and frequently surround smaller areas of active sliding. These features suggest forcing mechanisms that are larger and somewhat different from current conditions. Such forces may include earthquakes or unusually wet prehistoric climate cycles that may have caused higher ground water table and more wave attack than at present. Some support for the hypothesis of formerly wetter climate is found at Garibaldi where much of the town sits on a large deposit of debris flows (mapped as unit PHf) that are now moderately consolidated, indicating age in the thousands or tens of thousands of years. The drainage at the head of this fan-shaped deposit does not have any evidence of modern debris flow activity, but this conclusion is based on a cursory field reconnaissance of the area. It would be wise to do a detailed examination of upslope areas to determine whether houses on this feature, particularly some built directly over the main drainage channel, are vulnerable to debris flows, albeit smaller ones than in the prehistoric past.

Finally, there were a number of areas that were mapped as queried potentially active landslides (PAls?). These landslides have probably not experienced movements in hundreds of years, but they appear much fresher and better defined than most of the prehistoric landslides. An example is the landslide at the north end of Manzanita. The benched bluff there is a popular area for housing development, but the benches are a series of well-defined landslide blocks. These blocks are part of a large complex landslide that clearly cuts across ancient landslide debris that is probably tens of thousands of years old. It is possible that this landside and many others identified from aerial photos in inland areas have evidence of more recent movement. The detailed field investigation necessary to make this determination was beyond the scope of this regional investigation.

All landslide areas are potentially hazardous, but some are clearly more dangerous than others. Prehistoric landslide deposits nearly devoid of topography indicative of recent slope failure are probably not very hazardous as long as proper precautions are taken to manage storm water runoff and groundwater. Queried potentially active slides pose a much higher risk followed by potentially active and active slide areas. The latter should be avoided, if at all possible. If the natural slope is cut to a steeper angle by man or by nature, a formerly stable landslide, no matter how old, can become active. Geotechnical investigations are recommended in any mapped landslide area to check on the accuracy of this reconnaissance-level information.

CONCLUDING REMARKS

This report describes and documents a range of coastal hazards zones distinguished for the Tillamook County coastline. In particular, the report focuses on identifying maximum potential erosion distances for bluffs and for dune backed shorelines using two quite different but complementary approaches for these two different shore types.

Hazard zones on dune-backed beaches were determined from 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 found to range from 250 to 280 ft, and varies between the four littoral cells due to subtle differences in the beach morphologies between the littoral cells.

- *Scenario 2* (MODERATE-risk) is one of two "worst case" situations in which a severe storm event is coupled with a sea level rise of 1.3 ft. Maximum potential erosion distances (MPED) estimated for the Tillamook coastline under this particular scenario vary considerably, with an average MPED that ranged from 415 to 460 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 460 to 510 ft.

The range of shoreline retreat predicted for dune backed beaches is clearly quite large for Tillamook County, and reflects the uncertainty in predicting future shoreline behavior based purely on extreme wave erosion events. Shoreline retreat estimated for Tillamook County ranged from ~120-1,400 feet, depending on the water level scenario chosen and the local beach conditions. Despite the low probabilities of some of the extreme water level scenarios adopted for Tillamook 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. For example, recent erosion at places like Cape Lookout State Park has already approached close to the shoreline retreat predicted by some of the worst-case scenarios.

Three complementary erosion hazard scenarios were mapped for bluffs utilizing bluff erosion rates, potential for block failures, and empirically derived angles of repose for the bluff materials. These three scenarios have similar risk levels to the dune hazard scenarios:

- *Scenario 1 (*HIGH risk) portrays the zone of bluff retreat that would occur if only gradual erosion at a relatively low mean rate were to occur after the slope reaches and maintains its angle of repose. The time interval of erosion was assumed to be 60 years.

- *Scenario 2* (MODERATE risk) portrays an average amount of bluff retreat that would occur from the combined processes of block failures, retreat to an angle of repose, and maximum erosion for ~60-100 years. The zone boundary is derived by placing it halfway between the high and low risk boundaries.

- Scenario 3 (LOW risk) illustrates a "worst case" for bluff retreat in ~60-100 years. The zone portrays the bluff retreat that would occur if a bluff suffered a maximum slope failure, then eroded back to its angle of repose and continued to gradually retreat for ~100 years. For bluffs composed of Holocene to Pleistocene dune sand the additional bluff top retreat from rapid response to short-term wave erosion events and potential subaerial erosion is achieved by adding a 100 percent safety factor to the erosion calculations, and making sure that the resulting bluff top retreat corresponds to at least a 50 percent factor safety for the angle of repose (i.e. a 2:1slope). This degree of retreat has a low probability and could easily take much longer than 100 years, but reflects the extreme uncertainty of predicting how a large sand bluff might respond to erosion events.

An active erosion hazard zone has also been mapped which portrays the area of coastal bluffs and dunes that is being actively eroded by waves and the mass movements directly precipitated by wave action. This zone is by its very nature the least speculative of all of the hazard zones, since it is directly observable and requires no theoretical projections into the future. On dune-backed beaches the active hazard zone is mapped at the vegetation line. On bluff backed shorelines the active hazard zone includes all areas of active mass movement (soil creep, landslides, etc.) that are driven by coastal processes; hence it includes the bluff face and ends at the bluff top or top edge of an active or potentially active coastal landslide. The active hazard zone was mapped from observations of 1994 aerial photos supplemented by fieldwork and by analysis of 1998 LIDAR data. The high, moderate, and low risk zones may be viewed as potential future expansion of the active hazard zone.

While this report illustrates a reasonably simple and reproducible means of establishing erosion hazard zones for coastal Tillamook County, it is by no means the only way. Ultimately coastal erosion is such a complex process with so many variables that predicting its future progress should only be done by highly experienced teams of geologists and experts in coastal processes. Ideally, these investigations should be done on a site-specific basis using extensive geotechnical and oceanographic data. The map data presented here is no substitute for this type of detailed analysis.

The results of this investigation do, however directly illustrate to the user the uncertainty that will likely accompany any mapping technique. For example, the predicted 60-100-year bluff top retreat is highly uncertain, especially for bluffs prone to large single slide block failures. Based purely on the empirical calculation techniques, these uncertainties ranged from 484 feet for the basalt bluff at the pocket beach south of Cape Meares to 60 feet for resistant sandstone and basalt bluffs. When the possibility of destabilizing inland landslide areas was factored in, the worst-case hazard zones widened hundreds or thousands of feet in some cases. The most extreme example is the Cape Meares landslide where the hazard zones became as wide as ~7500 feet.

A major source of uncertainty in predicting gradual retreat in all of the bluffs was in the erosion rate data, which suffered from being:

1) Too sparse (only 72 spot rates were measured), and;
2) Based on a short (=55 years) observation period that included some significant beach accretion.

Some of the inherent uncertainty in the erosion rate data was overcome by projecting all bluff tops to an empirically determined angle of repose, and calculating bluff retreat at this angle for 60-100 years. Adding maximum estimated error to erosion rates and adding a maximum slope failure event to 100 years of gradual erosion achieved additional conservatism. This conservatism was taken a step further for Holocene to Pleistocene dune sand bluffs by:

1) Adding a 100 percent safety-factor to erosion rates, and;
2) Making sure that the worst-case erosion scenario always reached at least 2:1 slope.

This degree of conservatism was fully justified for the dune sand bluffs because of their quick response to erosion and potential bias of the empirical erosion rate data to low values owing to beach accretion during the time of erosion rate determinations.

Another major source of uncertainty was predicting the size of single slide block failures that could break off from a coastal bluff. Empirical data was gathered from Tillamook and Lincoln County on maximum block failure width, but it was clear that some blocks might actually be fragments of earlier larger blocks, whereas other large intact slide blocks may have undergone unknown amounts of wave erosion. Both factors tended to bias the data to smaller block failures. Hence, the approach of using the largest maximum observed block failure width to predict the "worst case" extent of bluff retreat seems justified. A series of empirical equations and locally derived maximum block failure widths guided the use of this data in drawing the bluff hazard zones. While block width did increase with bluff height, it did so in complex ways, apparently increasing to hundreds of feet where some threshold bluff height was reached that varied from about 150-160 feet for bluffs with Pleistocene to Holocene soil at the base, to ~70-80 feet for bluffs with seaward-dipping Tertiary sedimentary rocks. Inserting this factor into the worst-case hazard zone calculation enabled the width of the low hazard zone to be determined, the portion of the width dependent on gradual erosion being insignificant.

The user is cautioned that empirical equations correlating bluff height to maximum block failure width have significant uncertainties, particularly for bluffs prone to failure from weak Pleistocene soil at the base. The observations for bluffs with clay-rich Pleistocene soil are tentative, because of the unknown effect of paleotopography on hard rock underlying the soil where the data was collected.

RECOMMENDATIONS

Available time and support for this project was insufficient to provide an accurate assessment of erosion rates along the bluffed shorelines of Tillamook County. Those few erosion rate estimates presented in this report are based on local "rates-of-opportunity" and were derived from features that could be easily relocated on more recent aerial photos. To overcome this deficiency, it is recommended that additional work be directed towards ortho-rectifying[3] a number of historic aerial photographs. For example, this approach would enable the bluff top or landslide headwall positions to be accurately mapped over periods of decades to a century. Tracking bluff changes continuously along the length of littoral cells could reveal significant variation in erosion rates,

[3] Ortho-rectification means removing distortions from the photo, so it can be used as an accurate map of the features that it depicts.

which may be a function of bluff-toe protection provided by the fronting beach and dune systems, or a function of variations in rock strength. Generation of accurate erosion rates for all bluffed shorelines should be the highest priority for refinement of the hazard zones presented in this report.

Ortho-rectification of historical photography would also enhance our understanding of the temporal and morphological response of beaches and dunes in Tillamook County. This information, when added to available historical shorelines from topographic maps, would provide additional historical perspective improving our ability to better predict future beach and dune evolution.

Monitoring shoreline and bluff changes in the future is particularly critical for two reasons. Perhaps most importantly, regular monitoring can provide early warning of shoreline and slope stability 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.

Mapping of previous erosion cuts resulting from coseismic subsidence from Cascadia subduction zone earthquakes would give a ground truth check on the cuts predicted by the geometric model. Ground penetrating radar coupled with radiocarbon and other dating techniques would help delineate these pre-historic erosion events.

Analysis and monitoring of offshore bathymetry is essential for tracking large-scale sand movement. These data when combined with the acquisition of measured beach and shoreline data would allow more sophisticated and accurate modeling of each littoral system. The ultimate effect of these refinements would be to decrease the amount of uncertainty and probably the width of the predictive hazard zones.

Finally, more detailed analysis of mapped debris flows and landslides is needed. Of particular interest are prehistoric, potentially active, and queried potentially active landslides fringing active landslides. These features may harbor active zones of mass movement not identified by the reconnaissance mapping of this investigation. Of the active landsides, detailed geotechnical analyses of the Three Capes Loop and Cape Meares landslides should have some priority, owing to their importance to the coastal highway system and lifelines. In particular, it would be wise to undertake a detailed examination of areas upslope of the prehistoric debris flow fan at Garibaldi to determine whether houses on this feature, particularly some built directly over the stream drainage channels, are vulnerable to rapidly moving debris flows.

ACKNOWLEDGMENTS

This investigation was supported by a professional services agreement with Tillamook County and from resources of the State of Oregon Department of Geology and Mineral Industries (DOGAMI). County funds were derived from the Project Impact program of the Federal Emergency Management Agency. The project was greatly facilitated by the Netarts Littoral Cell Management Planning Project supported by the Oregon Department of Land Conservation and Development, Oregon Parks and Recreation Division, and Tillamook County. We are especially grateful to John Beaulieu (Director of DOGAMI), Dennis Olmstead (Deputy State Geologist), Zhenming Wang (acting Earthquake Program Director for DOGAMI), Paul Komar (Oregon State University), John Marra (Department of Land Conservation and Development), Richard Rinne (Hart Crowser, Inc), and Doug Gless (H.G. Schlicker & Associates, Inc), for their insightful comments on this report. Thanks must also be extended to Randy Dana, Department of Land Conservation and Development, for his help in collating the NOS T-sheets, Chris Chickadel, Oregon State University, for helping out with the ARGUS photographic data, and James Good, Oregon State University, who offered helpful advice early on in the project. We are also extremely grateful to Stuart Albright of Hart Crowser, Inc. for sending invaluable geotechnical data from The Capes project. Eileen Hemphill-Halley of the US Geological Survey and University of Oregon kindly provided data analyses of diatoms present in Quaternary deposits of The Capes landslide.

REFERENCES CITED

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

Allan, J.C. and Komar, P.D., 2000b, Are ocean wave heights increasing in the eastern North Pacific?, EOS, American Geophysical Union.

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

Atwater, B.F., and Hemphill-Haley, E., 1996, Preliminary estimates of recurrence intervals for great earthquakes of the past 3500 year at northeastern Willapa Bay, Washington: U.S. Geological Survey Open-File Report 96-001, 87 p.

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

Benumof, B.T., and Griggs, G.B., 1999, The dependence of sea cliff erosion rates on cliff material properties and physical processes: Shore & Beach, v. 67, no. 4, 29-41.

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

Darienzo, M.E., and Peterson, C.D., 1995, Magnitude and frequency of subduction zone earthquakes along the northern Oregon coast in the past 3,000 years: Oregon Geology, v. 57, no. 1, 3-12.

Dolan, R., Hayden, B.P., May, P., and May, S., 1980, The reliability of shoreline change measurements from aerial photographs, Shore and Beach, 48(4), 22-29.

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

Geomatrix Consultants, 1995, 2.0, Seismic source characterization, in Geomatrix Consultants, Seismic design mapping, State of Oregon: Final Report prepared for Oregon Department of Transportation, Project No. 2442, p. 2-1 to 2-153.

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

Gorman, L., Morang, A., and Larson, R., 1998, Monitoring the coastal environment; Part IV: Mapping, shoreline changes and bathymetric analysis, Journal of Coastal Reseahc, 14(1), 61-92.

Graham, N.E., and Diaz, H.F., 2001, Evidence for intensification of North Pacific Winter Cyclones since 1948, Bulletin of the American Meteorological Society, v. 82, 1869-1893.

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

JISAO/SMA Climate Impacts Group, 1999, Impacts of climate variability and change in the Pacific Northwest, Unpublished report to the Pacific Northwest Regional Assessment Group, and the U.S. Global Change Research Program, 109p, November 1999.

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

Komar, P.D., 1986, The 1982-83 El Niño and erosion on the coast of Oregon, Shore & Beach, v. 54, 3-12.

Komar, P.D., 1997, The Pacific Northwest Coast: Living with the Shores of Oregon and Washington: Duke University Press, 199p.

Komar, P.D., Lizarraga-Arciniega, J.R., and Terich, T.A., 1976, Oregon coast shoreline changes due to jetties, Journal of the Waterways Harbors and Coastal Engineering Division, American Society of Civil Engineers, Vol. 102 (WW1), 13-30.

Komar, P.D., Good, J.W., and Shih, S.M., 1989, Erosion of Netarts Spit, Oregon: continued impacts of the 1982-83 El Niño: Shore and Beach, v.57, no. 1, p. 11-19.

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

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

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

Kroeger, E.B., 2000, The effects of water on planar features in compound slopes: Environmental & Engineering Geoscience, v. VI, no. 4, p. 347-351.

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

Merriman, T., and Wiggin, T.H., 1947, Civil engineers' handbook: New York, N.Y., John Wiley & Sons, p892.

Moore, L.J., 2000, Shoreline mapping techniques, Journal of Coastal Research, 16(1), 111-124.

Niem, A.R., and Niem, W.A., 1985, Oil and gas investigation of the Astoria Basin, Clatsop and Northenmost Tillamok Counties, Northwest Oregon: Oregon Department of Geology and Mineral Industries, OGI-14, 1:100,000-scale map.

Peterson, C.D., Barnett, E.T., Briggs, G.G., Carver, G.A., Clague, J.C., and Darienzo, M.E., 1997, Estimates of coastal subsidence from great earthquakes in the Cascadia subduction zone, Vancouver Island, B.C., Washington, Oregon, and Northernmost California, State of Oregon Department of Geology and Mineral Industries Open-File Report O-97-5, 255-269.

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

Priest, G.R, Saul, I., and Diebenow, J., 1994, Explanation of chronic geologic hazard maps and erosion rate database, coastal Lincoln County, Oregon: Salmon River to Seal Rocks: Oregon Department of Geology and Mineral Industries, Open-File Report O-94-11, 45p.

Priest, G.R., 1997, Chronic geologic hazard map of the Newport area, coastal Lincoln County, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-97-10, 1:4800 scale.

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

Priest, G.R, Saul, I., and Diebenow, J., 1997a, Chronic geologic hazard map of the Moolack-Agate Beach area: Oregon Department of Geology and Mineral Industries Open-File Report O-97-9, map at 1:4800 scale.

Priest, G.R, Saul, I., and Diebenow, J., 1997b, Chronic geologic hazard map of the Newport area: Oregon Department of Geology and Mineral Industries Open-File Report O-97-10, map at 1:4800 scale.

Revell, D.L., Komar, P.D., and Sallenger, A.H., in press, An application of LIDAR to analyses of El Niño erosion in the Netarts littoral cell, Oregon, Journal of Coastal Research.

Rinne, R.W., 2000, The Capes Homeowners Association slope regression study, Oceanside, Oregon: unpublished geotechnical report prepared for The Capes Homeowner's Association by Hart Crowser, Inc., 26p.

Ruggiero, P., and Voigt, B., 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, 113p.

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

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

Schlicker, H. G., Deacon, R.J., Beaulieu, J.D., and Olcott, G.W., 1972, Environmental geology of the coastal region of Tillamook and Clatsop Counties, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 74, 164p., 18 maps.

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

Shoreland Solutions, 1994, Appraisal of chronic hazard alleviation techniques, with special reference to the Oregon coast, Unpublished report to the Department of Land Conservation and Development, 112p.

Shoreland Solutions, 1998a, Chronic coastal natural hazards model overlay zone, Unpublished report to the Department of Land Conservation and Development, 43p.

Shoreland Solutions, 1998b, Pacific City foredune management plan, Unpublished report to the Pacific City Beachfront Homeowners Association, 58p.

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

Terich, T.A., and Komar, P.D., 1974, Bayocean Spit, Oregon: History of development and erosional destruction, Shore and Beach, Vol. 42, 3-10.

United States Geological Survey, 2000, http://www.csc.noaa.gov/crs/tcm/index.html

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

Wells, R.E., Snavely, P.D., Jr., MacLeod, N.S., Kelly, M.M., and Parker, M.J., 1994, Geologic map of the Tillamook Highlands, northwest Oregon Coast Range: US Geological Survey Open-File Report 94-21, 1:62,500 scale maps and original digital files.

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

APPENDIX A

EPISODIC VERSUS GRADUAL COASTAL BLUFF EROSION

If erosion is strictly gradual, with small bits of rock or soil eroding away in about the same amounts every year, then measured erosion rates can be used with great confidence to predict where the bluff edge will be in the future. Unfortunately, erosion is seldom that gradual. Bluffs tend to erode in chunks or blocks of varying size. Wave erosion itself is highly episodic, with large amounts of erosion occurring during particularly severe storms.

Whether bluff erosion is gradual or highly episodic, is very much dependent on whether a particular bluff is prone to small or large block failures. If very small blocks (<10 ft) are the general mode of bluff failure, then erosion appears to be a more gradual process with the occurrence of numerous failure events per 60-100 years for all but the hardest rocks. Obviously low bluffs (<10 ft high) can only result in small block failures, whereas higher bluffs may or may not erode by failure of larger blocks. If medium-size (10-50 ft) blocks sometimes slide, then erosion appears to be more episodic with a few of these larger events occurring in a 60 or 100-year time frame. If the bluff is subject to failure of large blocks (>50 ft wide), then erosion appears to be highly episodic with probably only 1 or (at most) 2 events occurring over a 60-100 year time frame, even though smaller block failures may also be occurring in the intervening years. In some cases, depending on the geology, a maximum block failure may require a highly unusual event such as an earthquake or sustained periods of extreme rainfall to trigger a failure. The latter type of bluff failure generally involves large deeply penetrating bedrock landslides.

Once a large block (or blocks) slides down in front of the bluff, it will protect it from further wave erosion and may buttress it for many years; in this case only minor retreat of the headwall of the landslide will occur. However, if the slide continues to actively move seaward, then the buttressing effect is removed and new block failures of various widths can occur as fissures open up and material slides into them. If the headwall is composed of highly unstable soil, then small sloughing events will happen very soon after each forward movement of the active block. If the headwall is composed of harder rock, then there may be a prolonged period of time before anything happens to the headwall, even with active seaward movement of the block. Therefore, wave erosion at the toe of the slide debris in front of hard rock bluffs can be nearly decoupled from erosion at the headwall. Conversely, in soft soil bluffs, such as The Capes landslide, where wave erosion of the landslide toe causes seaward slide movement (see Appendix D), sloughing of the headwall is very closely coupled to erosion at the landslide toe.

Significant (=~60 ft high) bluffs composed of seaward-inclined mudstone, siltstone, and sandstone are an example of bluffs prone to deep bedrock slides. Large slide blocks (hundreds of feet wide) may begin to move long before previous blocks have been removed by wave erosion. This movement is generally quite slow, taking decades for lateral and vertical displacements of a few feet, but eventually the block will break up and cause total loss of property. The Jumpoff Joe landslide (Appendix D), and Schooner Creek landslide (Figure A1) of Lincoln County are examples.

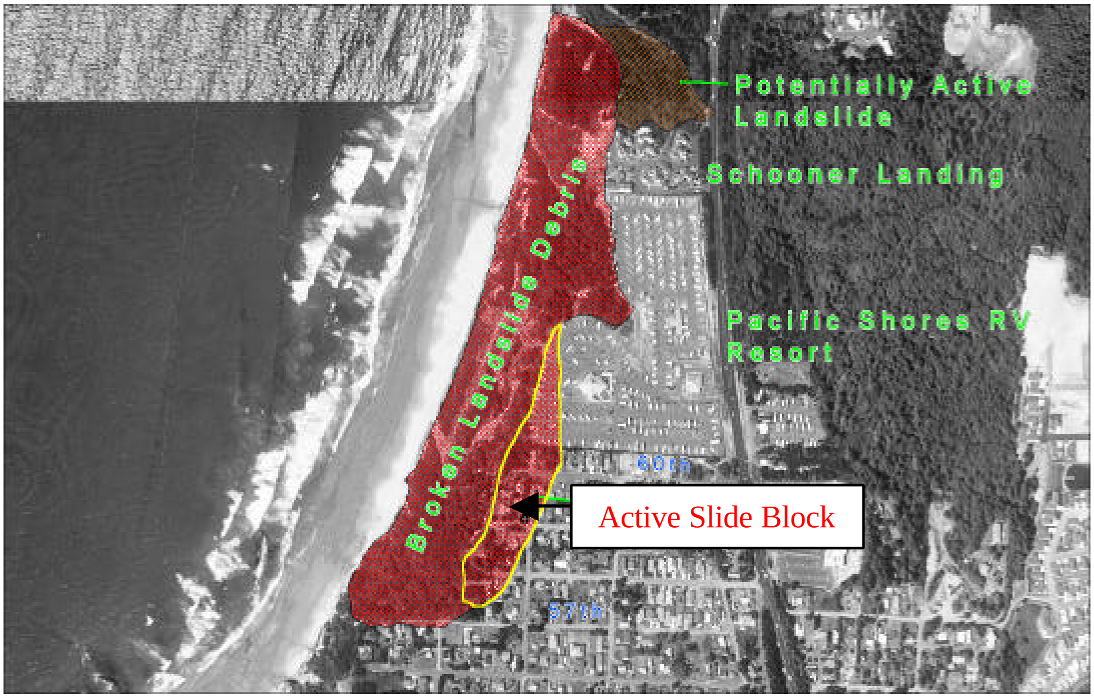


Figure A 1 Schooner Creek landslide of Newport, Oregon showing an active slide block that has begun to displace city streets over the last few decades but has only a few feet of lateral and vertical displacement. Meanwhile, the broken landslide debris in front of this block continues to move seaward in response to wave erosion and high groundwater, opening up fissures in front of the block. Movement on the active block has apparently ceased from about May of 2000 to present (June, 2001). This period has been characterized by unusually low rainfall on the Oregon coast.

The bottom line is that the bluffed coastline will, overall, retreat at some regionally slow rate in response to sea level rise, wave strike (local storminess, etc.), and rock hardness, even though some bluffs may retreat in bigger chunks than others. It may therefore take a millennium to see the long-term retreat rate of bluffs subject to large, rare block failures. This factor causes most analyses of bluff retreat rate on large landslide-prone bluffs to be inaccurate, because the observation times are too short, generally less than 100 years. In the present study the maximum observation time for most areas is about 55 years, the age difference between 1939 aerial photos of the US Army Corps of Engineers, and the 1994 DOQ's of the US Geological Survey.

At the other extreme are Holocene sand bluffs subject to mostly small (=24 ft) sloughing failures. These bluffs respond very quickly to wave erosion and are likely to be in approximate equilibrium with it. Analysis of bluff retreat over relatively small (~50 year) time periods may yield fairly reliable long-term erosion rates on these and other bluffs composed of moderately to poorly consolidated soils.

Somewhere in the middle, in terms of uncertainty for erosion rate determination, are low (<30 foot) bluffs of rock. These bluffs generally erode gradually, because they are too low to break off in large blocks either by sliding or toppling. Because of their hardness, they erode relatively slowly, so they tend to recede mainly when major storms produce vigorous wave attack. This produces a more episodic pattern of erosion than the soft soil bluffs. The harder and less fractured the rock, the slower it will erode and the longer it will take to get a reasonable idea of its overall erosion rate.

These interpretations and observations are consistent with the fairly smooth coastline of Oregon, which really shows major deviations only at headlands composed of hard, crystalline rocks such as basalt. In these areas erosion rates are likely to be negligible over 50-100 years. For example, comparisons of the 1868 topographic map of Yaquina Head with present-day maps and photos reveals many fine-scale topographic features that have persisted at the shoreline without obvious modification for 133 years.

APPENDIX B

EXPLANATION OF SPOT EROSION RATE DATABASE

Introduction

Erosion of a coast reflects the landward recession of the shore relative to some known datum point (indicated as negative rates in feet per year), while accretion characterizes the seaward progradation or advance of a shore (characterized by positive rates in feet per year). Most rates are referenced from the top of the bluff or sea cliff, but a few rate estimates are for the bluff toe; this is explained in the description data field of the digital database. A seaward moving landslide toe can maintain a constant shoreline position, even as waves remove material; hence, erosion rates for active or potentially active sea cliff landslides and slide blocks are for the headwall (top edge of the stable bluff behind the landslide or slide block). Only three headwall rates are listed; two are located at the small landslide at Crab Avenue in Netarts, and one is at the headwall of The Capes landslide. The lateral change of headwall position in both cases indicates that erosion was from quite small sloughing of the headwall. Owing to lack of data, no rate of erosion is estimated for the headwalls of prehistoric landslides or slide blocks.

