Geologic Hazards of Development on Sand Dunes along the Oregon Coast

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Abstract

Sand dune geologic hazards are caused by wind erosion, water erosion and flooding from storm waves and rip currents, water erosion and flooding from tsunamis, and water contamination of freshwater aquifers and associated pollution of beaches and rivers. Some natural high-oblique and parabola dunes have been stabilized to become conditionally stable with regard to wind erosion. However, developments on these stabilized high dunes as well as on older stabilized high dunes have caused fresh groundwater pollution, in addition to associated beach pollution.

Jetty construction and associated natural vegetation disturbance have caused extensive sand blowing and deposition to occur. Stabilization because of the dune hazard favored the use of European beachgrass because it transplanted well and was vigorous enough to grow up through as much as three feet of sand burial. This grass has spread naturally from the area where it was planted to extend throughout the coast. Primarily because of the introduced European beachgrass, about 79 miles of conditionally stable foredune had formed on the Oregon Coast by the early 1970's. Hundreds of homes were placed on this new foredune before dune regulations prevented further development. Therefore, many structures are vulnerable to ocean water erosion and flooding, as well as to a tsunami flood hazard.

Introduction

There are 314 miles of ocean-facing Oregon coastline; 195 miles, or 62 percent, contain some form of present or past sand dune activity. Inventories done in the early 1970's showed 125,400 acres of sand dunes of various types and 38,980 acres of associated wet interdune areas (Reckendorf, 1975). This paper will briefly explain the history of sand dune development along the Oregon Coast and the components of the dune resource that reflect the land-use carrying capacity and wise use of the dune and interdune resources. The effects on land use from sand dune stabilization and plant introduction will be explained, as well as the traditional effects from housing development.

Setting

The beaches and dunes of the Oregon coast are relatively recent geologic features. By tracing the processes that have acted upon the coastal landscape through time, climate, marine influences, geology, soils, plant succession, and human settlement, the dynamic nature of these beaches and dune systems can be better understood.

Study Area and Sand Sources

The dune evaluation will cover the area from the Columbia River at the Oregon-Washington border to the California state line. There are three sources of sand available to form sand dunes along the study area: (1) erosion of coastal rock formations, coastal terraces, spits, and dunes; (2) sand supplied by rivers; and (3) offshore sand on the wave-cut platform of the continental shelf that is brought landward by currents. Storms along the Oregon coast provide a seasonal near-shore sand supply, whereas lower-energy waves and currents, which occur on a continual basis, transport the near-shore sand to beaches and tidal inlets (Peterson et al., 1982).

Climate and Marine Influences

The climate in Oregon's coastal zone is mild, with small seasonal variations in temperature. Winters are wet and cool, and coastal fog, which occurs in the warmer months, reduces the moisture loss that would otherwise occur during the dry summer months (Reckendorf, 1975).

Winds are generally from the northwest during the summer and the south, southeast, and southwest during the winter (Reckendorf, 1975). Along the central Oregon coast there is a tendency for low-velocity offshore east winds during January. The Oregon coast receives the full force of storms that move inland from the Pacific Ocean. The result is heavy precipitation and winds potentially exceeding hurricane speed of >74 mph in the winter. Winds can be expected to reach 90 to 100 mph once in a hundred years (COE, 1974).

Waves reaching the coast generate longshore currents in the near-shore area that are important in the movement of sand along the beach and in associated beach erosion. When waves break at an angle to the shoreline, they generate a current that flows parallel to shoreline. These currents, together with the waves, produce a transport of sand along the beach, known as littoral drift (Komar, 1979). Winds and associated waves tend to arrive from the southwest during the winter months and from the northwest during the summer months. As a result, littoral drift has a tendency to change directions from season to season, within specific subregions of the coast confined by headlands or jetties. These subregions are called cells. Work by Chesser and Peterson (1987) showed that based on physiographic and mineralogic analysis, there are at least 17 major littoral cells along the Pacific Northwest coast. Their results showed that longshore transport is highly correlated to prevailing wave approach angle. In addition, they indicated that episodic events may overshadow seasonal cycles of transport.