All of the erosion rate estimates presented in this database appear to represent gradual erosion of the bluff by relatively small amounts. No evidence was found of bluff retreat associated with the failure of large (=40 foot) blocks. This suggests that most of the erosion data for coastal bluffs in Tillamook County was from minor sloughing and weathering.

Location of the spot erosion rates is generally referenced to some local feature such as a house or road intersection that was used to track the location of the bluff edge from photo to photo. The measurement was taken in an east-west line from this point to the coastline (i.e. perpendicular to the coast).

Landslide Erosion Rates

Because many deeply penetrating landslides and slide blocks move in discreet episodes separated by long periods with little or no erosion, generalized rates in these areas should be determined by tracking the headwall position over a 100 years or more. Since the observation time was limited to the 55 years between 1939 and 1994 photos, truly accurate measurements of headwall retreat rates are not possible. Nevertheless, positional changes that could be measured are summarized in the database. The only places where such retreat could be measured had headwall changes that were the product of gradual sloughing of the headwall rather than as major block failures. Observations of the historical photos were also consistent with this hypothesis. For example, extensive evidence of shallow sloughing of the Pleistocene dune sand could be identified from photos of the headwall at The Capes landslide.

Erosion Rate Calculation

Erosion rates were estimated in most bluffed areas by comparing modern and historical house-to-bluff distances. The modern distance was measured with MAPINFO geographic information system (GIS) software utilizing the 1994 DOQ's of the US Geological Survey. In most cases the historical distance was taken from 1967 vertical air photos of the Oregon Department of Transportation. In a number of cases, distances were measured where a recognizable feature had persisted since the 1939 photos of the U.S. Army Corps of Engineers. Corrections for radial and other photographic distortions on the 1967 and 1939 photos were determined by estimating the photo scale near the point of interest, by measuring (in GIS) the distance between features that persisted from 1967 or 1939 to the time of the 1994 DOQ.

Error

The error listed for each measurement was calculated by taking the root mean square of errors. Errors are as follows:

1. Uncertainty in measurement from resolution of the DOQ was generally about 10 feet, when checked against known house dimensions relative to linear measurements at the maximum (zoomed) scale in GIS view(s).
2. Uncertainty in hand measurements utilizing a 20th inch engineer's scale on the 1939 and 1967 photographs. This error was about 0.01 inches (0.2 ^{20ths} inch). At the photo scales of about 1 inch = 900 to 1000 feet for the 1939 photos and 1 inch = 500 feet for the 1967 photos, these errors translate to about 10 feet and 5 feet on the ground, respectively.
3. Uncertainty from radial and other photographic distortion of the 1939 and 1967 photos was not directly measurable except as variance among three trial measurements of photo scale in each case. The one sigma (68 % confidence) error among these measurements was taken as a proxy for this source of error. The relatively large scale of these two sets of photos decreased the potential error from this source (see explanation of scale dependence in Moore, 2000). Error from this source averaged about 33 feet for the1939 air photos and about 18 feet for the 1967 photos.
4. The positional data derived from the 1998 LIDAR data was assumed to have negligible horizontal error (± 2.6 ft).

The error listed for each erosion rate is the root mean square of the above errors divided by the time interval used for the measurement. The mean measurement errors for erosion rates for various time intervals are summarized in Table B1.

Table B 1 Mean measurement errors for erosion rates for various years.

Time interval	*1939-1967*	*1939-1994*	*1939-1998*	*1967-1994*	*1967-1998*	*1994-1998*
Mean error (ft/yr)	0.59	0.60	0.15	0.47	0.14	2.57

As might be expected, the longer the time interval between measurements, the smaller the error. Similarly, the smaller the individual measurement errors the smaller the error. These two factors combine to make the 1939 to 1998, and 1967 to 1998 the most precise measurement intervals. The same factors combine to make the 1994-1998 interval the least precise. Data from that interval were not used in this study.

Long-term Shoreline Erosion Rates

The spot erosion rate data presented here does not necessarily represent the rate of long-term shoreline change in the future. The rates simply show what has happened at selected sites for the intervals indicated. In some cases the long-term shoreline change rate can be roughly inferred from analysis of the other geological and observational data. For example, relatively high rates of erosion occurred at the town of Cape Meares after construction of jetties at the mouth of

Tillamook Bay (see section on Tillamook County Historical Shoreline Positions). Nevertheless, modern-day rates of erosion appear to be negligible, suggesting that the littoral system nay have reached a quasi-equilibrium state since the jetties were constructed. Likewise, there are several zero rate measurements for basalt and sandstone bluffs. This does not mean that these bluffs do not erode, only that the time interval of the observation is too short to measure the erosion. At the other extreme are spot erosion rates of 2 or more feet per year for a few sites on dune-backed shorelines; again, this does not necessarily mean that the shorelines continue to respond in the same manner (i.e. in the directions and at the rates indicated). Dune-backed shorelines fluctuate back and forth by large amounts on an annual or inter-annual basis in response to storms and cyclic changes in patterns of longshore drift. The listed rates are simply “snap shots” of the positional change between historical photos.

Areas with shoreline protection structures (rip rap, sea walls, etc.) probably have erosion rates near zero until the structures fail (see maps for location of these structures), but the detailed engineering analysis needed to predict the likelihood of failure was beyond the scope of this study. No rates are estimated in these areas.

The most important control on coastal bluff erosion rate is the material properties (Benumof and Griggs, 1999), provided the waves have access to the bluff. If waves do not have access to the bluff (e.g. the bluff is protected by dunes), bluff retreat will progress slowly in response to subaerial weathering. No rates were measured for dune-protected bluffs. Hence, all the erosion rates measured in this report are governed by material properties of bluffs under open coastal wave attack. Table B2 summarizes the bluff erosion rates based on the bluff composition. Rates were correlated to rock and soil type in the lower bluff face based on field observations and from the geologic maps of Schlicker and others (1972), Niem and Niem (1985), and Wells and others (1994). Preferred rates for the main bluff compositions are shown underlined in bold in the table. Preference was given to mean rates with the least measurement error and with at least 6 spot measurements.

As shown in Table B2, basalt and resistant sandstone erode at a rate of 0.05 ±0.16 ft/yr and 0.08 ±0.15 ft/yr respectively. These rates are so slow that they are at or below the measurement error (<0.2 ft/yr). Tertiary sedimentary rocks composed of interbedded siltstone, claystone, and sandstone erode at 0.19 ±0.25 ft/year, while softer Quaternary sediments erode at 0.25 ±0.24 ft/yr. Although there is some suggestion that softer materials erode faster, in reality all rates for all rock types are the same within the variance and measurement errors. The analysis of historical shoreline data summarized previously suggested that episodes of beach accretion occurred on the coast during the main observation interval, 1967 to 1994, making it likely that the rates are biased to some extent toward low values.

Comparison of Long-term Shoreline Change in Lincoln County

The erosion rates listed here are similar to those from Lincoln County. In Lincoln County, Priest (1999) found that the Tertiary sedimentary rocks eroded gradually in areas without deep bedrock landslides at a rate of ~0.26 ft/yr (8 cm/yr). Bluffs with Quaternary deposits such as Pleistocene marine terrace sands, eroded at about the same rate, if fronted by wide dissipative fine sand beaches like most of Tillamook County coastline. Higher rates of erosion (0.6 ft/yr) were found where narrow coarse sand beaches fronted the bluffs of Pleistocene marine terrace sands.

High erosion rates (0.9-1.6 ft/yr) were also found in Lincoln County for bluffs composed of Tertiary sedimentary rocks subject to deep-seated bedrock landslides (Priest, 1999). Calculation of rates for these bluffs required use of an 1868 topographic map to obtain a long enough observation period to capture enough large (80-300 foot) slide block events to provide a meaningful estimate of long term erosion. Such old maps are not available for this investigation. The only bluffs of this type can be found at the Three Capes Loop landslide near Tierra del Mar, north Manzanita, and Smuggler Cove (south of Cape Falcon). Aside from internal failures within the landslides in these areas, headwall retreat was not measurable since the 1939 aerial photography. It is not clear that the high rates of headwall retreat measured in Lincoln County can be applied to Tillamook County. The sensitivity of rates of headwall retreat to the occurrence of even one maximum slide block failure during the observation time makes even the Lincoln County rates difficult to interpret. Use of such rates to predict headwall retreat can be very misleading, especially in the context of land use planning decisions (Priest, 1999).

Table B 2 Erosion rate data for bluffs of Tillamook County with most precise data shown in underlined in bold. ± σ = one standard deviation, or the error at 68 percent confidence based on the scatter of rate measurements from the mean rate for each rock type. The number of spot measurements used for each mean is also given. Error = mean of root mean square measurement errors for individual measurements. Sed. Rocks = Tertiary sedimentary rocks, consisting of interbedded sandstone, siltstone, and mudstone. Quat. Dep. = Quaternary (Pleistocene to Holocene) deposits of dune sand, colluvium, ancient landslides, and alluvium showing slight to moderate consolidation; No. = number of spot erosion measurements; n.d. = no data.

Rock Type	*1939 to 1967 (ft/yr)*	*1939 to 1994 (ft/yr)*	*1939 to 1998 (ft/yr)*	*1967 to 1994 (ft/yr)*	*1967 to 1998 (ft/yr)*
Basalt	-0.05	-0.01	0.00	-0.13	0.10
± Sigma (ft/yr)	0.11	0.02	n.d.	0.23	n.d.
± Meas. Error (ft/yr)	0.16	0.27	0.12	0.28	0.11
Number of Samples	6	6	1	10	1
Sandstone	-0.19	-0.14	-0.13	-0.09	-0.08
± Sigma (ft/yr)	0.25	0.15	0.14	0.12	0.10
± Meas. Error (ft/yr)	0.69	0.29	0.11	0.24	0.15
Number of Samples	12	12	12	12	12
Sed. Rocks	n.d.	n.d.	n.d.	-0.21	-0.19
± Sigma (ft/yr)	n.d.	n.d.	n.d.	0.28	0.25
± Meas. Error (ft/yr)	n.d.	n.d.	n.d.	0.24	0.09
Number of Samples	n.d.	n.d.	n.d.	10	10
Quat. Dep.	-0.3	-0.36	n.d.	-0.25	-0.33
± Sigma (ft/yr)	0.15	0.49	n.d.	0.24	0.41
± Meas. Error (ft/yr)	0.28	0.35	n.d.	0.26	0.28
Number of Samples	2	2	n.d.	12	2

There were no bluffs in Lincoln County that are an exact geologic analogue to the bluff at the The Capes area near Oceanside. The bluff there is composed of ~100 feet of dune sand sitting on top of weak Pleistocene colluvial, alluvial, paleosol, and debris flow deposits that cause failure of slide blocks as much as ~350-ft wide. Drilling in the headwall of the landslide revealed basalt and dense basalt colluvium at elevations of 57 to 66 feet. Hence, it is unlikely that the gradual erosion rate of 0.41 ft/yr measured from topographic data of 1939 to 1998 will continue once the bluff top reaches the angle of repose for the capping section of Pleistocene to Holocene dune sand (Rinne, 2000). Retreat of the headwall could, however, occur through landslide processes, but this is not well understood at present.

The only area with erosion rate data for resistant sandstone in the Lincoln County study was a sandstone headland at the community of Otter Rock. For this area Priest and others (1994) list a spot erosion rate of 0.09 ft/yr with no estimate of the error. This low rate is similar to that found in Tillamook County.

In Lincoln County basalt bluffs had erosion rates not significantly different from zero for observation times up to 122 years (Priest, 1999). Similar insignificant erosion was noted in Tillamook County, although observation times were really inadequate to measure basalt erosion.

Recommended Erosion Rates for Bluffs in Tillamook County

All of the bluff erosion data appear to represent gradual erosion free of episodes of retreat from deep bedrock sliding. None of lateral retreat distances were large enough to indicate that blocks =40 feet failed. This allows the rates to be used as reasonable estimates of gradual wave erosion independent of the effect of large block failures. The effect of block failures is treated in the Appendix C.

Table B3 summarizes rates that will be used for this investigation. These rates are the preferred rates from Table B2 rounded to appropriate significant figures. For more conservative calculations, a maximum error is added to the mean. The maximum error is the larger of the two sources of uncertainty, the mean value of measurement error (mean of the root mean square of scaling errors, field errors, etc. for all. measurements) or the one sigma error (variance in the spot rate data set).

Table B 3 Erosion rates assumed for coastal erosion hazard calculations in Tillamook County for bluffs exposed to open coastal wave erosion. The conservative rate is the mean rate plus the estimated error, either mean measurement error, or the one sigma error for the variance of the measurements from the mean, whichever is greater. The values in parentheses have an additional safety factor of 2 to cover uncertainties in estimation of erosion rate for soft soil and sand bluffs. The values in parentheses will be used for Quaternary deposits. See Appendix B for explanation of how the rates were determined.

Rock Type	*Estimated Mean Erosion rate (ft/yr)*	*Conservative Erosion Rate (ft/yr)*
Basalt	0.1	0.2
Resistant sandstone	0.1	0.2
Interbedded sandstone/siltstone/claystone	0.2	0.4
Quaternary deposits	0.25 (0.5)	0.5 (1.0)

APPENDIX C
BLOCK FAILURE WIDTH DATA

Objectives

The objective was to determine how much of a bluff might fail in a single landslide or rock fall event. In general the measured block failure widths apply best to the local area where the measurement was made. Nevertheless, geologic analysis of the data can yield useful insights into the likely block failure widths on bluffs with geology similar to areas where the data was generated. Maximum block failure width is particularly useful for estimating the “worst case” hazard scenarios where gradual erosion, as measured in Appendix B, is accompanied by block failures.

Most of the larger landslides in Tillamook and Lincoln County appear to be translational failures, whereby blocks break away from the bluff face and move laterally with little backward rotation of the block. In theory the width of any individual block should correlate with bluff height (e.g. Kroeger, 2000). The empirical analysis here shows that this is in general true, especially for failures in bluffs with weak Pleistocene to Holocene soil at the base. It may well be true as well for the other major source of large slides, seaward-dipping, fine-grained Tertiary sedimentary rocks. However, the empirical data for the combined Lincoln and Tillamook County show that it may not be a simple linear relationship. Instead, there appears to be a threshold of bluff height, above which large block failures hundreds of feet wide are possible and below which only shallow sloughing and rock falls occurs.

Method of Measurement of Block Failure Width

Block widths were measured on 1939 and 1967 aerial photos, 1994 DOQ’s, and in the field. Landslide widths were measured from the base of the headwall of the landslide to the projected outer top edge of each block. Where rock fall was the dominant mode of failure, as on most of the basalt and resistant sandstone bluffs, maximum single failure widths were estimated from what appeared to be fresh cliff failures that produced crescent-shaped reentrants in the cliff top or from blocks identified at the bluff toe. The largest uncertainties were:

1. Erosion that may have decreased the width
2. Fragmentation of the block after initial failure at some unknown time in the past

Listed error is estimated uncertainty from scaling the width from the aerial photo or digital orthophoto quadrangle and geographic information software. In a few cases where the outer edge of the block was hard to define, the amount of error was visually estimated and added to other sources of uncertainty.

Results

Table C1 summarizes the data sorted first by rock type and second by block failure width. Also shown is the geographic area of the measurement, the identification number in the database, and geologic unit symbols (basal unit first) from standard geologic maps. The height of the failed bluff is indicated by the headwall height. All Tertiary sedimentary rock sites in the database hve beds dipping toward the ocean and bedding strike sub-parallel (=~18°) to the bluff strike.

Table C 1 Coastal slide block failure widths for Tillamook County.

ID	Geographic area	Slide block Width (ft)	Error (ft)	Headwall Height (ft)	Geological Unit	Failed rock/soil
34	N. of Daley Lake	39	5	140	Talbs	Basaltic sandstone
14	N. Side Maxwell Point	8	5	200	Tgr	basalt
13	N. Side Maxwell Point	14	5	200	Tgr	basalt
22	N. side, Cape Falcon	46	5	200	Tgr	basalt
7	Cape Meares S. side	47	57	280	Tgr	basalt
3	Cape Meares S. side	51	23	280	Tgr	basalt
2	Cape Meares S. side	69	23	280	Tgr	basalt
9	Cape Meares S. side	92	23	120	Tgr	basalt
11	Cape Meares S. side	92	23	120	Tgr	basalt
12	Cape Meares S. side	92	23	120	Tgr	basalt
6	Cape Meares S. side	179	57	280	Tgr	basalt
5	Cape Meares S. side	189	47	280	Tgr	basalt
10	Cape Meares S. side	235	34	120	Tgr	basalt
4	Cape Meares S. side	368	299	280	Tgr	basalt
8	Cape Meares S. side	471	236	280	Tgr	basalt
35	Cape Lookout State Park	5	0.5	10	Qt	Pleistocene colluvial and alluvial deposits
36	Cape Lookout State Park	2	0.5	19	Qt	Pleistocene colluvial and alluvial deposits
19	Crab Avenue, Netarts	16	2	40	Qt	Pleistocene colluvial and alluvial deposits
20	Crab Avenue, Netarts	22	2	40	Qt	Pleistocene colluvial and alluvial deposits
16	The Capes landslide	24	2	200	Qb	Pleistocene to Holocene dune sand
18	Crab Avenue, Netarts	43	2	40	Qt	Pleistocene colluvial and alluvial deposits
17	Fall Creek, N. side	120	15	150	Qt + Qb	Pleistocene colluvial and alluvial deposits
21	Netarts, N. of marina	250	15	250	Qt + Qb	Pleistocene colluvial and alluvial deposits
15	The Capes landslide	350	5	200	Qt + Qb	Pleistocene colluvial and alluvial deposits
23	Cove Beach	87	5	80	Tsc2	Tertiary sedimentary rocks
28	S. of Tierra del Mar, N. buttressed slide	89	22	140	Toms	Tertiary sedimentary rocks
25	N. Manzanita	138	5	200	Tal + Taa	Tertiary sedimentary rocks
26	N. Manzanita	161	5	200	Tal + Taa	Tertiary sedimentary rocks
29	S. of Tierra del Mar, N. buttressed slide	175	25	140	Toms	Tertiary sedimentary rocks
30	S. of Tierra del Mar, Largest Slide	200	22	120	Toms	Tertiary sedimentary rocks
32	S. of Tierra del Mar, Largest Slide	200	20	120	Toms	Tertiary sedimentary rocks
31	S. of Tierra del Mar, Largest Slide	225	25	120	Toms	Tertiary sedimentary rocks
24	N. Manzanita	230	5	200	Tal + Taa	Tertiary sedimentary rocks
27	N. Manzanita	340	15	200	Tal + Taa	Tertiary sedimentary rocks
38	N. Manzanita	420	177	400	Tal + Taa	Tertiary sedimentary rocks
39	N. Manzanita	420	265	400	Tal + Taa	Tertiary sedimentary rocks
37	Smugglers Cove	442	221	320	Tsc2	Tertiary sedimentary rocks
1	Cape Meares Landslide	500	50	80	Als	Holocene active landslide deposits

Discussion

Basalt bluffs

Measurable block failures were absent from most basalt bluffs. Most of these bluffs had smooth cliff faces with rock fall material at the base. In a few instances such as the pocket beach immediately south of Cape Meares, a few large slide block failures occur. The largest of these was 471 feet wide on the 1939 aerial photo (measurement 8, Table C1). This block subsequently broke up into smaller blocks (measurements 2-7, Table C1). According to the geologic map of Wells and others (1994), this large slide block is bounded north and south by faults, which may explain its anomalous behavior relative to most other basalt bluffs. In this same pocket beach, but immediately south of the fault-bounded landslide, there are block failures up to 235 feet wide (numbers 9-12, Table C1). If the pocket beach immediately south of Cape Meares is disregarded, the maximum block failure width for basalt bluffs is ~39-49 feet; virtually all of these block widths were measured on bluffs greater than about 100 feet in height.

The rock fall scars at Maxwell Point, at 8-14 feet wide (numbers 13 and 14, Table C1), are probably evidence of the largest rock falls that can occur on most high (>100 foot bluffs) basalt bluffs in the County. On lower bluffs the maximum width of rock falls and topples are much smaller, approximating the joint maximum joint spacing of ~3-8 feet. It was beyond the scope of this study to discriminate between bluffs on the basis of joint spacing.

Tertiary sandstone

Sandstone bluffs at Cape Kiwanda and the basaltic sandstone bluff immediately north of Daley Lake appear to erode in the same way and at about the same rate as basalt bluffs (see Appendix B). No large, deeply penetrating landslides are apparent, even though bluff height is on the order of 80-160 feet. Debris on the beaches below these bluffs appears to be up to a few feet in diameter with one block estimated at ~39 feet in diameter on a 1967 aerial photo. These blocks are probably from rock fall or toppling. Sandstone, as long as it is free of weak interbeds of siltstone or claystone, appears to erode very gradually rather than episodically in large slide block failures.

Tertiary sedimentary rock with interbedded siltstone and claystone

Tertiary sedimentary rock composed of seaward dipping, interbedded siltstone, claystone and sandstone is prone to translational block slides with individual failures ranging from 87 to 340 feet wide (Table C1). The maximum block failure width is therefore similar to that for the same type of bluff in Lincoln County (Priest, 1999). The largest landslide in Tertiary sedimentary rocks is the Cape Meares landslide on the north side of Cape Meares. That slide has had so much down slope movement over such a large area that initial block failures have long since broken up into numerous smaller blocks, making block width measurements there useless. Large masses of the completely fragmented landslide sometimes fail coherently in horseshoe-shaped chunks up to 500 feet wide at the toe of the landslide (measurement 1, Table C1).

There is modest correlation (correlation coefficient of ~0.8 for a third order polynomial) between bluff height and maximum block failure width for bluffs composed of seaward dipping Tertiary sedimentary rocks (Figure C1). There is little correlation between bluff height and maximum block failure width for similar rocks in Lincoln County; there bluffs 70-160 feet in height have many block failures on the order of 300 feet wide (Figure C2). In central Lincoln County these rocks commonly form slide blocks up to 330 feet wide in bluffs as low as 80 feet; specific examples are the slide blocks at Mark Street and Jumpoff Joe (NW llth Street) in Newport (Priest, 1997). A similar maximum block failure width of 340 feet is found in Tillamook County just north of Manzanita , but in a bluff 200 feet high within a larger landslide. The larger landslide there failed from a headwall ~400 feet high where two block failures are ~420 feet wide. The combined Lincoln and Tillamook County data clearly suggest that the maximum block failure width for bluffs 60-200 feet high should be ~340 feet. For bluffs 300-400 feet in height, the maximum block failure width of Table C1, 442 feet, is appropriately conservative. Since there is no data, a linear extrapolation between these two widths (maximum block failure width = (bluff height + 200)/1.1765) is probably adequate for bluffs of intermediate height. These block failure widths are the most conservative values that can be extrapolated from the Tillamook and Lincoln County data.

Using the most conservative block failure widths is justified because of two major uncertainties:

1. Historical photography is generally inadequate to check whether smaller blocks are remnants of formerly larger blocks, now broken up by down slope movement.
2. The present block, if exposed to wave erosion, could have been reduced in width some unknown extent since it was emplaced.

Regarding bluffs lower than ~60 feet high and composed of seaward-dipping, fine-grained sedimentary rock, there was no local data to judge maximum block failure width. There are very few bluffs of this type on the Tillamook County coast, but observations of them in Lincoln County indicate that they erode gradually rather than by large block failures. Most block failures seen in these bluffs in Lincoln County are shallow sloughs on the order of 30-40 feet wide or less. However, there is currently no comprehensive database of these smaller block failures for the lower bluffs in Lincoln County. Clearly, the driving forces necessary to form large translational block slides reaches some kind of a threshold at ~60-70 feet of bluff height, unless the rocks are very weak. An examination of weak material such as Pleistocene sediments may shed some light on the worst case for failure of weak low Tertiary sedimentary rock bluffs. As explained below, the lower bluffs of Pleistocene sediment tend to form blocks according to the equation block width = bluff height/1.25. This method should yield appropriately conservative values for low Tertiary sedimentary rock bluffs as well.

Pleistocene to Holocene soil, alluvial, and colluvial deposits

Essentially all of the block slides in these units occur where clay-rich, weak, colluvial debris flow, and alluvial soils are in a significant (>1 m) amount of the bluff face and the bluff height is at least 40 feet high. These deposits are typically in paleo-valleys probably cut in the bluffs during the Pleistocene low stand of ~50,000 to 10,000 years ago. One sample of a rooted stump in silty clay paleosols at the base of The Capes Landslide yielded carbon-14 age of 38,900 ± 680 radiocarbon years before present (BP). A split of the same sample yielded an age of >47,070 BP[4]. Only fresh water diatoms were found in sediment above and below this paleosol, consistent with a low-sea-stand sequence. This soil sequence was subsequently buried by 100-200 feet of dune sand probably blown in shortly before and during the Wisconsin Ice Age and Holocene

[4] All carbon-14 dating is by Beta Analytic, Inc., University Branch, 4985 SW Court, Miami, Florida, 33155; dates are reported as radiocarbon years before present (RCYBP) with "present" defined as 1950 A.D. Modern reference standard was 95% of the C14 content of the National Bureau of Standards' Oxalic Acid & calculated using the Libby C14 half life (5568 years). Quoted errors represent 1 standard deviation statistics (68% probability) and are based on combined measurements of the sample, background, and modern reference standards. Measured C13/C12 ratios were calculated relative to the PDB-1 international standard and the RCYBP ages were normaized to –25 per mil. Quoted ages are not based on calendar years. Calibration to calendar years should be calculated using the conventional C14 age.

transgression. The soil sequence could not support the thick dune when coastal erosion driven by steadily rising sea level cut into the slope over the last several hundred years. A large landslide formed at some point, probably driven by the steep slope and possibly by earthquake shaking. This same sequence of events probably accounts for many of the landslides in Quaternary deposits elsewhere on the Oregon coast.