Sand deposited on the beaches is exposed at low tide, dries quickly, is caught by the wind, and is carried inland to form dunes. Vegetation established on the sand provides lodgment for the sand and accelerates sand dune development.

Study Area Geologic History

At the end of the Cretaceous (66 million years ago) the state of Oregon was covered by a shallow sea, except for the Klamath and Blue Mountains. A loose chain of volcanic sea mounts was forming on the ocean floor at about the location of the present Coast Range. The lava flow from the volcanic centers were pillow basalts and breccias of oceanic theolitic basalt composition. These are now viewed as the Siletz River Volcanics and related units (Drake, 1982). These rock units provide distinctive dark green augite sand

supply to the beaches and resistant volcanic rock that forms steep gravel and cobble beaches.

Low islands of basalt were built that were first uplifted by plate tectonics and then subsided. The archipelago accreted to the western margin of North America, and a series of forarc basins filled with marine deposits from Eocene (38-54 million years ago) through Pliocene age. Middle Eocene turbidites (Tyee Formation) were deposited at depth on top of the theolitic basalts (Orr et al., 1992). The sandstones in the Tyee Formation would provide a high future sand supply of quartz and feldspars to the beach. The area then experienced a major tectonic uplift and associated erosion during the middle and late Eocene. Initially, the existing uplifted Klamath Mountains to the south contributed most of the detritus to the newly formed basins with distinctive heavy minerals such as pink garnet, epidote, and olivine (Reckendorf, 1975). As the watersheds extended to the east, the primary source of sediment was the Idaho Batholith (Orr et al., 1992). Volcanic activity persisted throughout the Eocene, so igneous materials frequently interbedded with sedimentary layers. By the late Eocene, tuffaceous silts, sediments of volcanic origin, and clays rich in organic matter began to be deposited by streams and rivers flowing from the surrounding highlands (Orr et al., 1992).

The Coast Range was uplifted by the late Oligocene (26-38 million years ago) and thick sills of gabbro were formed (Orr et al., 1992). Vast quantities of arkosic (high feldspar and quartz from granitic rocks) sediments from the Klamath Mountains were deposited in the basin during the Oligocene time. The deposition of marine sediments shifted westward, and siltstones and mudstones of the Nye Mudstone and related units were deposited in early Miocene. In middle and late Miocene, the near-shore-deposited sediments of the Astoria Formation were formed in the north (Drake, 1982). As the western edge of the North American plate was being buckled because of the subducting Juan de Fuca plate, lava flow from fissures in eastern Oregon reached the coast (Orr et al., 1992). The uplift of the Coast Range reached its greatest height about 12 million years ago.

Some of the Eocene to Pliocene sediments deposited in the forarc basins, were accreted to the continental plate as the Juan de Fuca and Gorda Plates subducted below the North American Plate. These additions increased the westward growth of the continent and can be observed today in sea cliffs. The accreted mudstones and siltstones, like those in the Nye formation, are subject to extensive erosion, and some of the seaward-dipping units are quite prone to landslide activity and the addition of sediment supply to the local littoral cells (Reckendorf, 1975).

In the Pliocene, and later through the Pleistocene and Holocene, the shoreline of western Oregon was shaped, and the river valleys that we see today were formed. Rapid erosion of the sandstones, siltstones, and volcanic rocks continued through the Pliocene and Pleistocene periods, and beginning about one million years ago extreme fluctuations in the sea level started to occur, associated with continential glaciation (Orr et al., 1992).

Pleistocene wave-cut platforms were formed during interglacial periods associated with eustatic high stands of sea level. At the time of sea level transgression some dunes were able to form and move inland associated with the new beach sand supply. Numerous high sea-level stands occurred during the Pleistocene, especially between 350,000 and 100,000 years ago (Cooper, 1958). Mixed beach progradation, as the sea level dropped and shoreline transgression associated with sea level rise occurred, several high sea-level stands occurred that correlate to equivalent coastal platforms. These former wave-cut platforms have been uplifted to various degrees at different locations by tectonic deformation associated with plate tectonics. Therefore, as many as five to seven coastal terrace levels, and associated dunes, can be found at various locations along the coast (Cooper 1958, and Reckendorf ,1996).