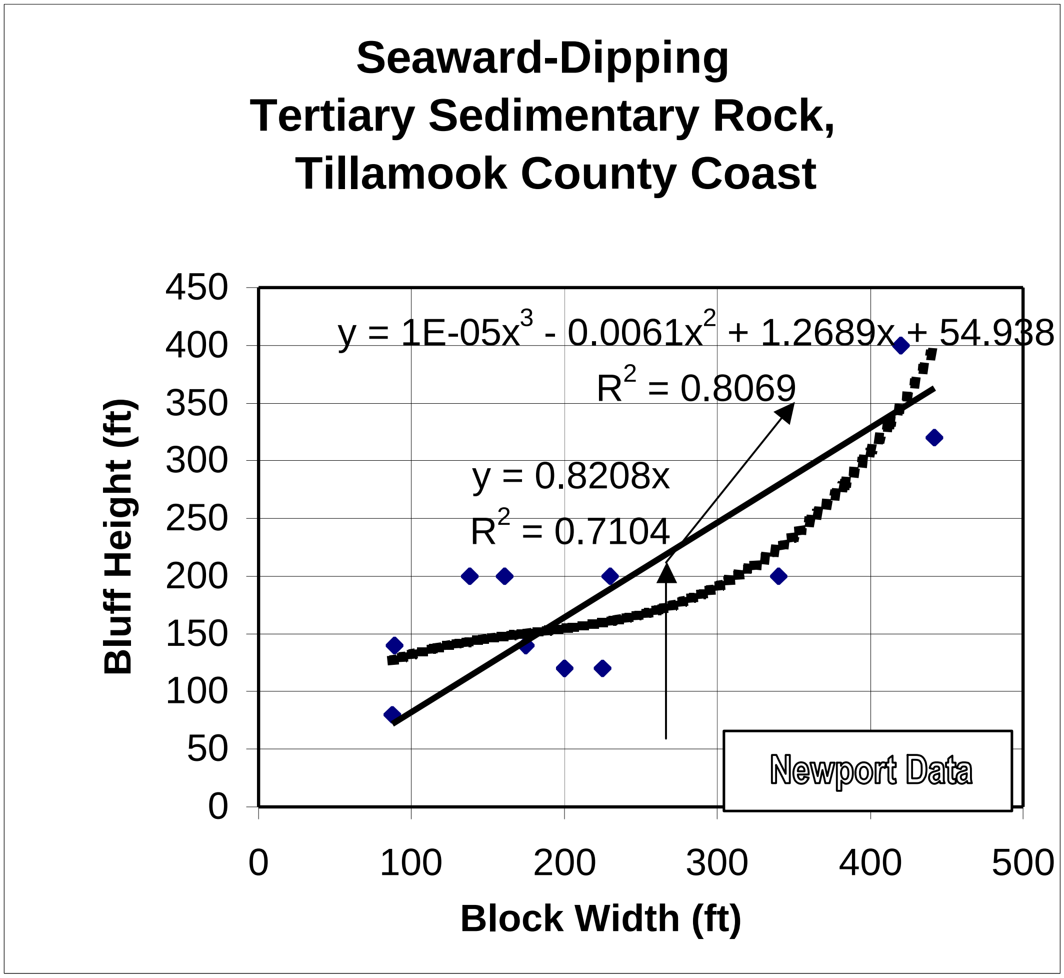


Figure C 1 Correlation of bluff height versus slide block width for seaward dipping Tertiary sedimentary rocks of coastal Tillamook County. Approximate range of values for the Newport-Beverly Beach area of Lincoln County (Figure C2) is shown by the bold rectangle. The third order polynomial regression (dashed line and upper equation) gives the best fit for predicting maximum block failure width for the Tillamook County data. The linear regression (solid line; lower equation) has a much poorer fit to the data. Arrows show most conservative interpretation (largest block width for a given bluff height) of the combined Newport and Tillamook data.

The youngest soils in partially consolidated clay-rich deposits yielded carbon-14 ages of 200 ± 60 and 560 ±50 radiocarbon years in two rooted tree stumps at Cape Lookout State Park near the north side of Cape Lookout. The younger stump lies in a soil overlying the older stump, which lies in the bluff face at the toe of the slope. These soils occur in bluffs only 10-15 feet high where only small, 2-5 chunks of the soil collapse when undercut by waves. All carbon-14 age data is summarized in Table C2.

Table C 2 Radiocarbon ages. Additional information is available on the digital database.

Field Number *(Laboratory Number)*	*Longitude*	*Latitude*	*Measured Age Radiocarbon years B.P.* *(error)*	*13C/12C Ratio*	*Conventional Age years B.P. Radiocarbon years* *(error)*
T-13 UPPER ROOT (Beta-137209)	-123.970344	45.353061	200 (60)	-25.0	200 (60)
T-13 LOWER ROOT (Beta 137210)	-123.970416	45.358060	560 (50)	-25.0	560 (50)
C-1 (Beta-116375)	-123.962226	45.4468613	38,900 (680)	-25.0	38,900 (680)
G-1 (Beta-116377)	-123.962226	45.4468613	>47,070	-25.0	>47,070

In contrast to the seaward dipping Tertiary sedimentary rocks, block failure width in weak but semi-consolidated Quaternary deposits on the high bluffs appears to correlate somewhat better with bluff height, although there is a similar threshold of bluff height at ~150-160 feet where bluff failure width suddenly increases to hundreds of feet (Figure C3). Bluffs less than 40 feet high, as at Cape Lookout State Park, generally erode gradually by undercutting and toppling of 3-5-foot chunks of the uppermost part of the bluff. Maximum block failure width is 43 feet for bluffs about 40 feet high and about 250-350 feet for bluffs on the order of 200-250 feet in height. A value of 120 feet appears to be appropriate for bluffs ~150-160 feet in height. The more uniform structure of these deposits probably contributes to more predictable correlation between bluff height and slide block width relative to the seaward dipping Tertiary sedimentary rocks.

The sparseness of the data for these bluffs (Figure C3) makes it difficult to have confidence in any correlation of bluff height to block failure width. Furthermore, the sparseness of data is also complicated by the possibility that the block failure width can be very dependent on the paleotopography of the underlying rocks, which in the area of the measurements is mainly basalt. This hard rock basement beneath the weak soils may be the actual control on block failure width, not bluff height. Nevertheless, a logarithmic regression fits the data fairly well (correlation coefficient = 0.84), capturing both the rapid increase in maximum bluff failure width for bluffs higher than 150 feet (Figure C3), and the near linear correlation for bluffs ≤150 feet high (correlation coefficient = 0.94 in Figure C4). Thus, for bluffs ≤150 feet high, the simple formula:

maximum block failure width = bluff height/1.25

can be used, if there is no local data. If there is no local data for bluffs >150 feet high, the formula:

Ln (maximum block failure width) = (bluff height + 81.8)/(48.9)

can be used. However, because it is mainly based on the two points at 150 and 200 feet height (Figure C3), it is simpler and just as accurate to use a linear extrapolation between the actual values at these points to yield the following equation:

maximum block failure width = (bluff height – 124)/0.2174.

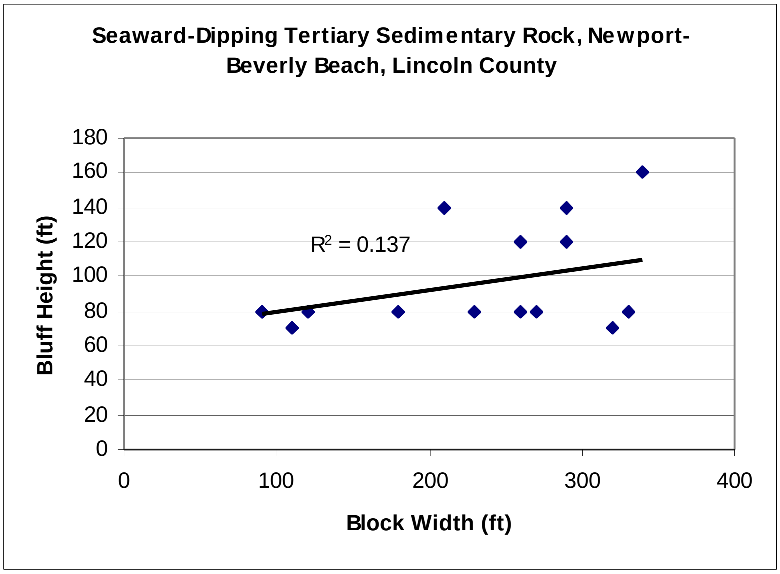


Figure C 2 Slide block widths for seaward-dipping Tertiary sedimentary rock bluffs ~70-160 feet high in the Newport to Beverly Beach segment of the Lincoln County coast. Area analyzed extends from the Johnson Creek on the north to Henderson Creek on the south. Most of the bluffs are about 60-80 feet high where the ~300-330 feet widths were measured; thus there is no simple correlation between bluff height and maximum block width.

Ignoring the point at 250 feet of bluff height is justified, because this width is for an ancient landslide block that may have undergone considerable erosion. Ignoring this point is also justified from the standpoint of using the most conservative values for hazard zoning.

Holocene to Pleistocene dunes

For the purposes of this investigation the erosion hazard zones for large dune sheets ~150-400 feet thick at Pacific City, Tierra del Mar, Sand Lake, Oceanside, and Manzanita were mapped under the assumption that they respond to erosion more as bluffs than as typical foredunes. This assumption is debatable, but it is equally difficult to make the case that shorelines backed by these high dunes will respond like typical dune-backed shorelines with much smaller sand volumes. For example, a modern dune-backed shoreline with dunes ~10-100 feet high will alternately erode and build back dunes on an annual or inter-annual basis. When waves erode a dune sheet 150-400 feet thick, unless there is a massive sand supply in the area, the dune is more likely to stay in the eroded condition, requiring a prolonged period of time for the dune to re-build. Likewise, the amount of sand that must be moved per erosion event is much larger in these large dunes than in typical foredunes, so that they should respond more slowly to wave erosion events. All of these factors make it difficult to confidently apply the geometric method of Komar and others (1999) to map erosion hazards on bluffs cut in these Pleistocene to Holocene dune sheets. Erosion hazard zones were therefore mapped on these bluffs in the same way as other bluffs, making it essential to establish a maximum block (in this case slough) failure width.

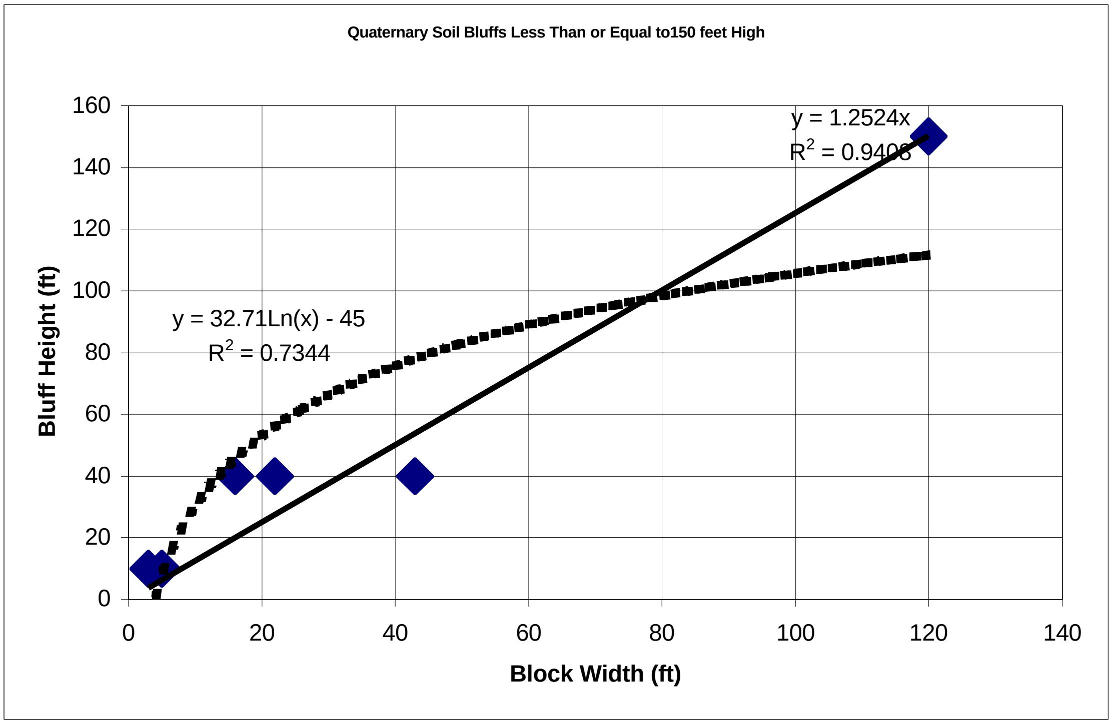


Figure C 3 Correlation of bluff height to block failure width for bluffs with significant (>1m) weak, clay-rich Pleistocene soils in the bluff face. The solid line is a linear regression; the dashed line is a logarithmic trend line. The amount of data is not really sufficient to establish a statistically significant equation but the logarithmic trend line is suggestive of how these bluffs behave. Problems with a simple correlation include observations of two or more block failure widths on a single bluff and unknown amounts of erosion on blocks prior to historical width measurements. The outlying point at 250 feet of bluff height is an example of a prehistoric block north of the Netarts marina that may have been extensively eroded, making the measured block width too narrow.

Where there is no weak Pleistocene clay-rich deposit at the base of a Pleistocene to Holocene dune sand bluff, block failures will be entirely shallow sloughing events mostly a few feet in width. On rare occasions, some of these sloughs may reach widths ~24 feet on the higher bluffs (measurement 16, Table C1). Therefore, for the purposes of this investigation a maximum block failure width of 24 feet will be assumed for bluffs composed of Pleistocene to Holocene dune sand.

Summary and Conclusions

Table C3 summarizes the range of maximum bluff failure widths for 39 coastal bluff measurement sites in Tillamook County. These data are a useful tool for mapping “worst case” erosion hazard scenarios where gradual erosion is periodically accelerated by sudden slope failures that cause a significant portion of a bluff to collapse.

The maximum block failure widths of Table C4 are appropriately conservative for the purposes of this investigation. Equations in the table should not be used where local data is available, since the equations are based on fits to the same data. For example, the data for Crab Avenue in Table C3 should take precedence over the equation of Table C4. Likewise, the user of these data should be fully aware that block failures for Pleistocene soils could be controlled by paleotopography on underlying basalt rather than the suggested empirical relationship with bluff height.

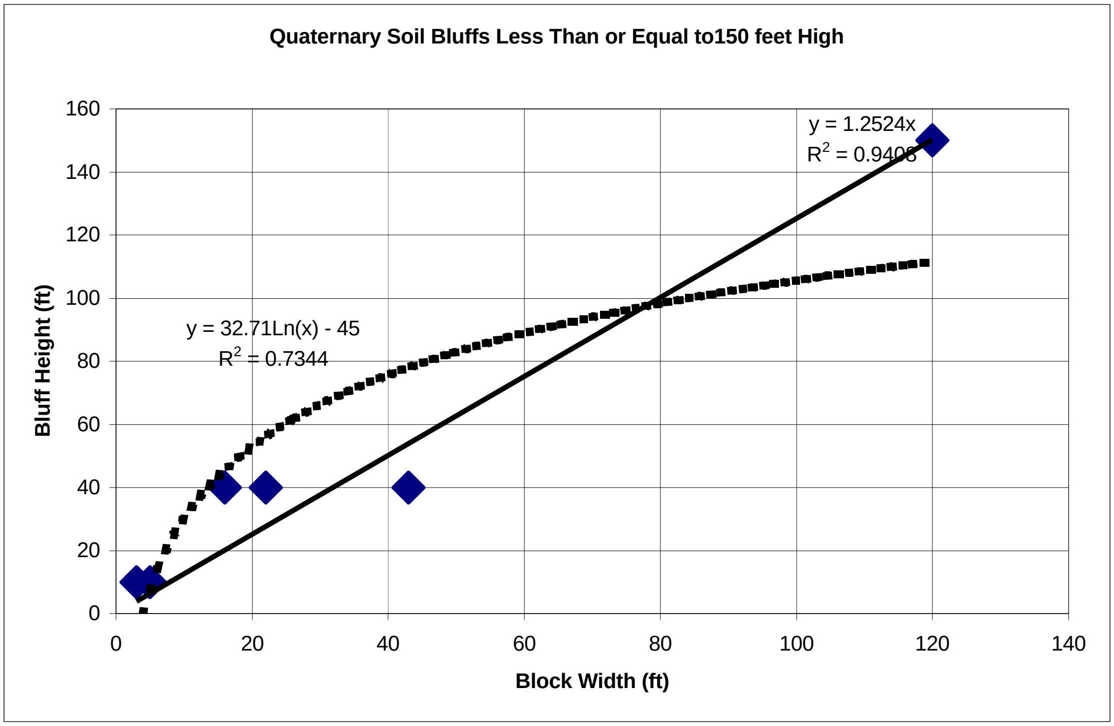


Figure C 4 Maximum block widths for bluffs =150 feet high appear to fit a linear regression (solid line) fairly well, when the regression is forced through the zero axis. Correlation coefficient, R^2, is 0.94. A logarithmic trend line (dashed line) is shown for comparison.

Table C 3 Summary of maximum block failure width measurements for Tillamook County. Values in parentheses are rounded to the appropriate significant figure from the actual measurement.

Bluff Material Causing Block Failure	*Maximum Block Failure Width (ft)*
Basalt subject mostly to rock falls and topples in bluffs < 100 feet in height.	8
Resistant sandstone bluffs 80-160 feet high	39 (40)
Basalt subject mostly to rock falls and topples in bluffs = 100 feet height.	47 (50)
Basalt at pocket beach south of Cape Meares	471 (470)
Seaward-dipping Tertiary sedimentary rocks on 60-200 ft bluffs	340
Seaward-dipping Tertiary sedimentary rocks on 300-400 ft bluffs	442 (440)
Holocene soil on 10 foot high bluffs (e.g. Cape Lookout State Park)	5
Pleistocene soil on 40-50 foot high bluffs (e.g. Crab Ave., Netarts)	43 (40)
Pleistocene soil on ~150 ft bluffs: (e.g. Fall Creek landslide south of Oceanside)	120
Pleistocene soil on ~200 ft bluffs: (e.g. The Capes Landslide south of Oceanside; prehistoric block north of Netarts marina)	350
Holocene to Pleistocene dune sand on high (>150 ft) bluffs	24

Table C 4 Maximum block failure widths used where there is no local data.

Bluff Material Causing Block Failure	*Maximum Block Failure Width (ft)*
Basalt subject mostly to rock falls and topples in bluffs < 100 feet high	8
Basalt subject mostly to rock falls and topples in bluffs = 100 feet high	49 (50)
Basalt at pocket beach south of Cape Meares	471 (47)
Resistant sandstone bluffs 80-160 feet high	~39 (40)
Seaward-dipping Tertiary sedimentary rock with fine grained interbeds on bluffs <60 feet high	bluff height/1.25
Seaward-dipping Tertiary sedimentary rock with fine grained interbeds on bluffs 60-200 feet high	340
Seaward-dipping Tertiary sedimentary rock with fine grained interbeds on bluffs >200 feet <300 feet high	(bluff height + 200)/1.1765
Seaward-dipping Tertiary sedimentary rocks with fine grained interbeds on bluffs 300-400 ft high	442 (440)
Holocene to Pleistocene soil in bluffs ≤150 ft high	bluff height/1.25
Holocene to Pleistocene soil in bluffs >150 ft high	(bluff height – 124)/0.2174
Holocene to Pleistocene dune sand bluffs	24

APPENDIX D

PROJECTION OF SLOPE OF REPOSE AT LANDSLIDE HEADWALLS

Introduction

Predicting where a landslide headwall is likely to end up requires projecting some stable slope angle from the subsurface intersection of the headwall with the slide plane. For conservative calculations, we assume that this angle is approximated by angle of repose of the bluff material. In many cases the subsurface inclination of the headwall and slide plane for deeply penetrating landslides is unknown. It is therefore useful to first examine some landslides that have known data on slide and headwall inclination, and then to develop techniques that can yield the necessary information with a proper degree of conservatism.

Schooner Landing Landslide, Newport, Oregon

Figures D1 and D2 illustrate a typical translational landslide at Schooner Landing in Newport, Oregon, where there is some subsurface geotechnical data. The landslide is in Tertiary sedimentary rock of the Astoria Formation, which dips about 9° seaward at this locality. Dip of the slide plane is not known but could be as low as 3° (Figure D2).

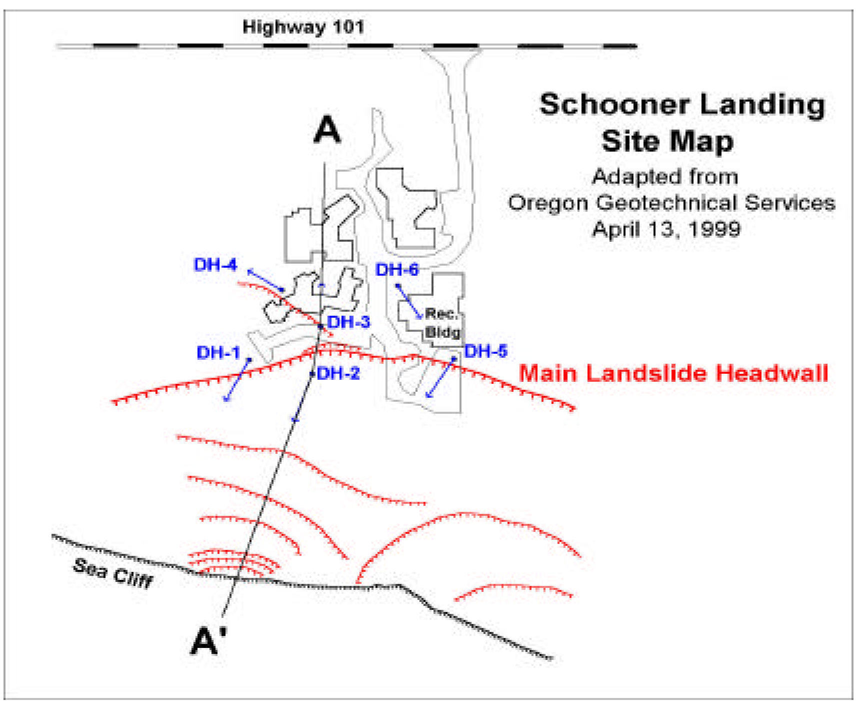


Figure D1 Map of Schooner Landing landslide showing location of headwalls of individual slide blocks. A-A' is the line of vertical cross section shown in Figure D2. Drill hole locations are also shown. Drill holes have inclinometer casing installed; lateral direction of movement is indicated by arrows.

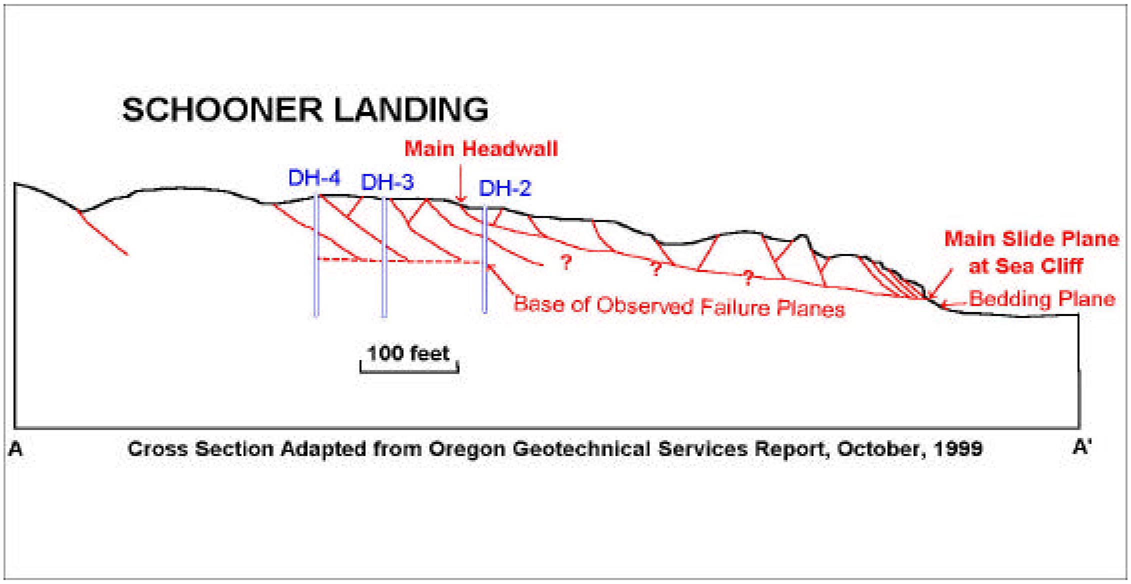


Figure D 2 Vertical cross section through the landslide at Schooner Landing. Known slide plane locations are at the drill holes and at the slide toe; all other locations are inferred. Projecting from the slide toe directly to the deepest drilled failure planes yields a slide inclination of about 3° (slope of 18:1). Inclination of the headwall fissure in the subsurface is not known, since this was not drilled.

The slide block at Schooner Landing is fragmented into a graben that is falling into the widening fissure zone at the headwall and into increasingly smaller blocks toward the toe. At the toe, the landslide becomes totally disaggregated slide breccia (Figure D3). The landslide toe at this locality lies a few feet above the bluff toe and is not very effectively eroded by waves. Hence, wave erosion, at least in this local area, may not be the main agent causing slide movement (Figure D3). Movement on a similar slide block with the same geology a few thousand feet to the south seems to correlate well with times of high rainfall, suggesting that groundwater pressure may be an important factor causing the movement. Probable low permeability of numerous siltstone beds in the Tertiary sedimentary rocks would increase the likelihood that groundwater could occur in confined aquifers, and that groundwater table could rise quite high in response to local rainfall.

Jumpoff Joe Landslide, Newport, Oregon

Figures D4-6 illustrate the geology of the Jumpoff Joe landslide at Newport, Oregon. The landslide is a large block that experienced dramatic movement in the 1940's, although it was well defined on 1939 aerial photos. The landslide is in Tertiary sedimentary rock of the Nye Mudstone, which dips about 14° seaward at this locality (Figure D4). Maximum slide block width was about 330 feet before much erosion occurred (measurements on 1967 and 1939 aerial photos). Translation straight down the stratigraphic dip should produce a single slide block about 190 feet wide, if the ~46 ft thickness of the Tertiary section is the controlling factor. Assuming that the Tertiary section controls slide width, a slide plane dip of about 8° would produce a 330 ft wide block. Dip of the slide plane in outcrop appears to be even lower than this (Figure D6).

Figure D 3 Landslide toe at Schooner landing. Toe material is totally disaggregated slide debris and the slide plane lies several feet above the beach.

Figure D 4 Geologic structure of the Jumpoff Joe bluff illustrating 14° dip of Tertiary sandstone of the Astoria Formation (sea stack and resistant material on end of the headland). The dark unit below the sandstone is the weaker Nye Mudstone, which fails as large landslides. About 34 feet of yellowish colored Pleistocene marine terrace deposits sit on the nearly horizontal wave cut platform that bevels the Tertiary sequence. Bluff is about 80 feet high at the highest point on the right.

Figure D 5 Southern slide block of the Jumpoff Joe landslide. This block lies immediately adjacent to the south side of the small headland illustrated in Figure D3. Before erosion, the block was 330 feet wide at its widest point. This block had numerous houses that were destroyed when downward and lateral displacement occurred in the 1940's.

Figure D 6. Nearly east-west cross section across the south end of the Jumpoff Joe slide block shown in Figure D4. Slide plane is at a very low, almost flat inclination in this exposure. A graben cuts the east side of the block at the black line, dropping overlying marine terrace deposits downward behind the laterally moving slide. Little or no backward rotation of the slide has occurred, so motion is mostly translation. Some of the basal Nye Mudstone (gray rock at base) has been cut out of the section by a combination of Pleistocene subaerial (low-stand) erosion and possibly basal shearing at the slide plane. Tan colored material forming much of the outcrop is Pleistocene low-stand soil; capping the upper few feet of the outcrop is marine terrace sand from a high sea stand.

The Capes Landslide, Oceanside, Oregon

Figures D7 and D8 illustrate The Capes landslide near Oceanside, Oregon. All observations and interpretations summarized here are from geotechnical data of Hart-Crowser and interpretations of Hart-Crowser geologist, Richard Rinne, as personal communications or from geotechnical reports shared with the authors. The current active slide movement is in weak Pleistocene soils that underlie about 100 feet of Holocene (?) dune sand. The inclination of the headwall in the subsurface is not known from drilling, but freshly sheared slip faces in dune sand at the headwall dip seaward at 45-60°. The inclination of the slide plane is near zero except at the toe where the slide rides up over the beach sand at a 14° angle. The currently active slide plane lies close to sea level, even near the toe of the headwall. As the slide block creeps toward the ocean, dune sand sloughs off the headwall in narrow (≤24 feet) slices that fill a widening fissure at the base of the headwall. The most dramatic headwall failure occurred in February of 1998 and threatened a number of condominiums built near the bluff edge (Figure D9). Likewise, the slide block itself is fragmenting into slices that are displaced downward toward the fissure. The result is a slide block that is effectively stretched and thinned about as much as wave erosion chews away at its seaward margin.

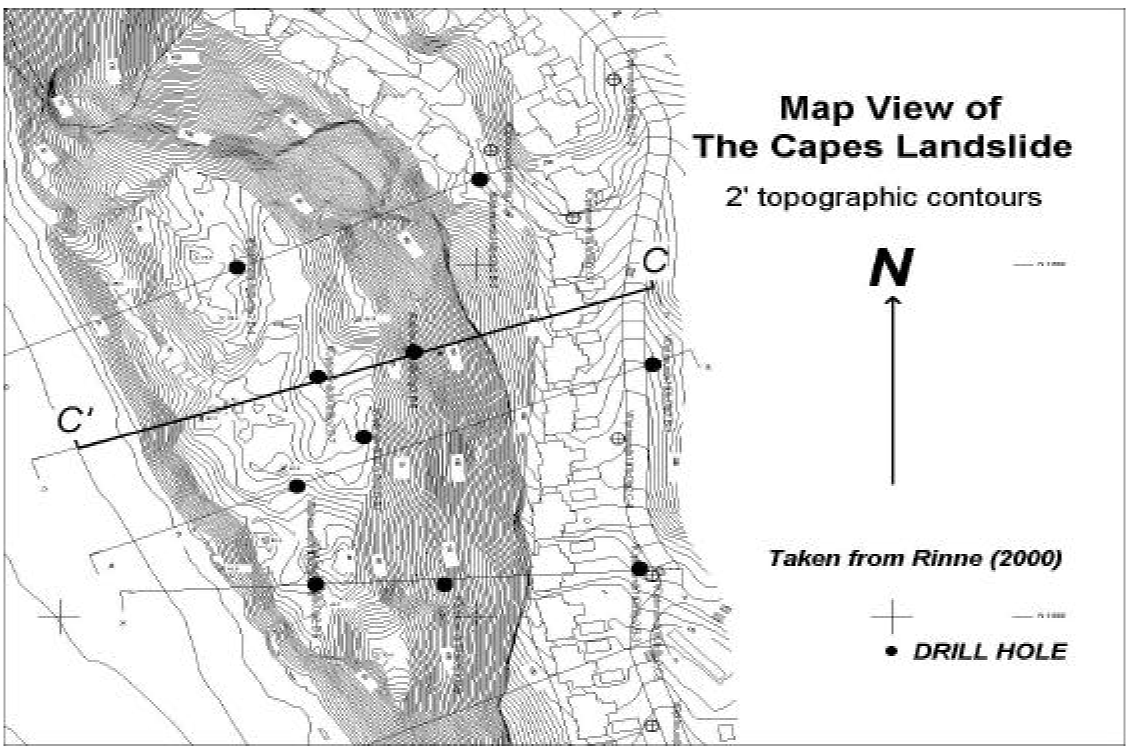


Figure D 7 Geologic map of The Capes landslide, Oceanside, Oregon (modified slightly from unpublished map of (Rinne, 2000).

In contrast to the landslide at Schooner Landing, movement of The Capes landslide is probably driven almost entirely by removal of support at the toe by wave erosion. This is inferred from the observation that the slide block moves very responsively to wave erosion, while ground water table remains quite low, owing to high permeability of the dune sand (Rinne, 2000, and personal communications, 1998-2001).

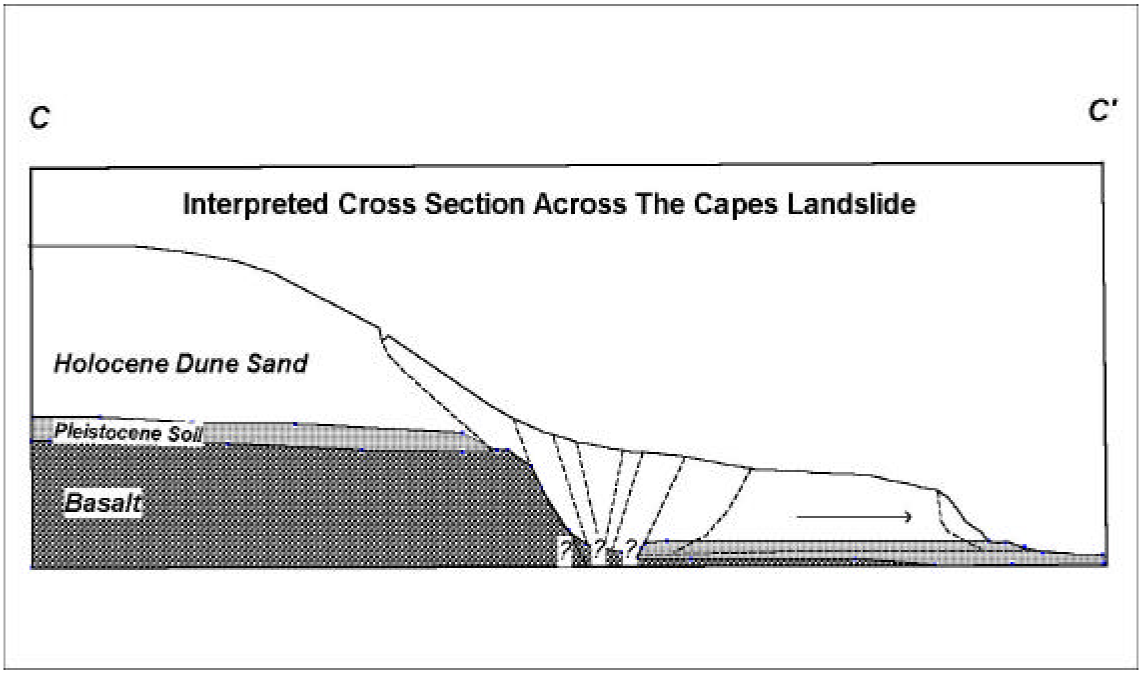


Figure D 8 Vertical cross section A-A' through The Capes landslide; see Figure D7 for location (generalized from cross sections of Rinne, 2000). The hard basalt escarpment at the foot of the headwall will make erosion very slow, once the slide block is eroded away and the overlying sand and Pleistocene soil reaches a stable slope angle.

Figure D 9 Headwall of The Capes landslide taken in summer of 1998. Holocene to Pleistocene dune sand has sloughed away, threatening the condominium at left.

Discussion

The Schooner Landing and Jumpoff Joe landslides are typical examples of large translational bedrock landslides in Tertiary sedimentary rocks of the Oregon coast. In most cases these landslides share the following attributes:

1) Seaward-dipping sequences of weak, fine grained sedimentary rocks
2) Landslides break back hundreds of feet in single block failures that can be much further back than would be indicated by simple failure down the inclination of the bedding planes.
3) The large failure width leads to the conclusion that slide planes often have lower dips than bedding. Exposures, general geometric considerations, and drilling data are consistent with low slide plane dips on the order of ~0-8°.
4) Movement frequently correlates to periods of high rainfall and high groundwater table.

The Capes landslide illustrated the following features of landslides in Pleistocene soils:

1. Near-horizontal sequences of paleosol, colluvium, and alluvium dominated by clay-rich, weak material can fail, especially if loaded with hundreds of feet of overlying dune sand.
2. Landslides can break back hundreds of feet in single block failures on bluffs ~200 feet high.
3. The landslides can move by straight translation on nearly horizontal slide planes.
4. Movement at The Capes correlates principally with removal of material at the toe by wave erosion. Groundwater effects appear to be a minor factor, since most of the bluff is composed of highly permeable dune sand. Nevertheless, groundwater may play a more important role in bluffs composed of thicker sequences of these clay-rich soils.

Translational sliding in all three-landslide examples occurred on relatively low dipping slide planes. Clearly inclinations can be higher. For example slides in Tertiary rocks can occur straight down bedding planes. Likewise, Pleistocene soils can lie on inclined bedrock surfaces.

When inferring how deep to project the exposed headwall slope into the subsurface, the lower the inferred dip of the slide plane and higher the dip of the headwall, the deeper will be the projected depth of intersection between headwall and slide plane (Figure D9). Slide plane dip will be assumed to be at a conservatively low angle where not known or reasonably inferred. A value of 3° (slope of 18:1) will be used for slides in Tertiary sedimentary rock. A value of zero will be used for slides in clay-rich Pleistocene soils.

In slides with unknown inclination of the headwall in the subsurface, projection of the headwall should be done with the inclination inferred from geotechnical data. The most conservative assumption is to project the exposed headwall vertically downward from its toe at the top of the slide mass to the slide plane (Figure D9). This assumption, in effect, presumes that a vertical fissure penetrates to a depth at the foot of the headwall; in other words, the type of shear one would get from purely tensional failure below the foot of the headwall (angle of internal friction ˜ 90º). The following formulas can be used to derive the horizontal distance, **S**, from the exposed toe of the headwall to the intersection of the some assumed stable slope angle such as the angle of repose, **R**, with the bluff top, assuming vertical projection of the headwall in the subsurface (Figure D9):

1. **<u>Tertiary sedimentary rock slides</u>**: <u>slide plane dip = 3° (slope = 18:1):</u>

***Formula D1*: S = R (H – L/18 + D)**

S = horizontal distance from the slide contact at the foot of the headwall to the projected intersection of the slope of repose behind the headwall
R = slope of repose (cotangent of angle of repose) for the headwall material
H = Vertical height of the exposed headwall
D = (Elevation of slide top at foot of headwall) – (elevation at the slide toe)
L = Horizontal width of the slide mass from toe to its top at the foot of the headwall

2. **<u>Slides in clay-rich Pleistocene soil</u>**: <u>slide plane dip ˜ 0°</u>

***Formula D2*: S = R (H + D)**

These simple formulas do not take precedence over good geologic reasoning. For example, subsurface geologic data at The Capes indicates that the inclination of the headwall shear in the subsurface is approximately 45º in the Holocene to Pleistocene dune sand (Rinne, 2000). Correlation of *in situ* properties of the dune sand to theoretical data predicted an angle of internal friction (ø) of ~34º for the sand (Stuart Albright, Hart Crowser, Inc., 2001, personal communication). The angle of internal friction of two samples of clay-rich Pleistocene soils at the base of The Capes landslide varied from 10º to 32º under varying conditions of confining pressure (Stuart Albright, Hart Crowser, Inc., 2001, data transmittal). Given that the theoretical inclination of a shear plane in the subsurface (∝) = 45º + ø/2, if the principal compressive stress is gravity, then the subsurface dip of a shear on the margin of a slide block should be ~62º in the sand, and ~50º to 61º in the underlying Pleistocene soil. A conservative value of 60º dip would be appropriate for both Holocene to Pleistocene dune sand and underlying Pleistocene soil, if there were no local geotechnical data to better constrain the dip. Taking this value into account, Formula D2 becomes:

***Formula D3*: S = [R/ (H + D)] – D cot 60º= S = [R/ (H + D)] – 0.5774D**

Formula D3 will be used in this investigation for such areas as Crab Avenue at Netarts, where slide blocks occur in bluffs of Pleistocene sediment.

Likewise, it is apparent from Figure D2 that the most likely dip of headwall shear planes (a) in slides of seaward dipping Tertiary sedimentary rock is between ~45º and 60º, so using a = 60º is more realistic than the most conservative assumption of 90º. Using the following general equation,

***Formula D4*: S = R [D+ H – (tan ß (D - L tan µ)/(tan ß – tan a))]**
a = shear plane dip below the headwall
ß = dip of the main slide plane beneath the slide block

the recommended formula for translational slides in seaward-dipping Tertiary sedimentary rock is:

***Formula D5*: S = R [D+ H - (tan 3 (D – L tan 60)/tan 3 – tan 60))]**

Conclusions

If slide plane configuration can be inferred from field relationships or detailed subsurface data, Formula D4 should be used for translational slides to project the potential headwall position once the headwall reaches its stable slope angle or the angle of repose for talus of the same material. If one knows nothing about the subsurface geometry of a translational slide and wants to be as conservative as possible, then Formula D1 is the most appropriate for seaward-dipping Tertiary sedimentary rocks, and Formula D2 for fine grained Holocene to Pleistocene sedimentary deposits. Geotechnical data supports the hypothesis that inclination of the headwall in the subsurface is likely ~60º for both Holocene to Pleistocene deposits and seaward-dipping Tertiary sedimentary rocks. Given this assumption, Formula D3 will be used for Holocene to Pleistocene sedimentary deposits, and Formula D5 for seaward-dipping Tertiary sedimentary rock. These two cases cover most deeply penetrating translational landslides in Tillamook County. The formulas are not appropriate for rotational slides or shallow slides on steep slopes.

APPENDIX E

Tillamook County coastal erosion hazard zones, and active, potentially active and prehistoric mass movements (mostly landslides), drawn on standard 1985/86 U.S. Geological Survey digital raster images. North is at the top of the page.

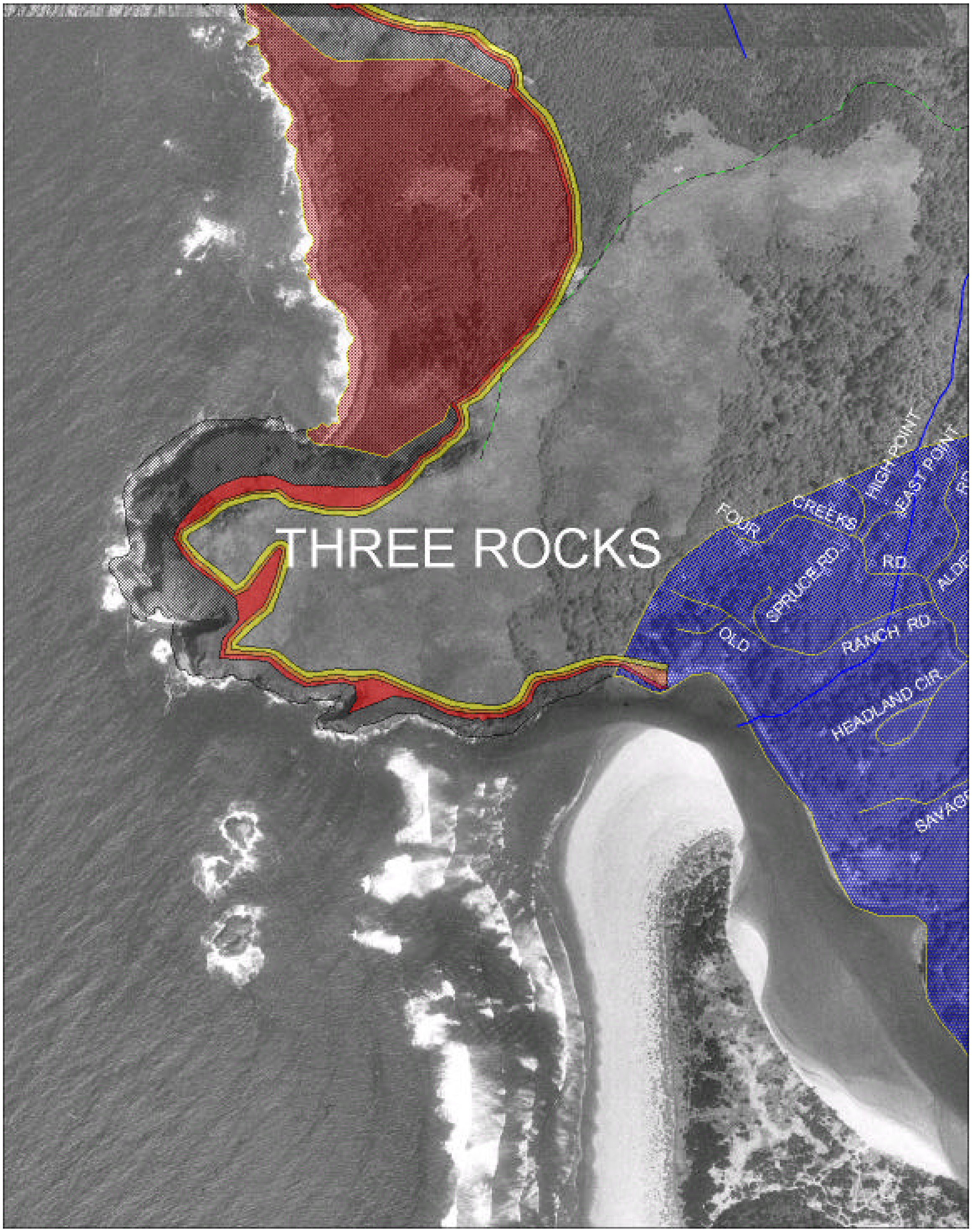
Maps progress sequentially from Cascade Head in the south, to Cape Falcon in the north. Additional landslide data are available east of the displayed maps. These data are not shown here, but are included as part of the digital files. Map scales are indicated with each figure.

<u>Key to Appendix E</u>

	Beach/dune toe junction as at April 1998
	Digital shorelines
	1998
	1997
	1994
	1985/1986
	1955
	1953
	1927
	Active erosion hazard zone
	High-risk coastal erosion hazard zone
	Moderate-risk coastal erosion hazard zone
	Low-risk coastal erosion hazard zone
	Active mass movement areas (landslides)
	Potentially active mass movement areas (landslides)
	Prehistoric mass movement areas (landslides)
	Quaternary landslide (not field checked for age or activity)

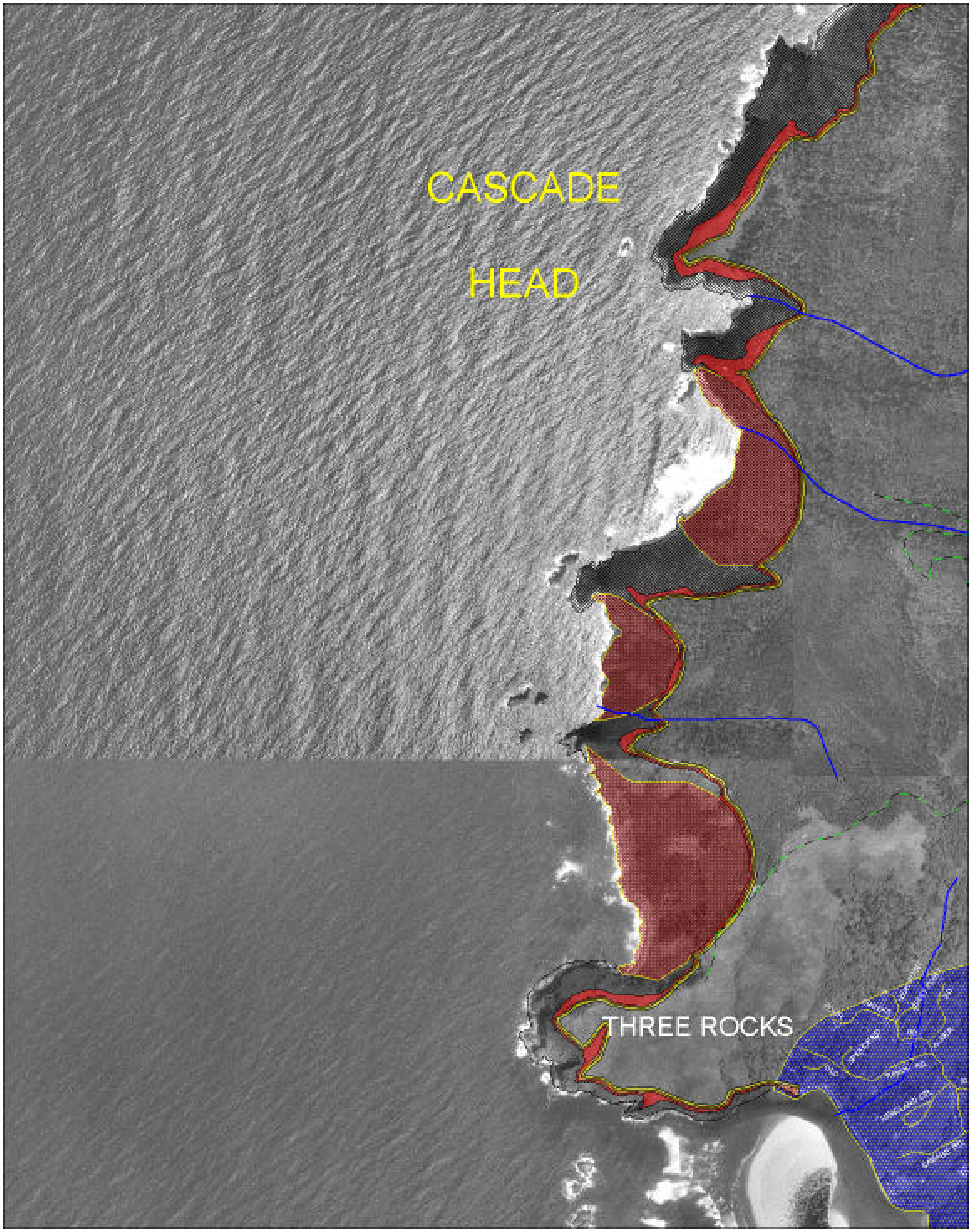
APPENDIX E (cont.)

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



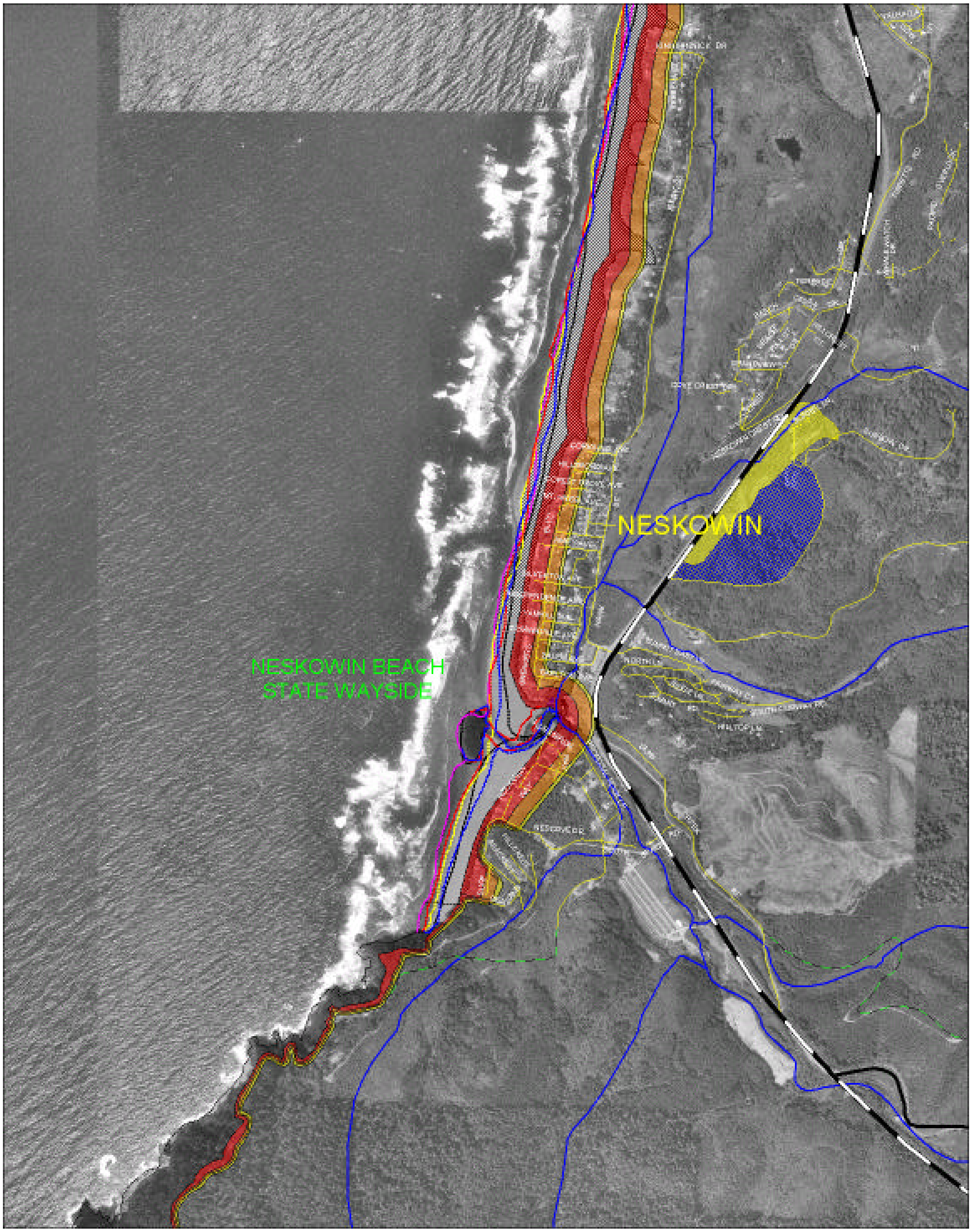
APPENDIX E (cont.)