It has been shown mineralogically (Scheidegger, et al., 1971) that sand derived from the Klamath Mountains occurs on beaches along the entire length of Oregon. Since present headlands confine the littoral cells, the mineralogy indicates that lower sea-level stands during glacial periods were many miles west of the present location. The Columbia River was certainly a major source of the beach and later dune sand, but much of its sand supply has moved to the north of the Columbia River. In addition to large quantities of quartz and feldspar, the Columbia River sand supply was high (45%) in the mineral hypersthene (Komar, 1992).

About five to seven thousand years ago, the rise of the sea level decreased as water approached its present level (Cooper, 1958). Associated with this sea-level stability would be sand dunes, as the sand supplied to a constant beach level moved inland.

Recent work by Burns and Peterson (1996) shows nine paleosols in a sand dune parabola at Cape Kiwanda on the north coast. The paleosols in the sand dunes represent periods of dune stability and date from only a few hundred years at the top to about 5,000 years near the bottom of the parabola near present sea level (Burns and Peterson, 1996). In the lower parts of the parabola, there was likely some late Holocene decrease (a few meters) in sea level to allow for periods of extensive beach sand exposure and new dune accumulation that buried the prior vegetated soil surface. These were likely followed by periods of vegetation growth and dune stability when the sand supply was cut off by higher sea-level periods. Eventually the parabola reached a height at which there was a sufficient volume of sand supply within the parabola to sustain some slowed parabola growth, even without a connection to a beach sand supply. Local conditions of climate, fire, and human disturbance likely influenced dune stability in the last few thousand years. Introduced grass species are an additional influence on dune stability in the last 75 years. The parabola is still slowly growing, but much of its beach sand supply has been cut off by housing developments and sand stabilization.

An aspect of the geologic history that has become very important in evaluating sand dune hazards is the history of subduction-zone earthquakes and associated tsunamis. Geologic evidence (subsidence of marshes and their burial) of great earthquakes

having occurred prior to European settlement is summarized in Madin (1992) and in Peterson and Priest, (1992). Part of the evidence is the marsh burial by zones of sand that thin landward and are thought to represent tsunami flood deposits. About a dozen estuary marshes between the central Oregon and central Washington coasts show evidence of subsidence about 300 years ago (Madin, 1992). However, the regional average for 11 events along the northern Oregon coast is 450 years, +/–150 years before present (Geomatrix, 1995). One of the concerns with a megathrust subduction-zone earthquake along the Oregon coast is that there may be as little as 20 minutes between the termination of the shaking and the advance of the tsunami (Peterson and Priest, 1992).

Dune Characteristics

There is considerable variation in the types of dunes occurring along various portions of the Oregon Coast. A generalized diagram of some of the major differences in dune characteristics important from a land use point of view is shown in Figure 1. The high dune with the precipitation ridge shown in Figure 1 might be a parabola or an oblique dune. The parabola dune type is elongate like a finger and reflects: (1) a vegetated stabilized surface that concentrates the wind at the point of weakness; (2) considerable initial thickness of sand; and (3) unidirectional wind source. An oblique dune would have a broad, sloping, windward ridge with a steep slip face that reflects winds blowing from the northwest in summer and southwest in winter. It is the crest of a group of oblique ridges that forms the precipitation ridge (precipitates sand on the vegetation below). The transverse dunes, as shown in Figure 1, are much smaller dune features, with a low, sloping windward side and a steep slip face that is perpendicular to the wind direction. The wavelike pattern of the transverse dune is partly destroyed in winter due to the winds changing direction but reforms again the next summer (Reckendorf, 1975).

The other major dune form shown in Figure 1 is the foredune. This dune form is a barrier ridge of sand immediately above the high tide line and paralleling the beach. If the dune form is actively growing because of sand deposition, it is called an active foredune and is unstable from both a wind erosion and ocean flooding and erosion point of view. If the dune becomes conditionally stable with regard to wind erosion, the dune form is called a conditionally stable foredune (Reckendorf, 1975; LCDC, 1995). This dune form is called conditionally stable, because even though the dune has temporary stability from a wind erosion point of view, the dune could be suddenly destabilized by fire. In addition, this dune form has minimal to no stability from winter ocean waves and flooding or from tsunamis.