Cascade Head (scale = 1:24,000 or 1 inch = 2,000 ft)



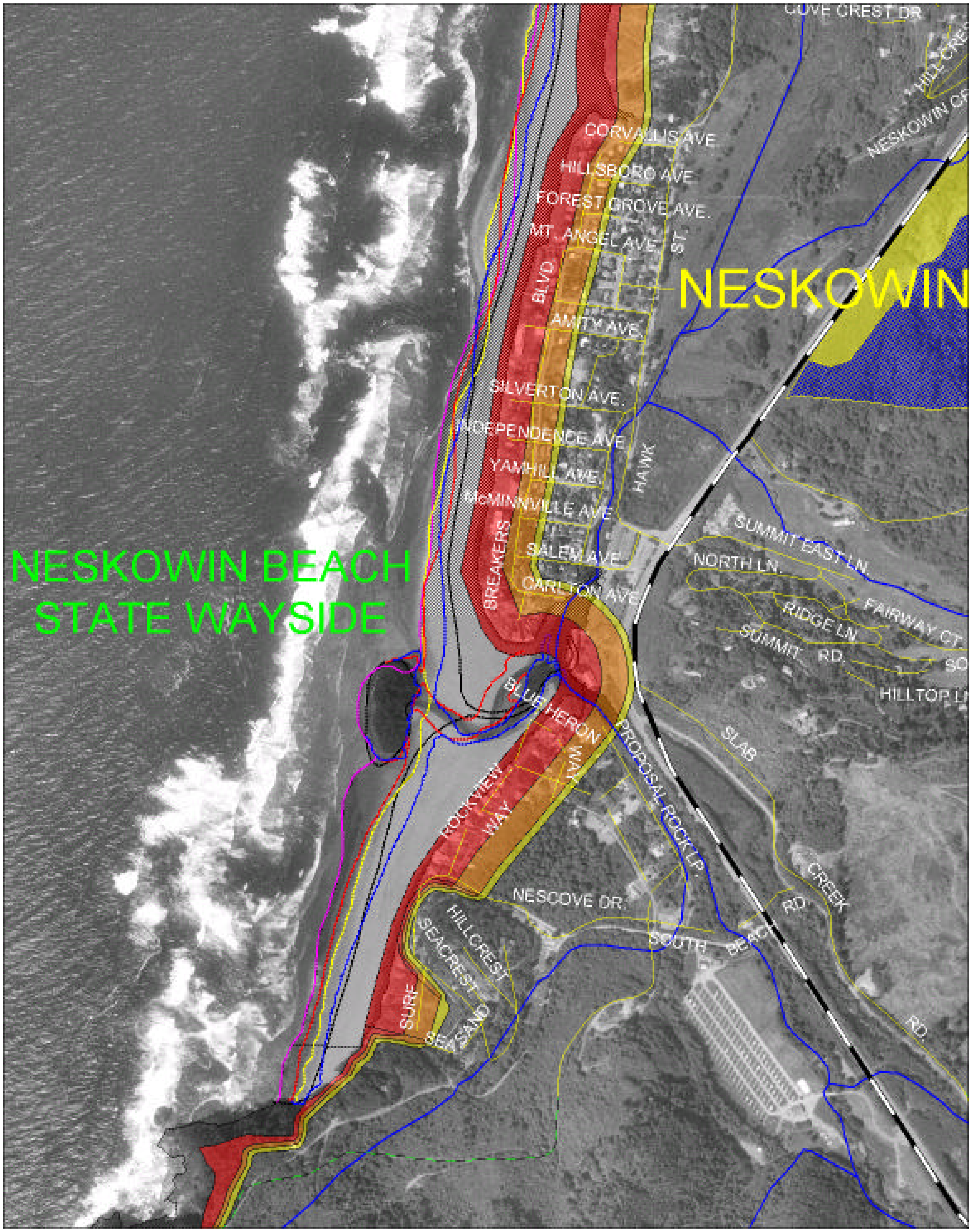
APPENDIX E (cont.)

Neskowin (scale = 1:24,000 or 1 inch = 2,000 ft)



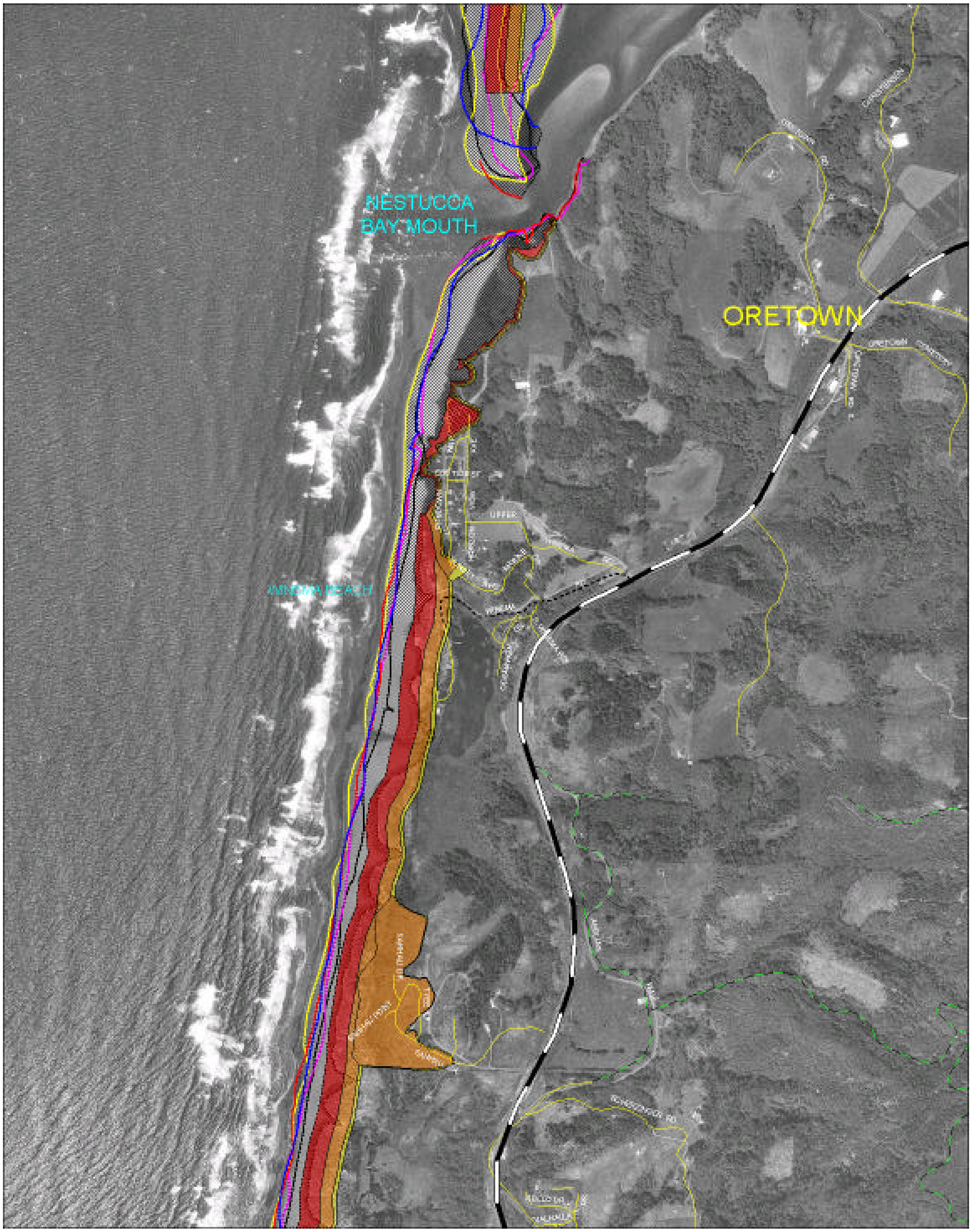
APPENDIX E (cont.)

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



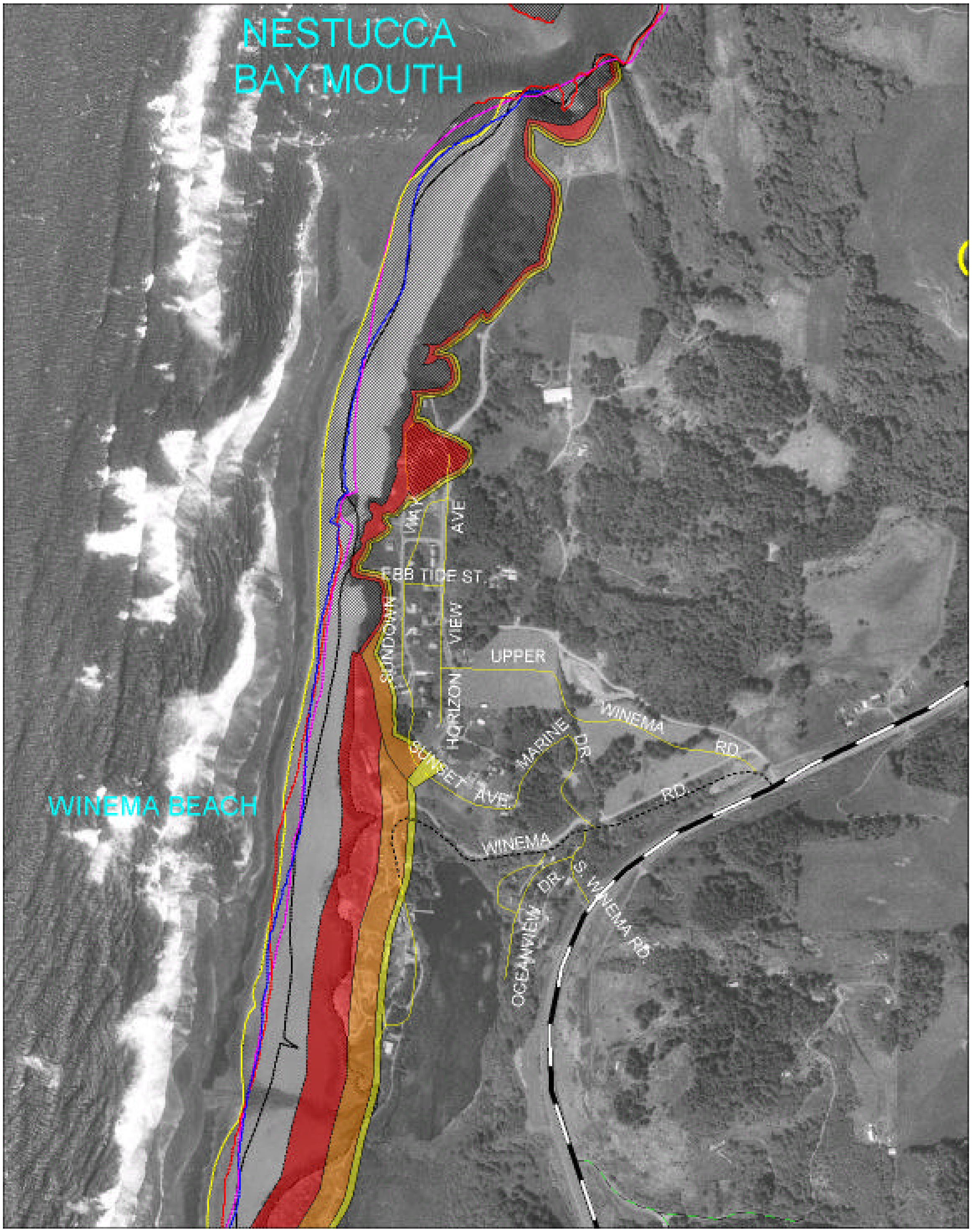
APPENDIX E (cont.)

Nestucca Bay Mouth (scale = 1:24,000 or 1 inch = 2,000 ft)



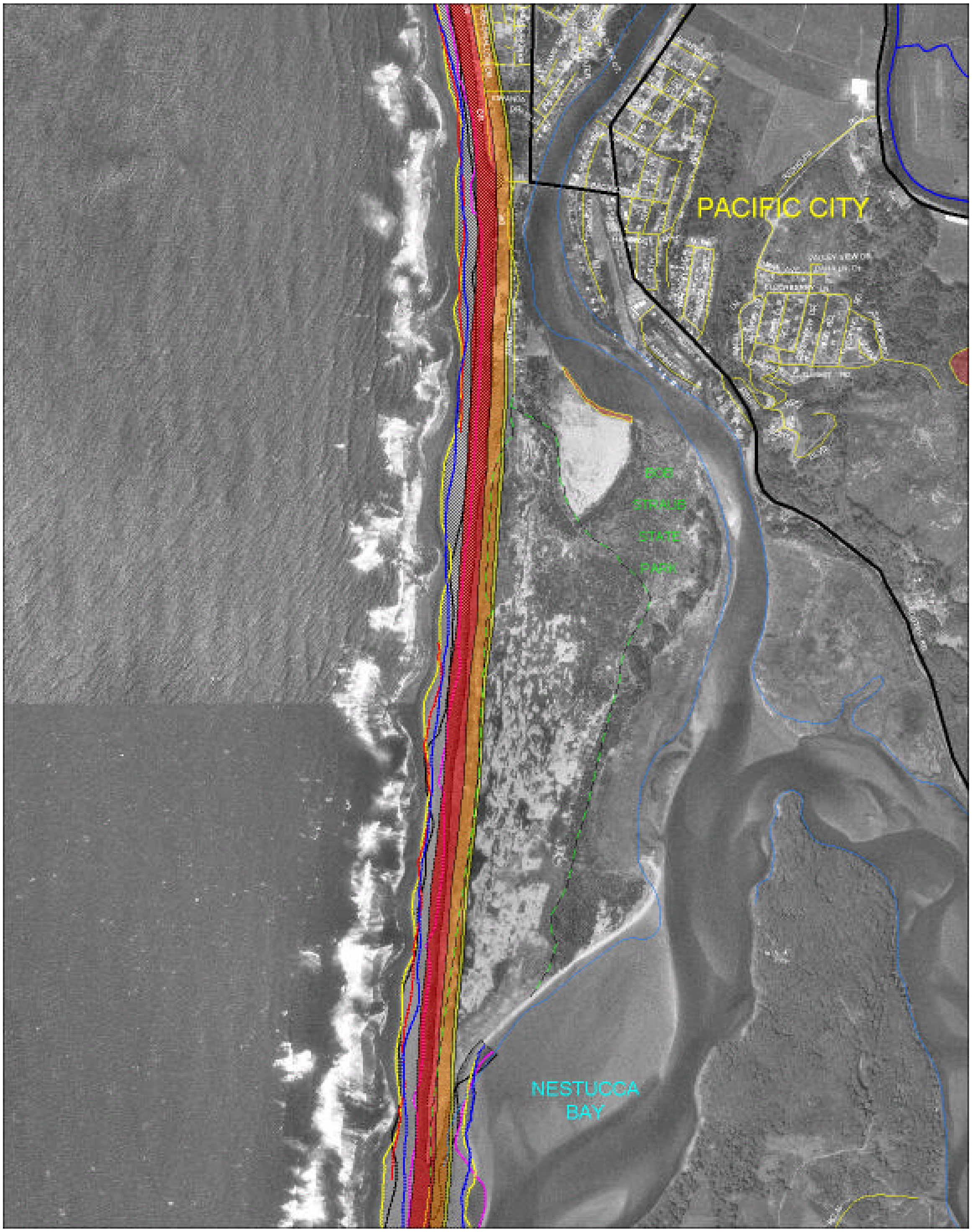
APPENDIX E (cont.)

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



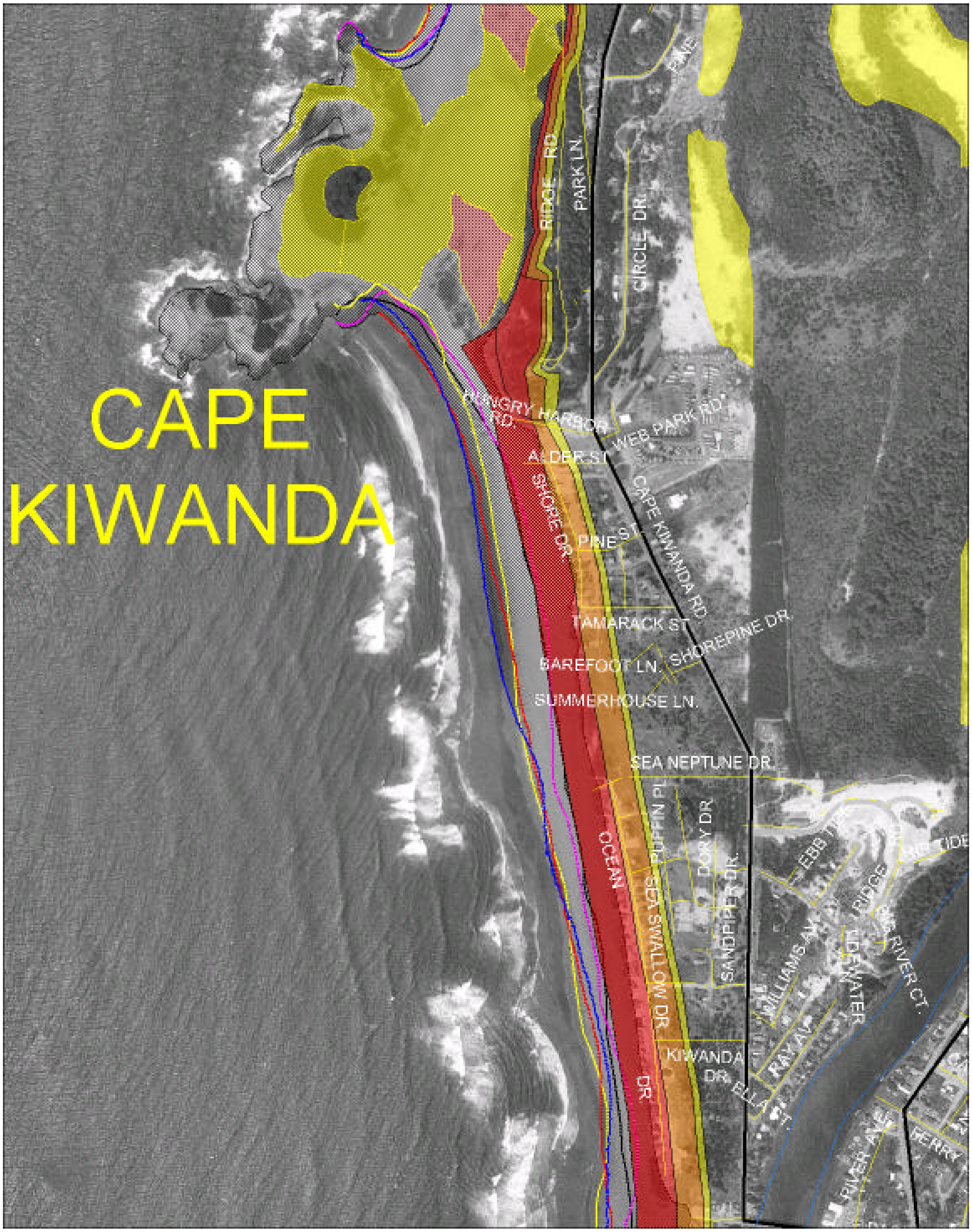
APPENDIX E (cont.)

Nestucca Bay/Pacific City (scale = 1:24,000 or 1 inch = 2,000 ft)



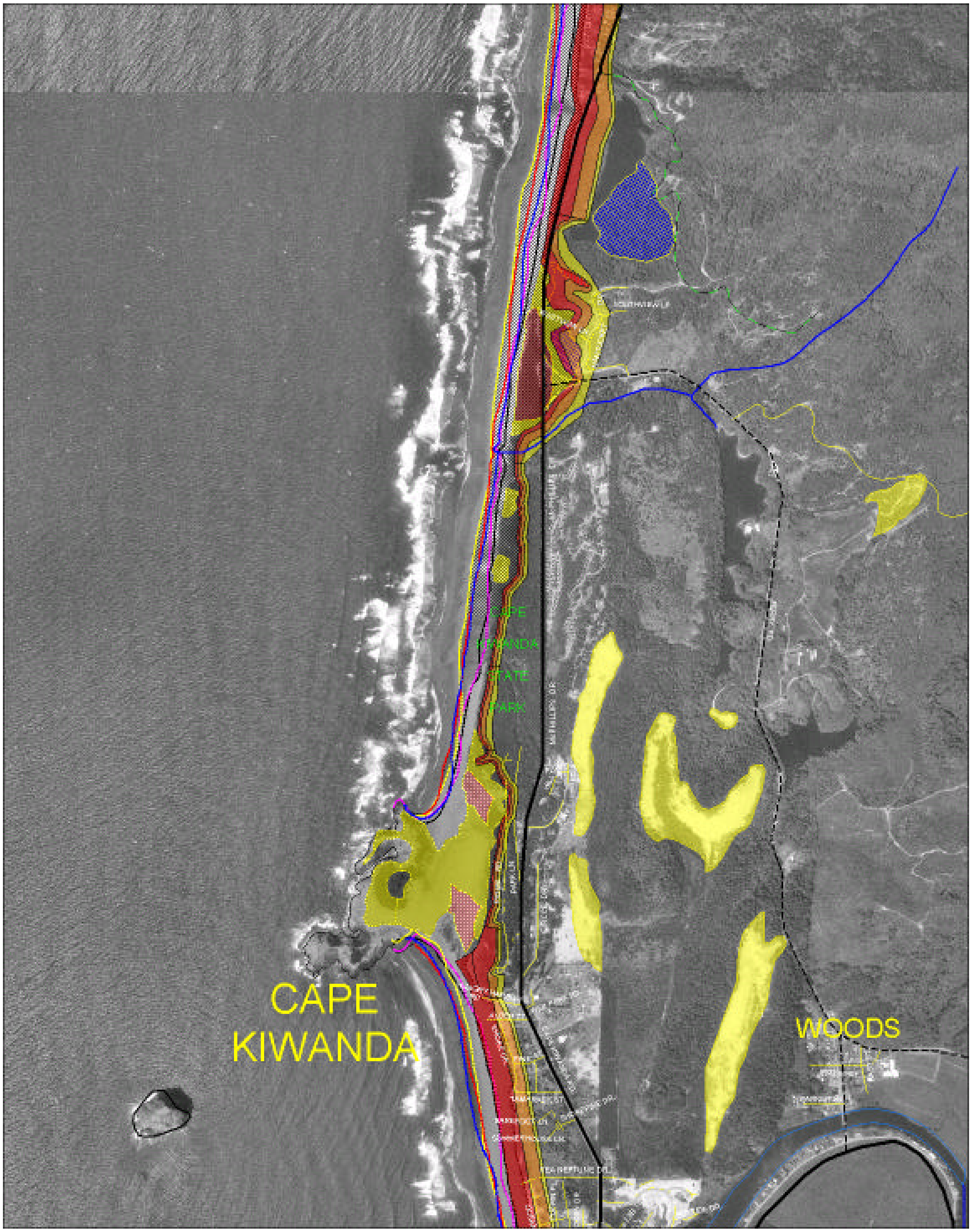
APPENDIX E (cont.)

Cape Kiwanda/Pacific City (scale = 1:12,000 or 1 inch = 1,000 ft)



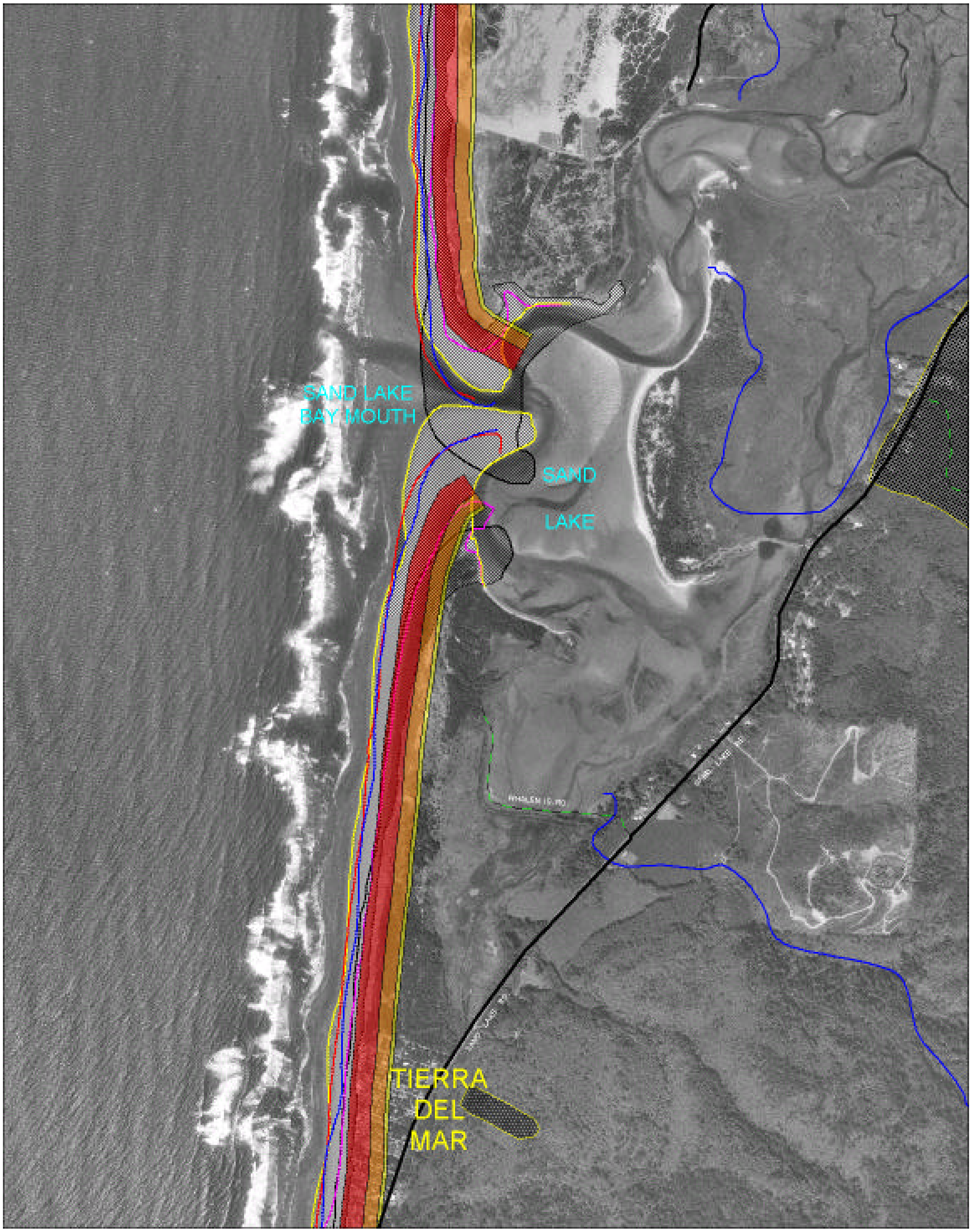
APPENDIX E (cont.)

Cape Kiwanda (scale = 1:24,000 or 1 inch = 2,000 ft)



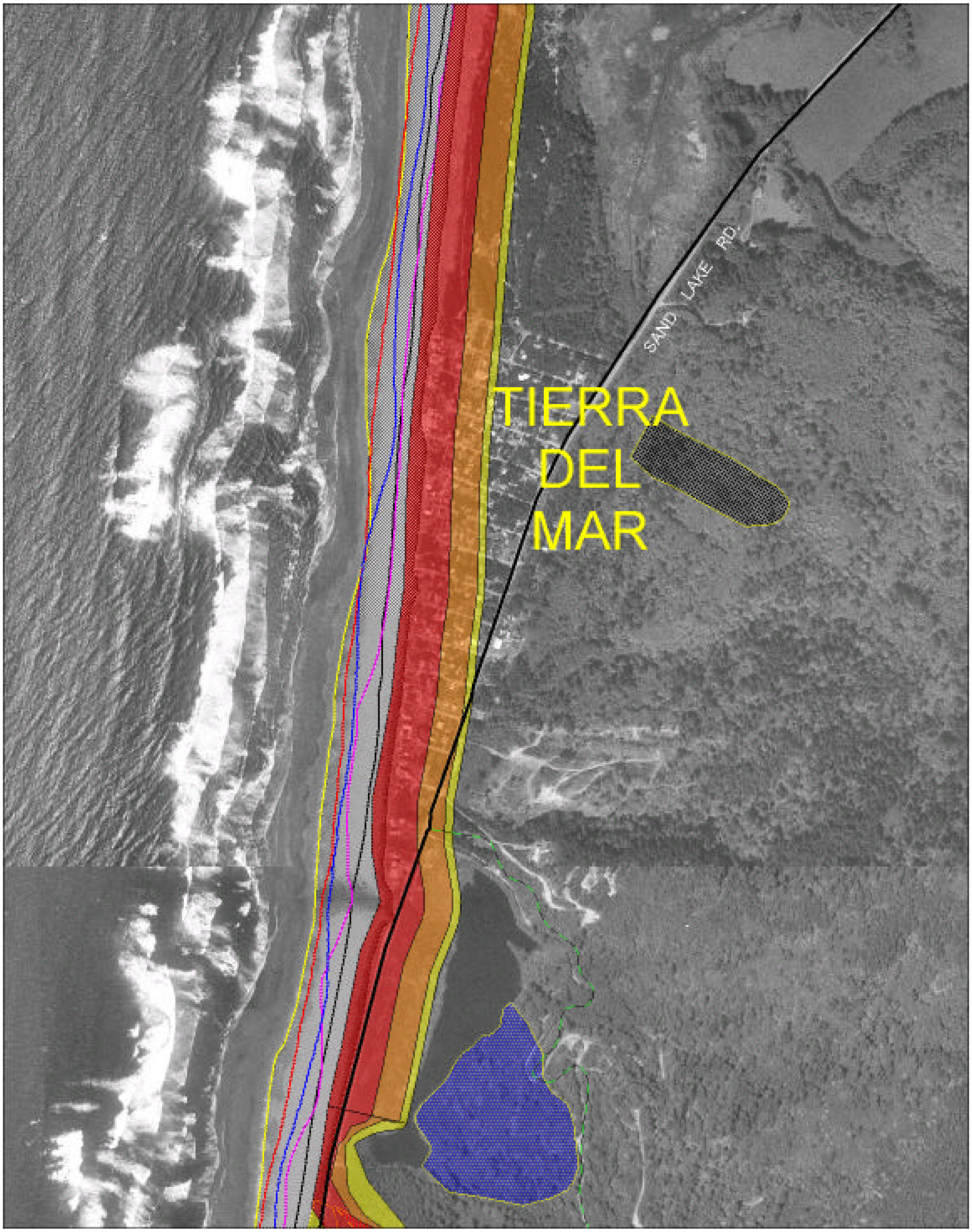
APPENDIX E (cont.)

Sand Lake (scale = 1:24,000 or 1 inch = 2,000 ft)



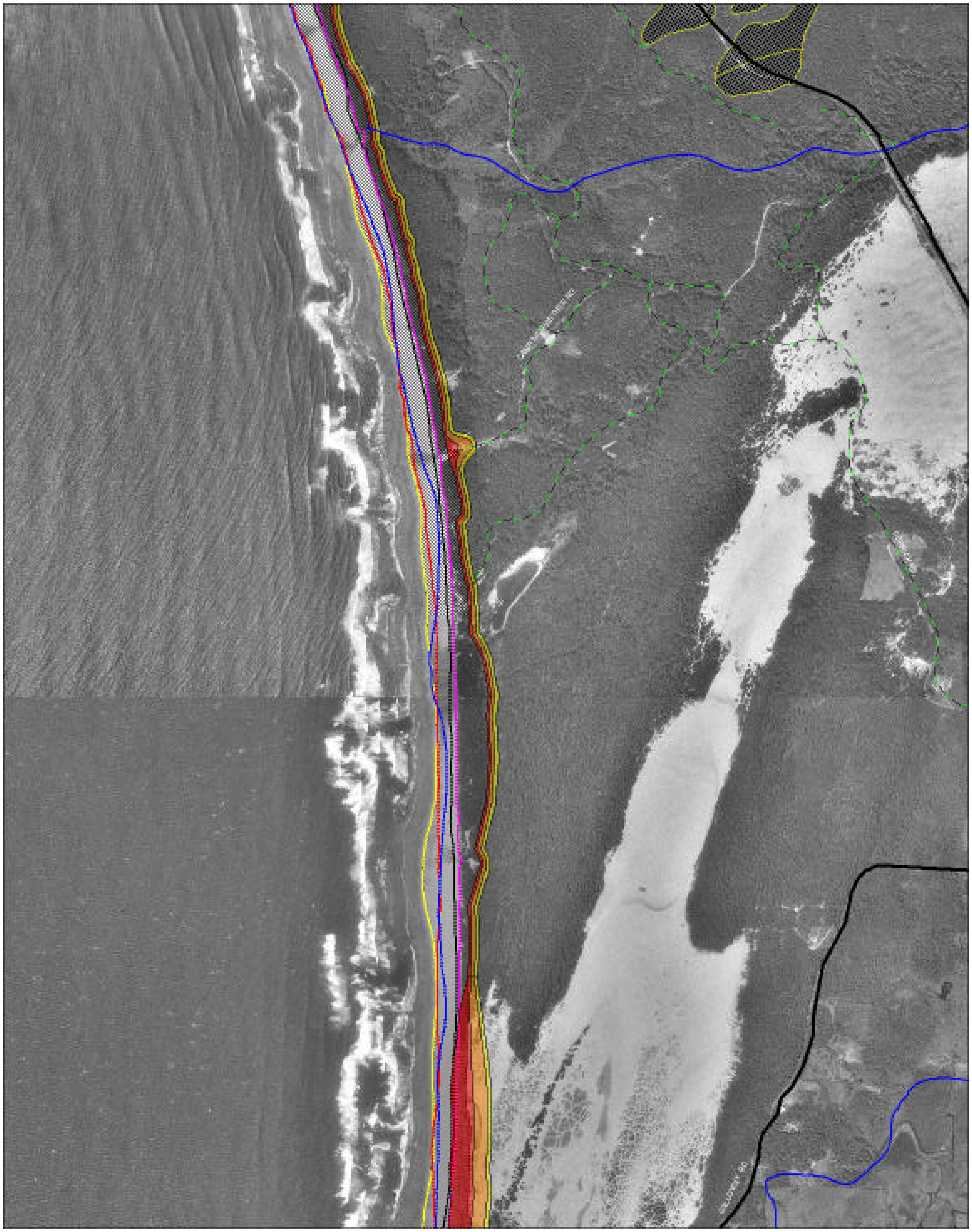
APPENDIX E (cont.)

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



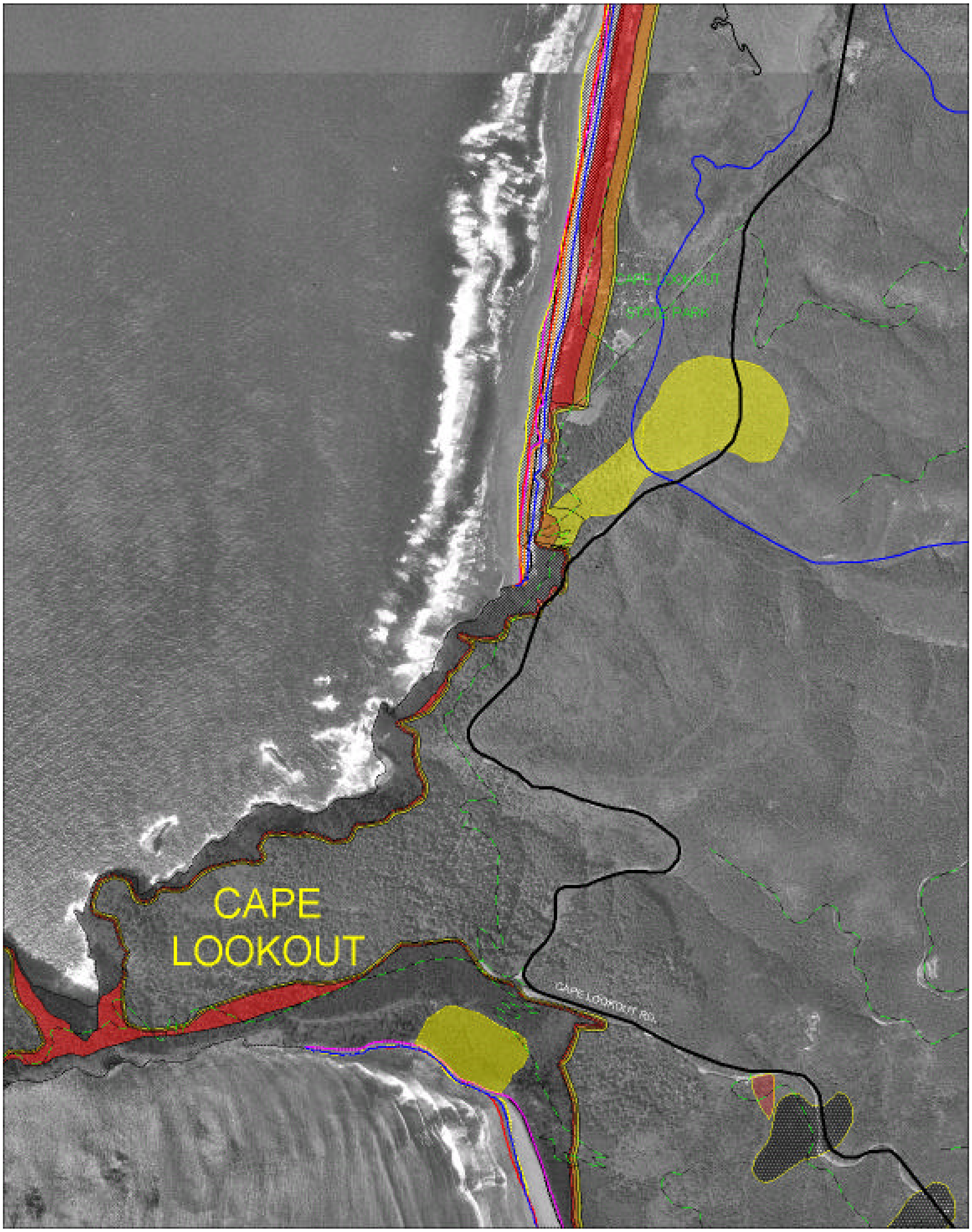
APPENDIX E (cont.)

Sand Lake/Camp Meriweather (scale = 1:24,000 or 1 inch = 2,000 ft)



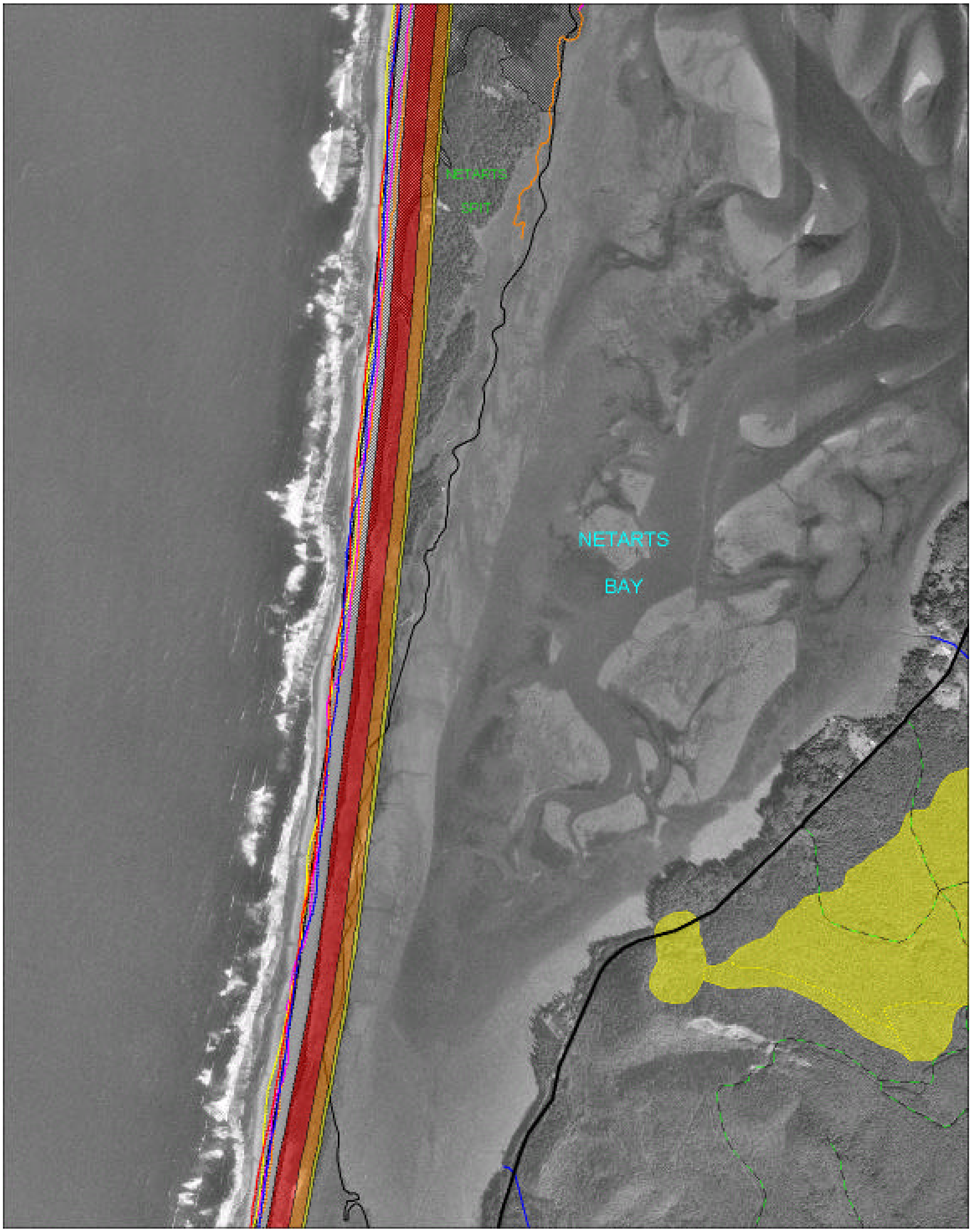
APPENDIX E (cont.)

Cape Lookout (scale = 1:24,000 or 1 inch = 2,000 ft)



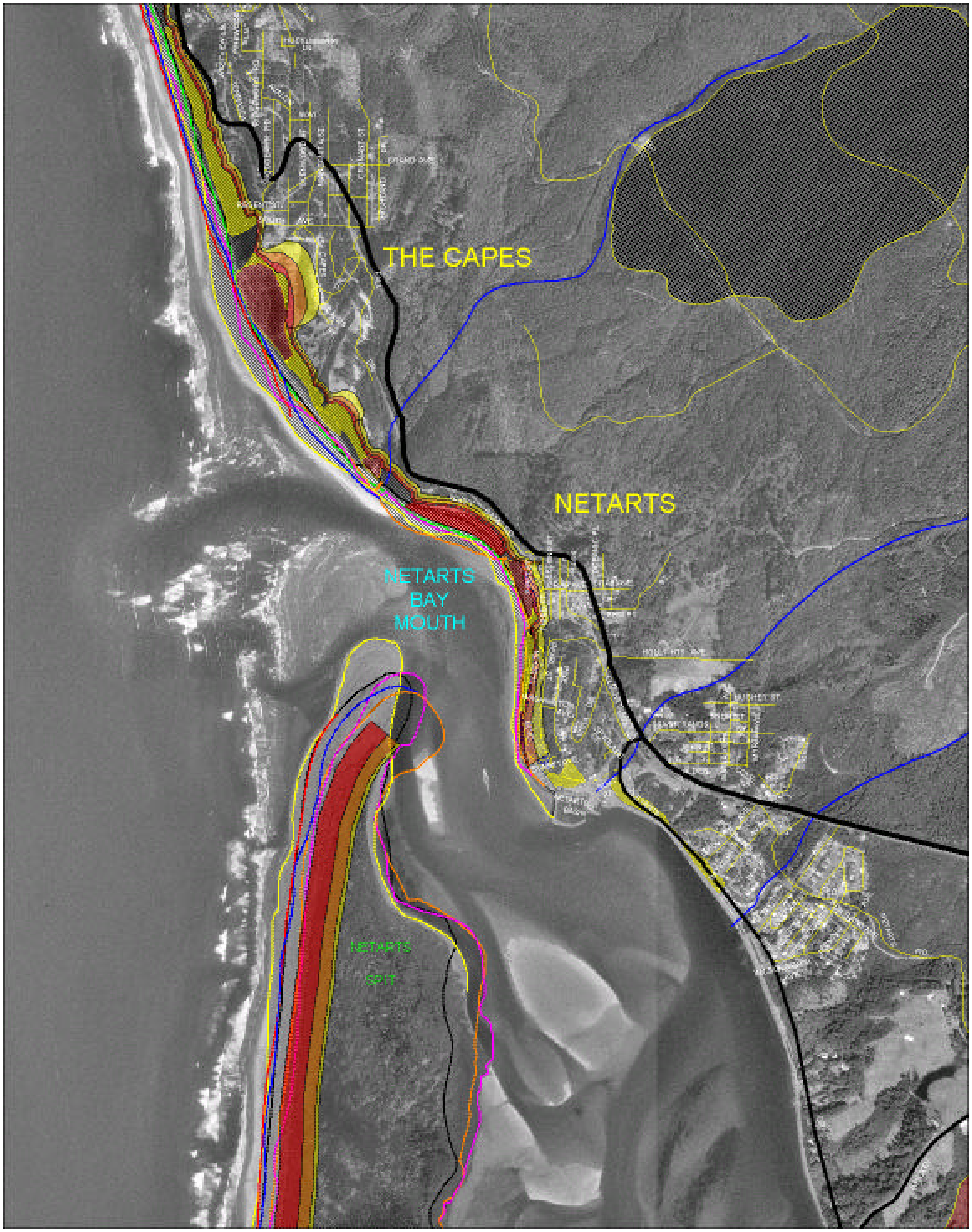
APPENDIX E (cont.)

Netarts Bay (scale = 1:24,000 or 1 inch = 2,000 ft)



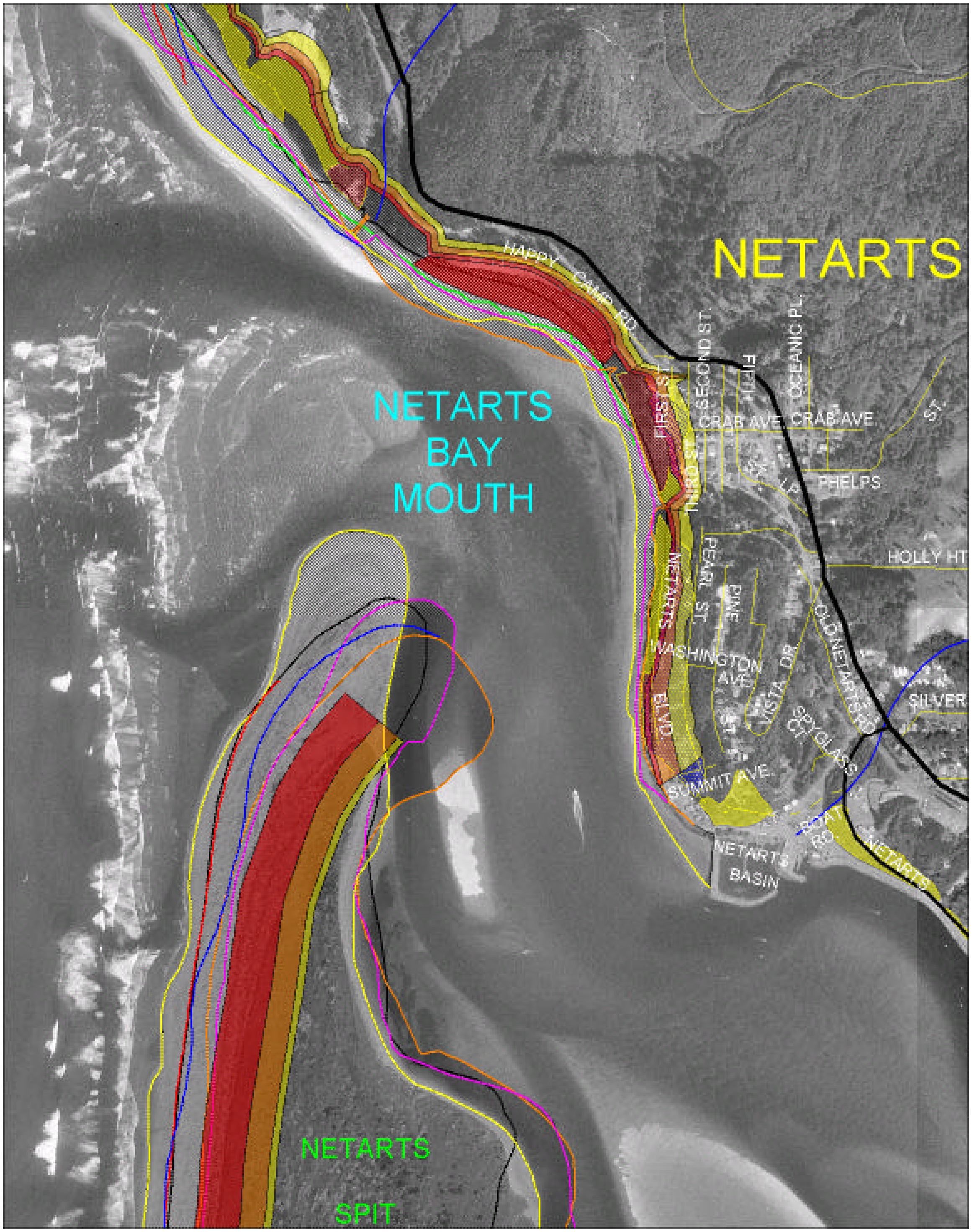
APPENDIX E (cont.)

Netarts Spit (scale = 1:24,000 or 1 inch = 2,000 ft)



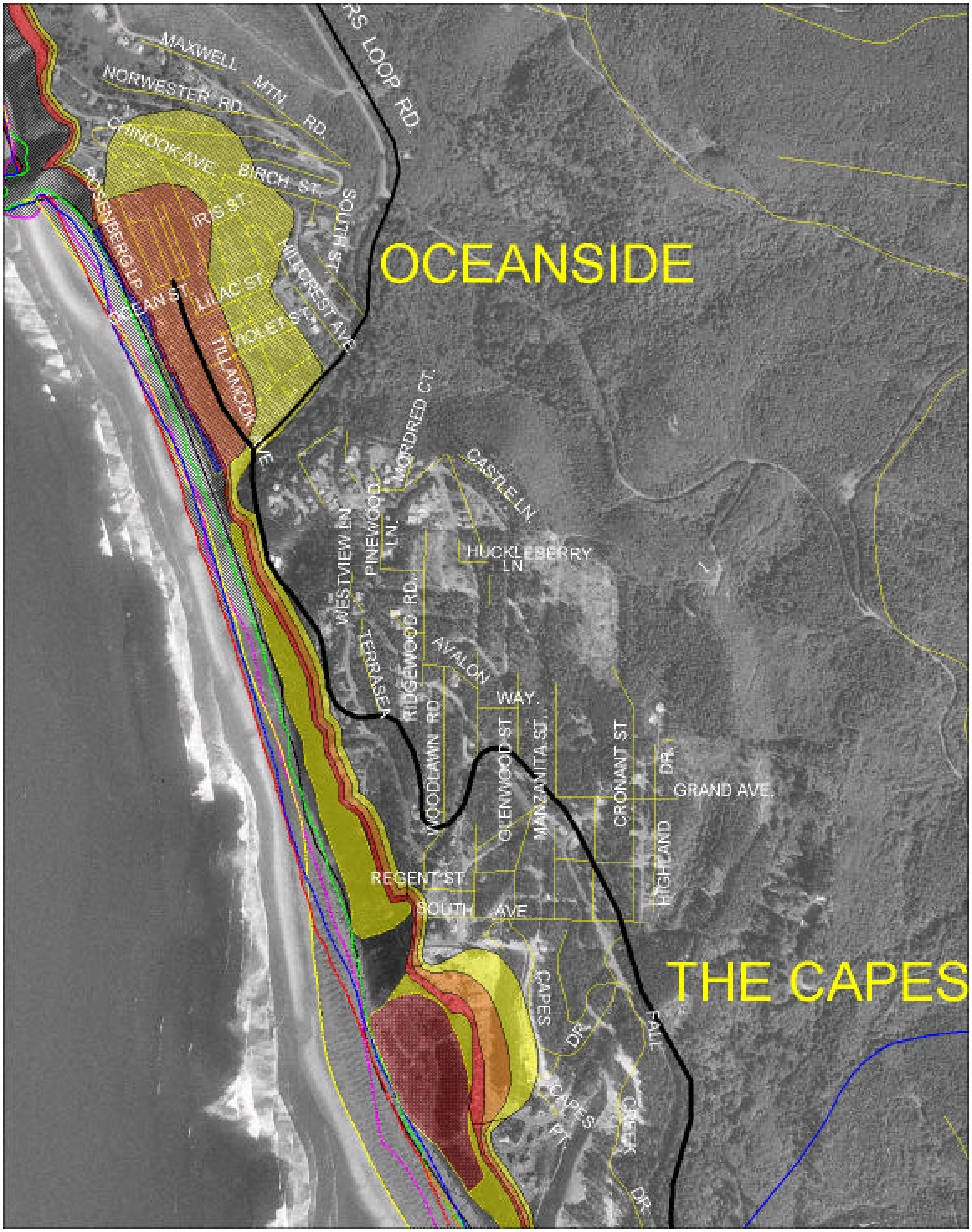
APPENDIX E (cont.)