Other dune forms defined for purposes of implementing LCDC Goal 18, are older foredune, open dune sand conditionally stable, younger stabilized dunes, and older stabilized dunes. These dune forms are discussed in Reckendorf (1975), including their land-use limitations and distribution along the coast of Oregon. In addition, as previously noted, there are older foredunes along the Oregon Coast, especially in Clatsop County on the Clatsop Plains, that are expressed as a series of parallel ridges.

Shoreline Characteristics and Dune Development

According to Cooper (1958), there had been a fundamental difference in the development of shoreline features north and south of Tillamook Head. He indicates that the Clatsop Plains, north of Tillamook Head, began to form at the base of wave cut bluffs following the period of maximum submergence. In contrast, Cooper (1958) indicates that the dunes to the south had already reached their furthest advanced development prior to the end of submergence. More specific work by Rankin (1983) in the Clatsop Plains (Figure 2) showed that submergence in the middle Holocene shoreline was up against the mountain front as late as 3,500 years before present. Shoaling of vast amounts of sand at the mouth of the Columbia River allowed the progradation and outward extension of the shoreline in a series of ridges which eventually formed a broad peninsula on the western part of the Clatsop Plains (Figure 2). Areas further from the mouth of the Columbia River, such as Seaside, do not extend out as far because the available sand supply is reduced, and longshore currents have a stronger influence.

Sea-level oscillations and associated prograding and transgressing shorelines are shown by Rankin (1983) to occur between 3,500 years to 110 years before present. These dates encompass the series of parallel ridge dunes, each of which was formed along the beach line. These parallel ridges have the appearance of former foredunes, although they are higher and wider than the current foredune, such as shown in the left part of Figure 1. Rankin's work (1983) showed that the highest rate of beach prograding and associated sand dune development has occurred since jetty construction at the mouth of the Columbia River. In other words, the present foredune was the fastest-growing but is the smallest of the parallel ridges on the Clatsop Plains.

South of Tillamook Head, the inland advance of the dunes halted by stabilization before the end of submergence (Cooper 1958), although undoubtedly there were episodes of reversal and geographic variations. The region extending 125 miles from Tillamook Head in Clatsop County to Heceta Head in Lane County is characterized by: (1) active and conditionally stable foredunes that are associated with spits; (2) narrow active and conditionally stable foredune areas fronting coastal terraces; and (3) isolated active open dune sand areas. About 35 percent of the open dune sand conditionally stable mapping unit, mapped on the Oregon Coast, occurs in this region (Reckendorf, 1975). Many of the active and conditionally stable foredunes have been built upon to obtain nearby beach access and views. There is limited remaining interdune deflation plain in this region, as most of the important wildlife habitat had been drained by the early 1970's. About 35 percent of the open dune sand, conditionally stable mapping units occurs as high dunes in this region. About 78 percent of the high dunes (i.e. parabolas and obliques) had been stabilized by the the early 1970's (Reckendorf, 1975).