Netarts/Happy Camp (scale = 1:12,000 or 1 inch = 1,000 ft)



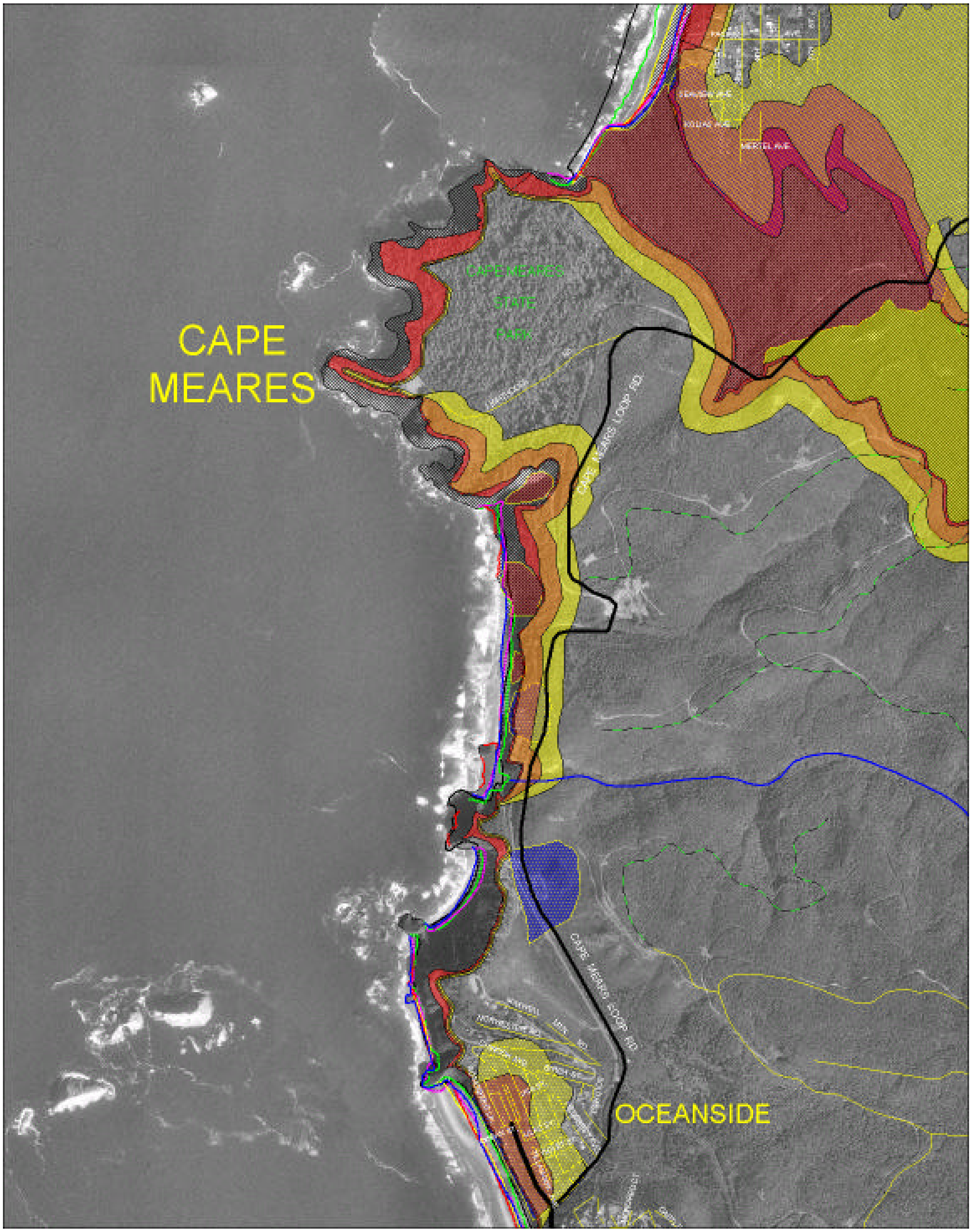
APPENDIX E (cont.)

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



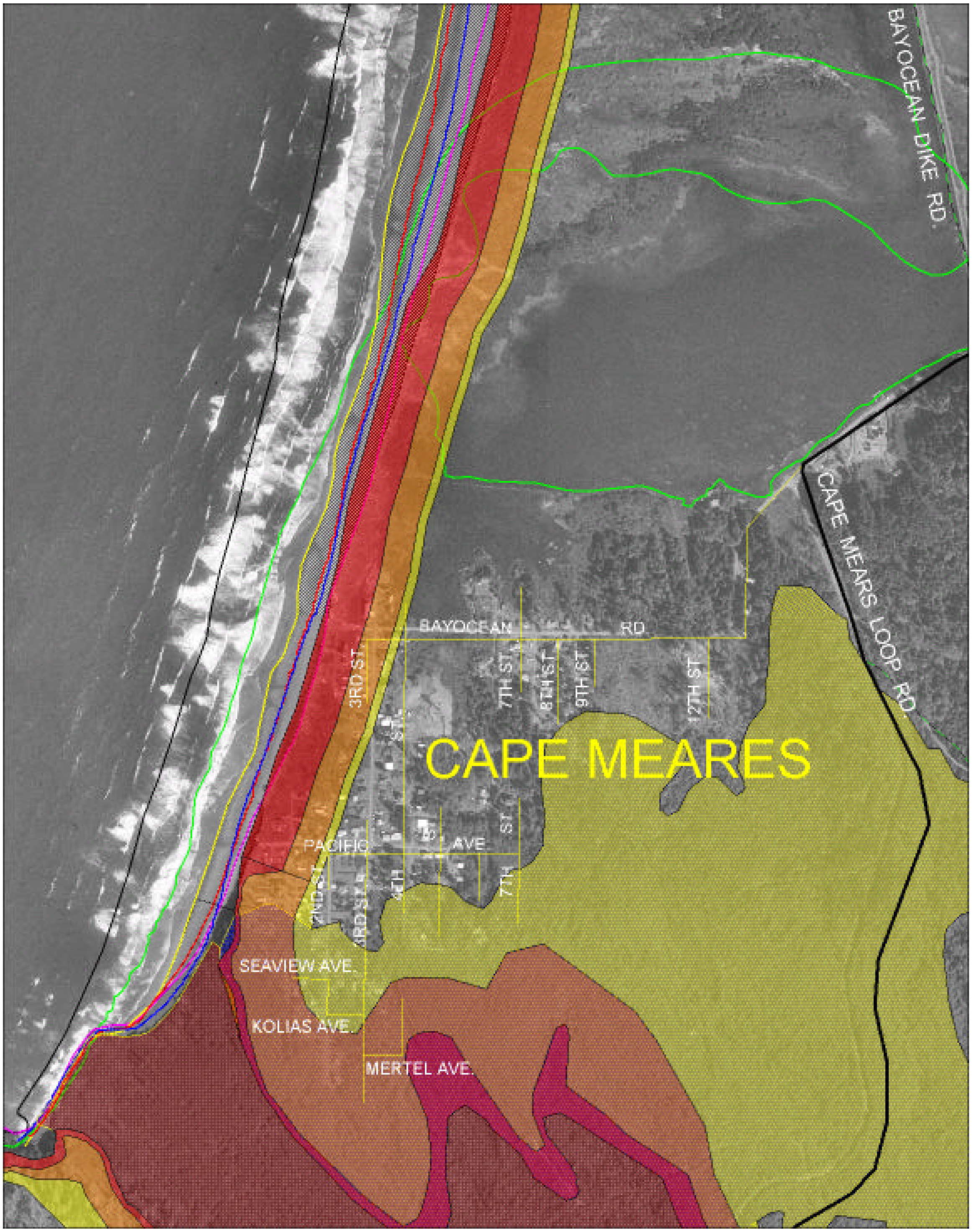
APPENDIX E (cont.)

Cape Meares (scale = 1:24,000 or 1 inch = 2,000 ft)



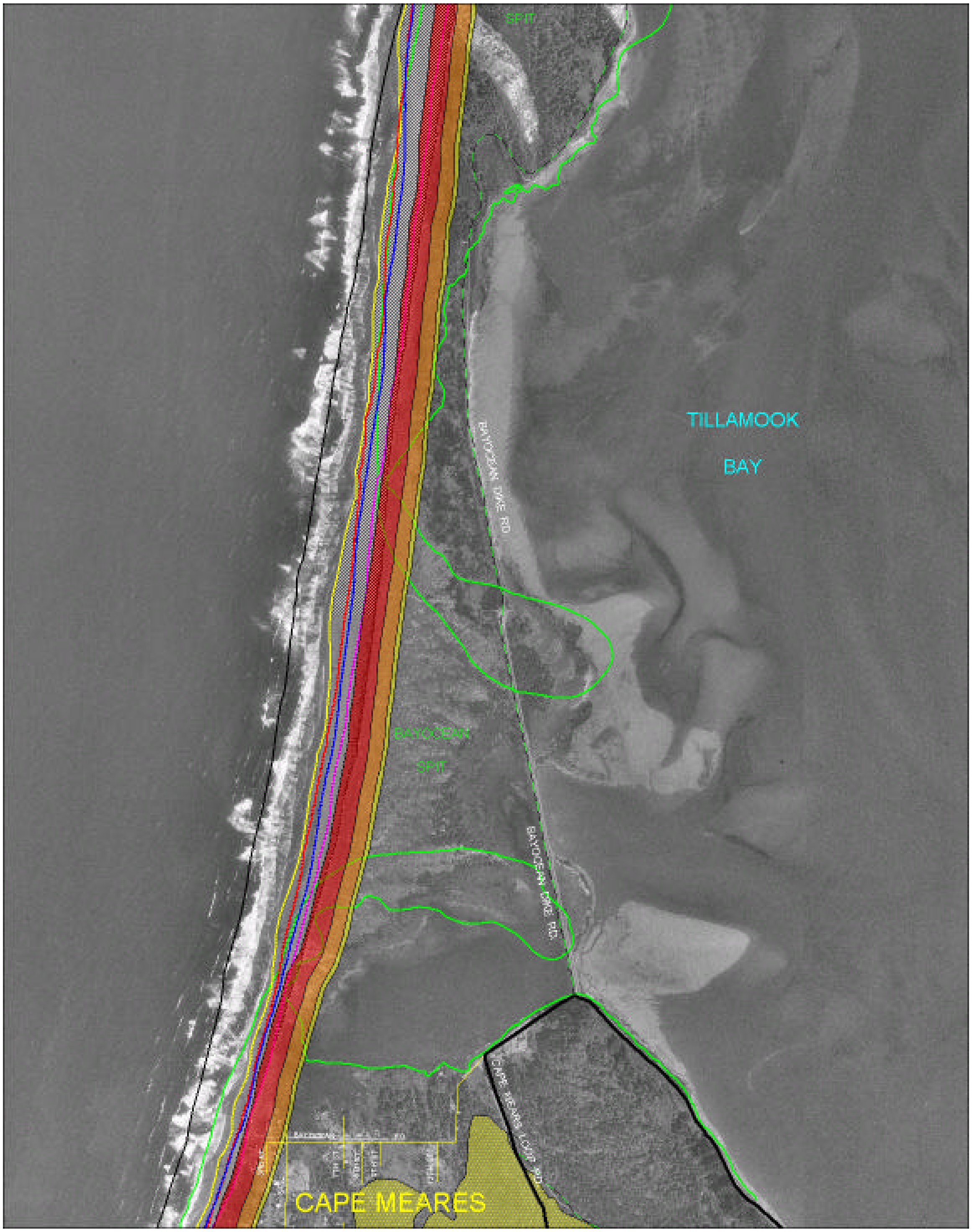
APPENDIX E (cont.)

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



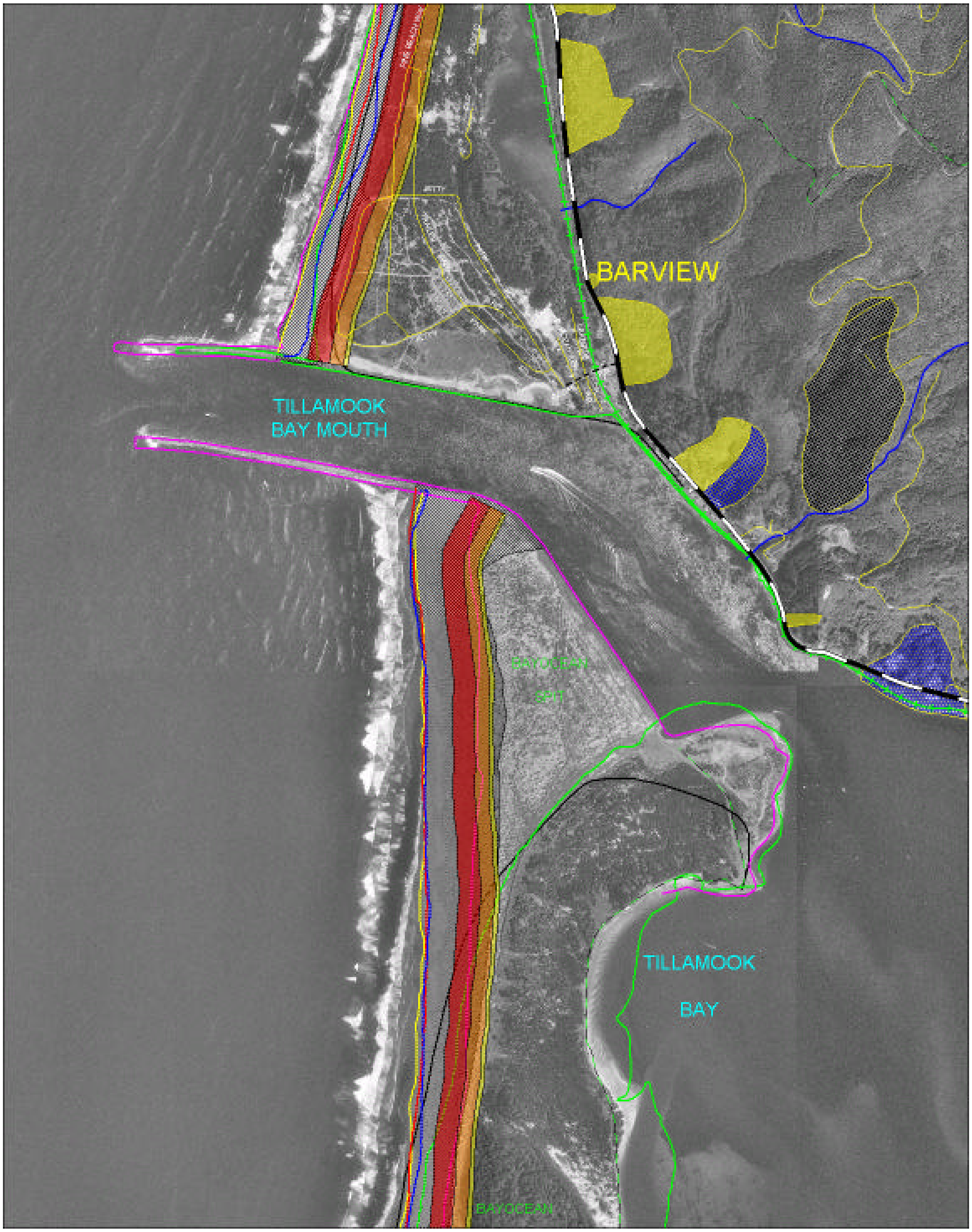
APPENDIX E (cont.)

Bayocean Spit (scale = 1:24,000 or 1 inch = 2,000 ft)



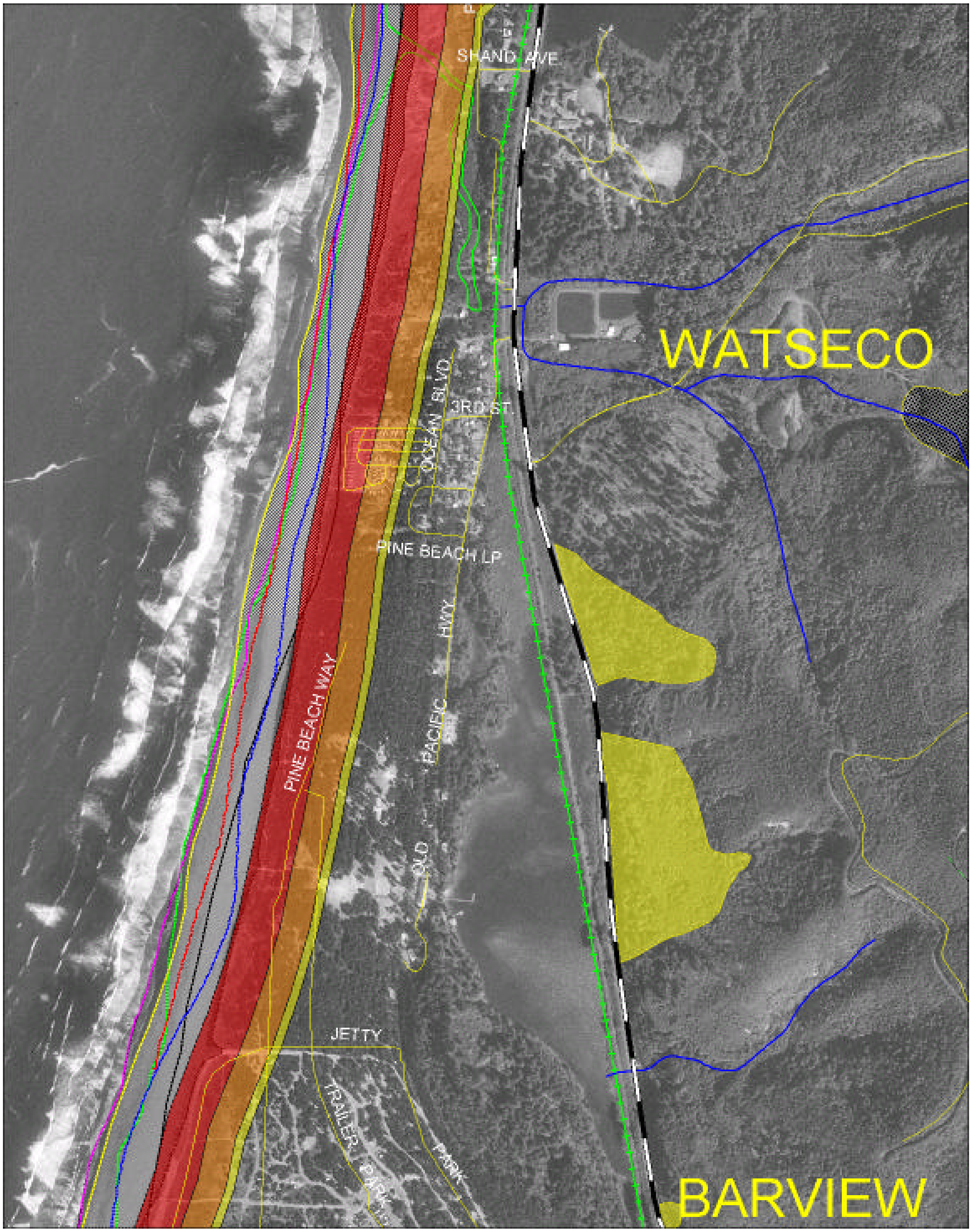
APPENDIX E (cont.)

Tillamook Bay Mouth (scale = 1:24,000 or 1 inch = 2,000 ft)



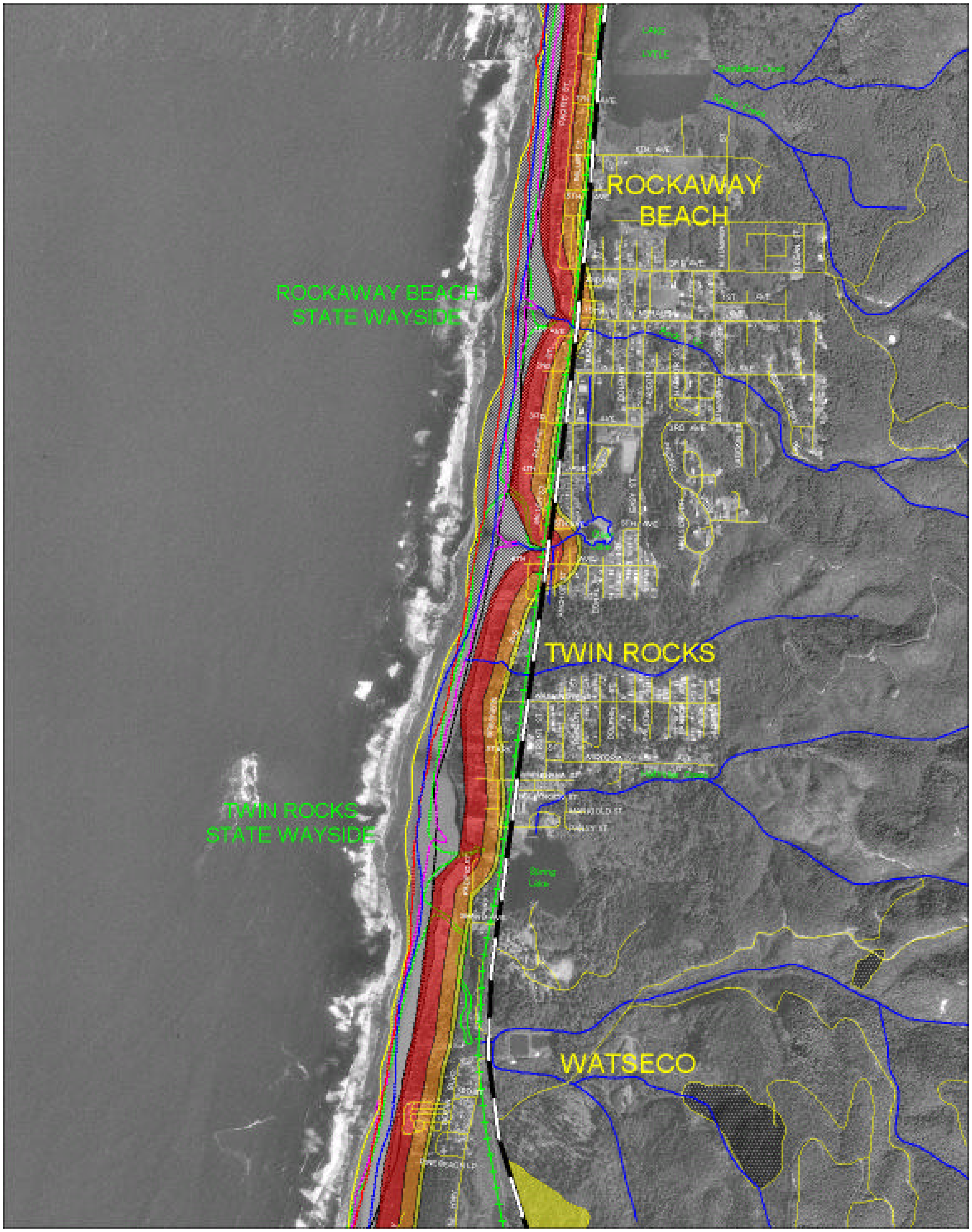
APPENDIX E (cont.)

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



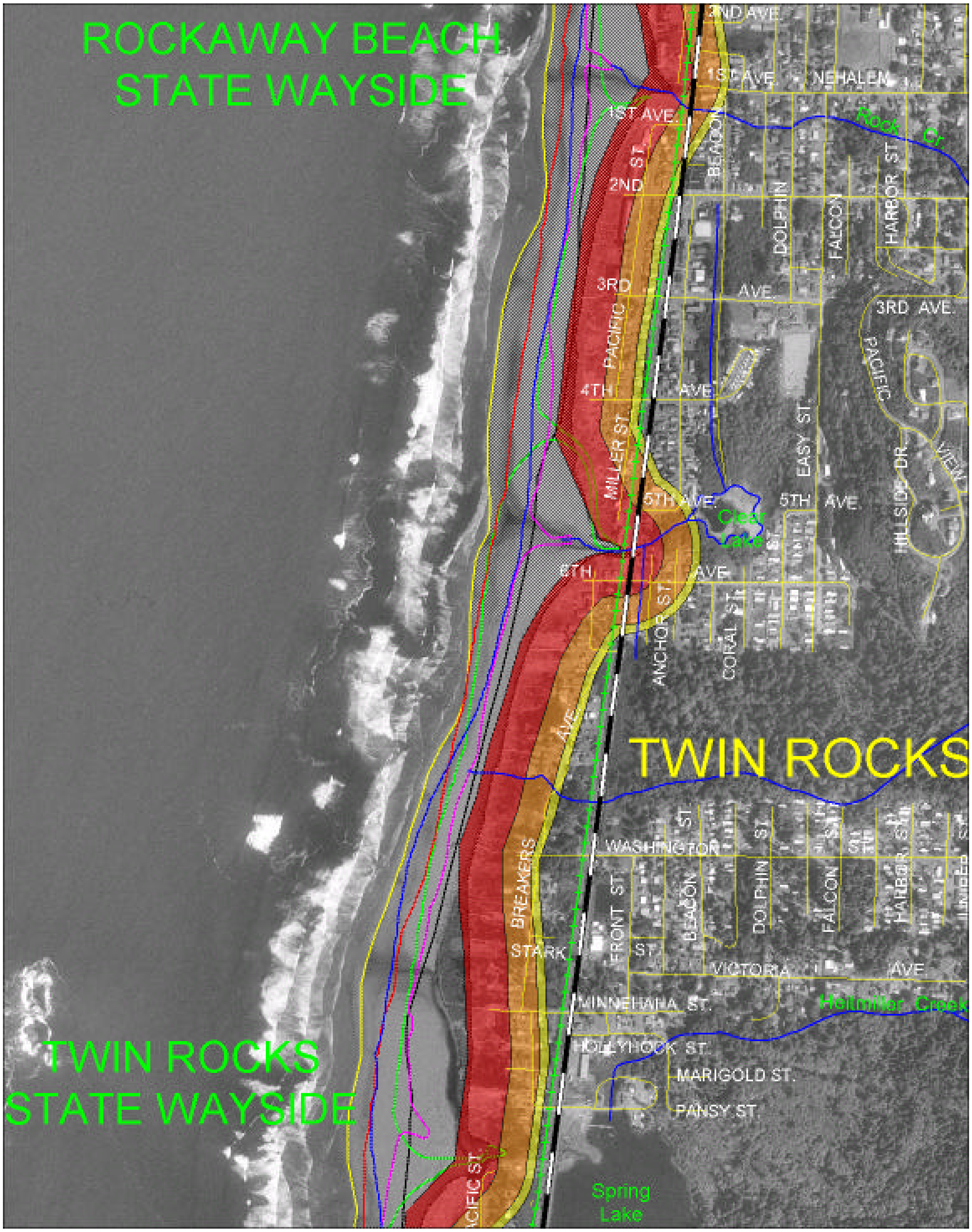
APPENDIX E (cont.)

Rockaway (scale = 1:24,000 or 1 inch = 2,000 ft)



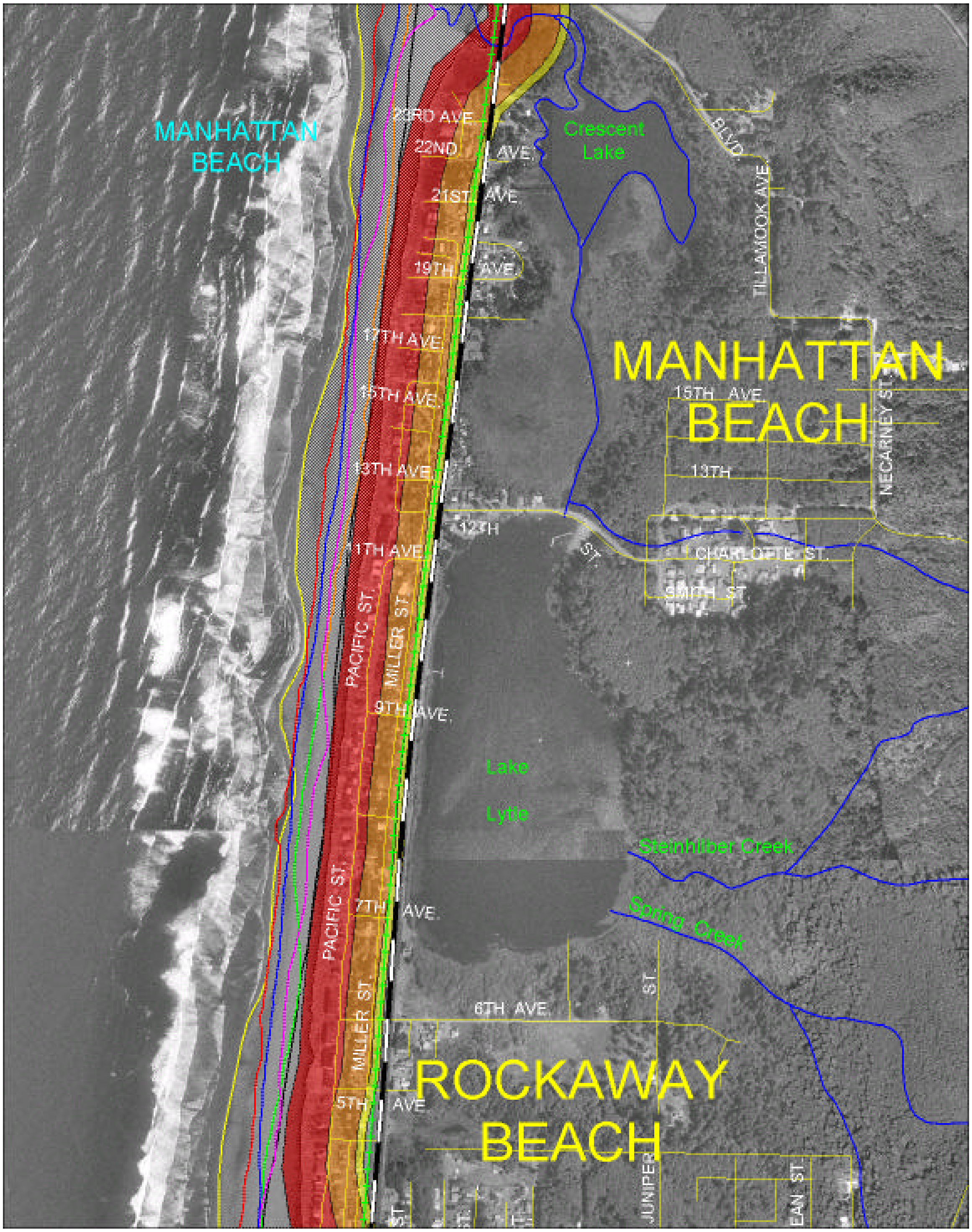
APPENDIX E (cont.)

Twin Rocks/Rockaway (scale = 1:12,000 or 1 inch = 1,000 ft)



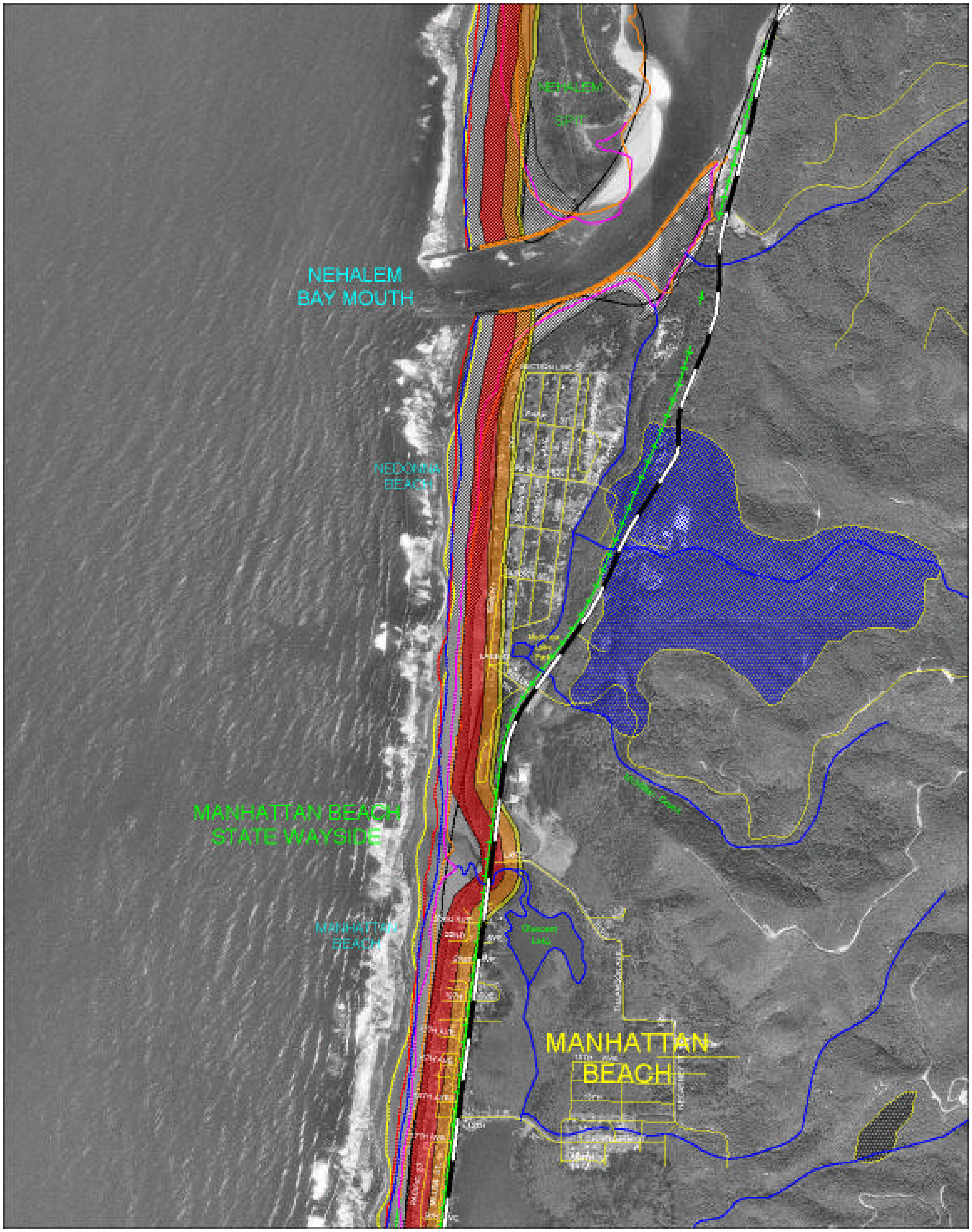
APPENDIX E (cont.)

Rockaway/Manhattan Beach (scale = 1:12,000 or 1 inch = 1,000 ft)



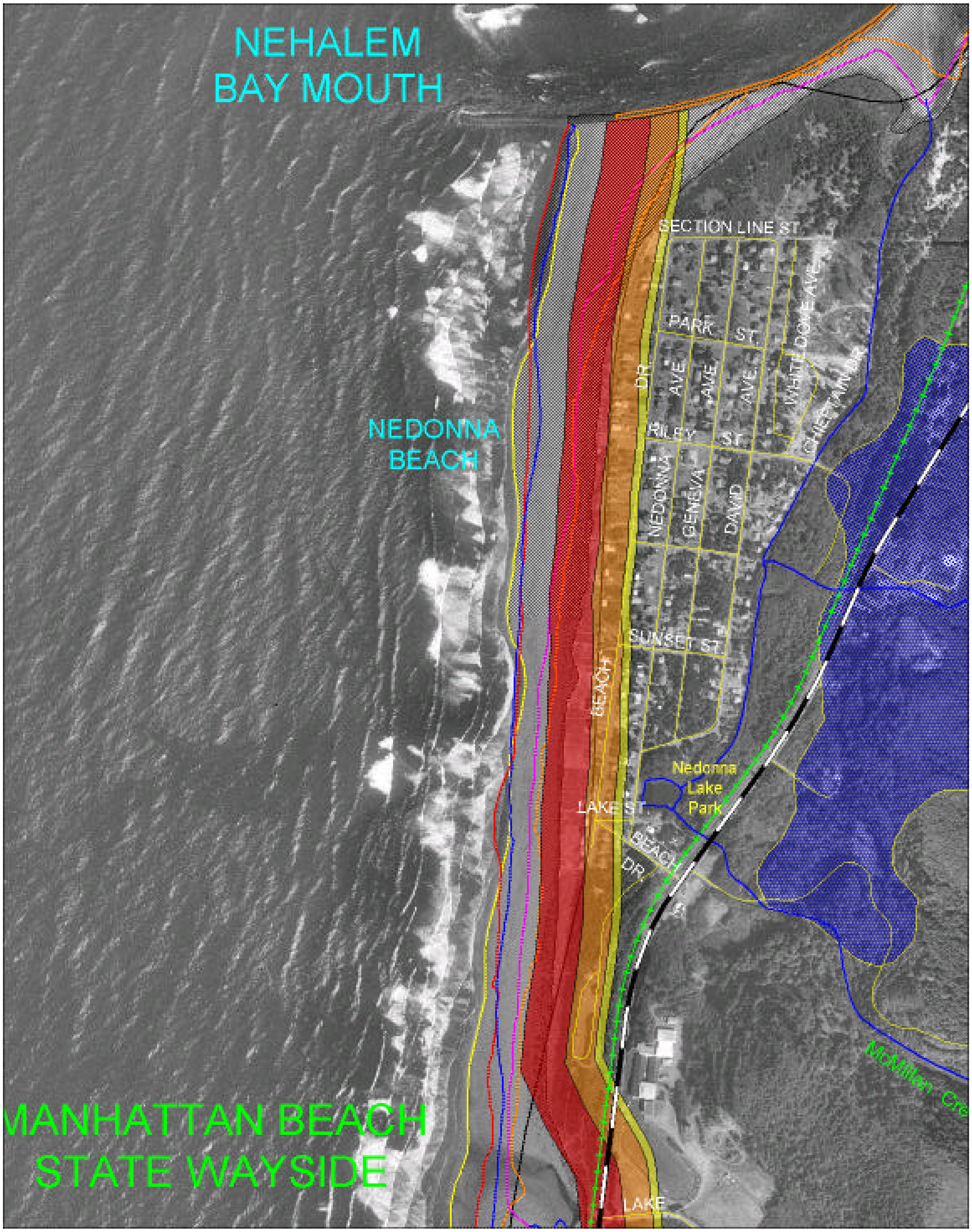
APPENDIX E (cont.)

Manhattan Beach/Nehalem Bay (scale = 1:24,000 or 1 inch = 2,000 ft)



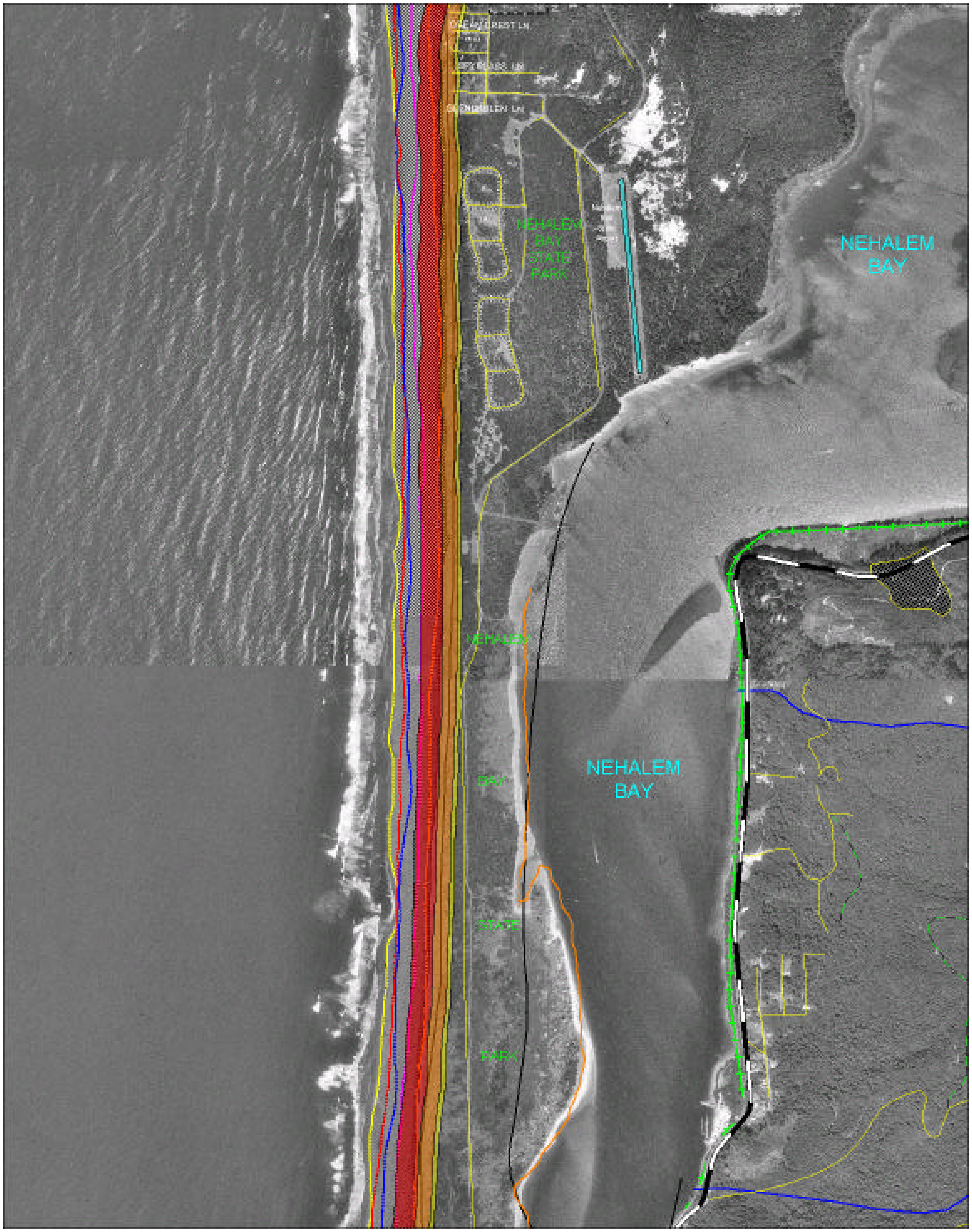
APPENDIX E (cont.)

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



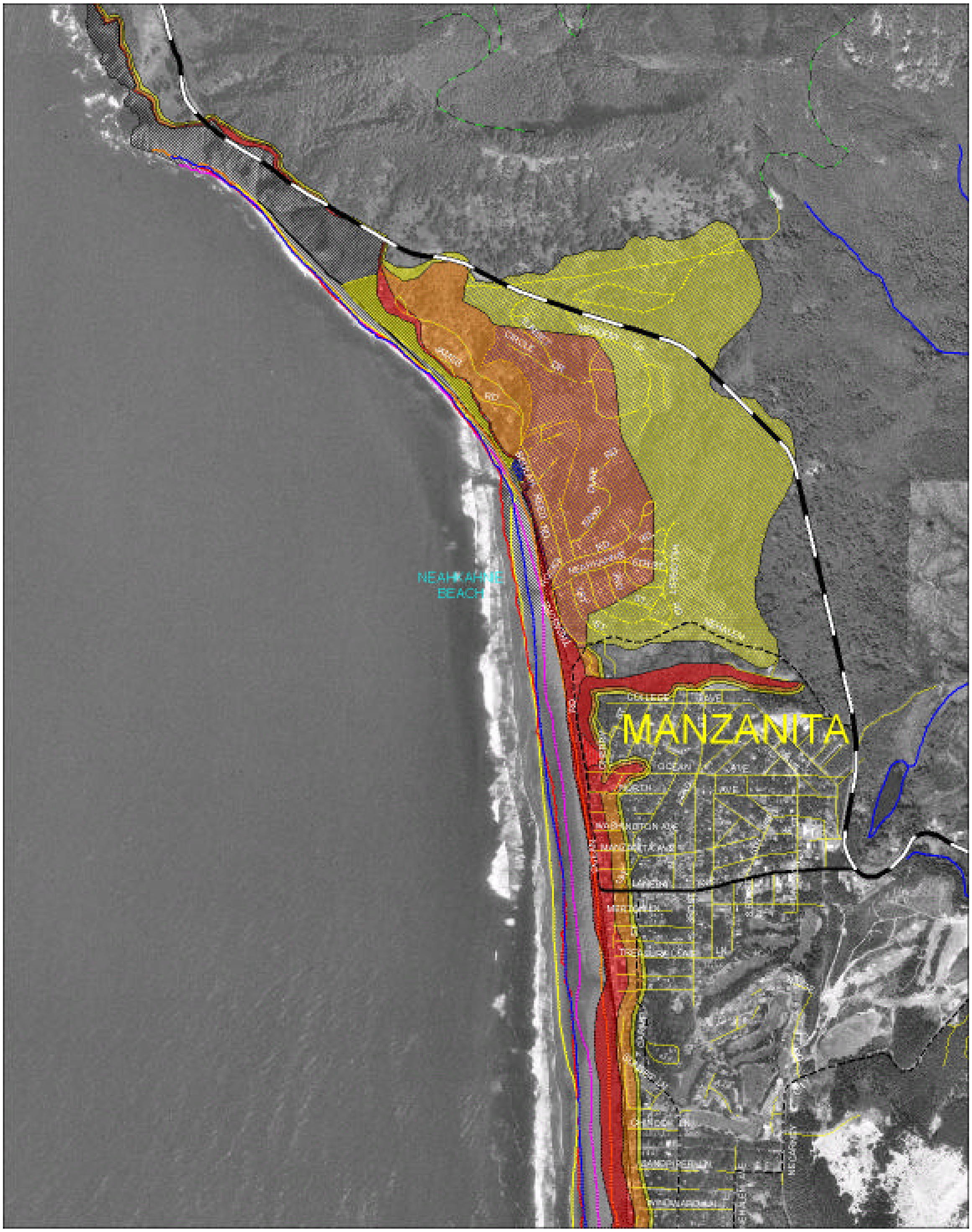
APPENDIX E (cont.)

Nehalem Bay (scale = 1:24,000 or 1 inch = 2,000 ft)



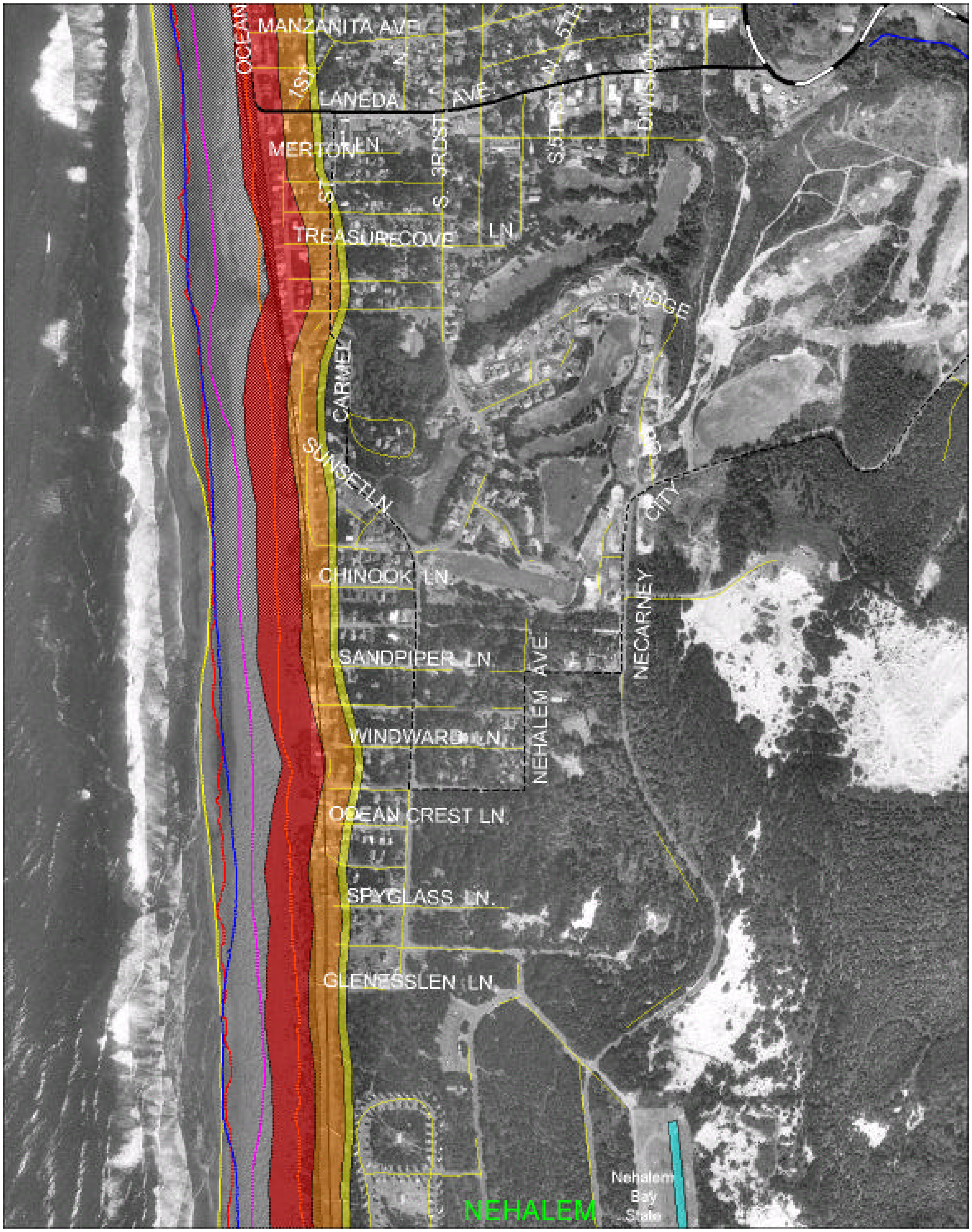
APPENDIX E (cont.)

Manzanita (scale = 1:24,000 or 1 inch = 2,000 ft)



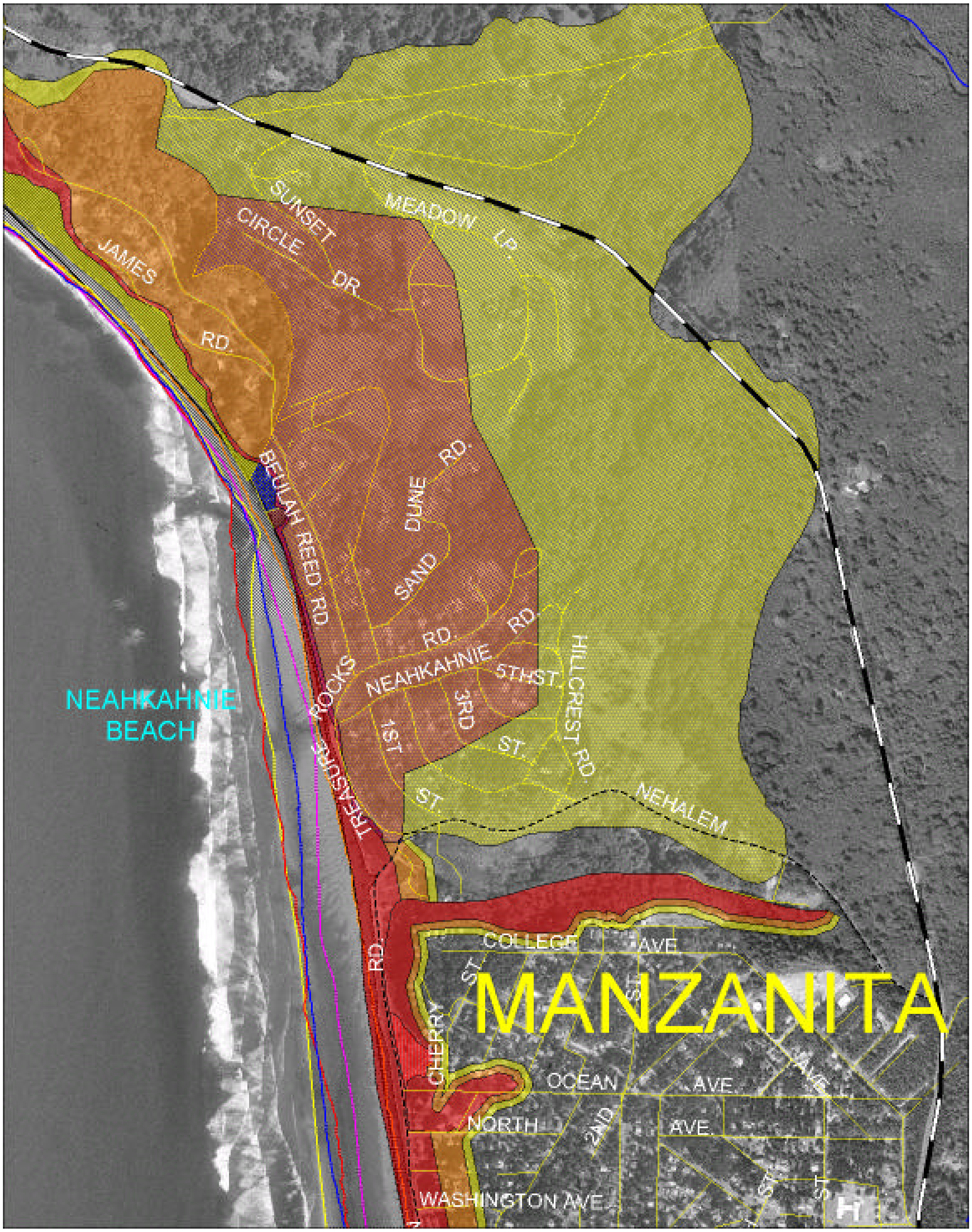
APPENDIX E (cont.)

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



APPENDIX E (cont.)

North Manzanita/Neahkahnie Beach (scale = 1:12,000 or 1 inch = 1,000 ft)



APPENDIX E (cont.)

Cape Falcon (scale = 1:24,000 or 1 inch = 2,000 ft)