A third region from Heceta Head to Cape Arago is called the Coos Bay dune sheet by Cooper (1958). It formed on a large area of coastal terraces that is 54 miles long. Over 85 percent of the active high dunes on the Oregon Coast occur in this region, along with
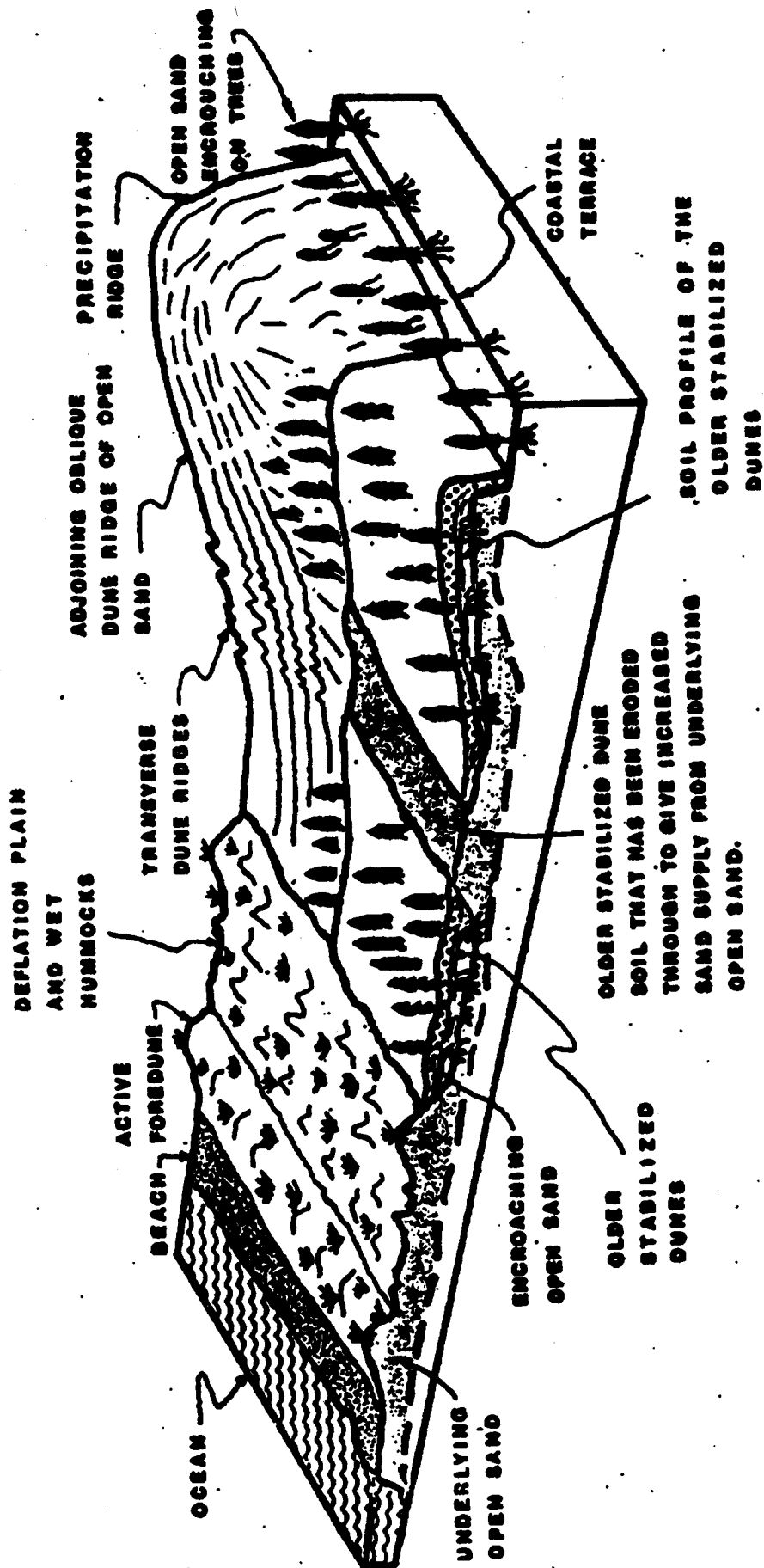
OCEAN

BEACH

ACTIVE FOREDUNE

DEFLATION PLAIN AND WET HUMMOCKS

TRANSVERSE DUNE RIDGES

ADJOINING OBLIQUE DUNE RIDGE OF OPEN SAND

PRECIPITATION RIDGE

OPEN SAND ENCROACHING ON TREES

COASTAL TERRACE

SOIL PROFILE OF THE OLDER STABILIZED DUNES

OLDER STABILIZED DUNE SOIL THAT HAS BEEN ERODED THROUGH TO GIVE INCREASED SAND SUPPLY FROM UNDERLYING OPEN SAND.

OLDER STABILIZED DUNES

ENCROACHING OPEN SAND

UNDERLYING OPEN SAND

Figure 1
Generalized Sand Dune Profile. Adapted from *Beeches and Dunes of the Oregon Coast*, Reckendorf, 1975.
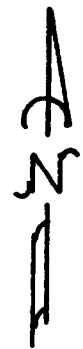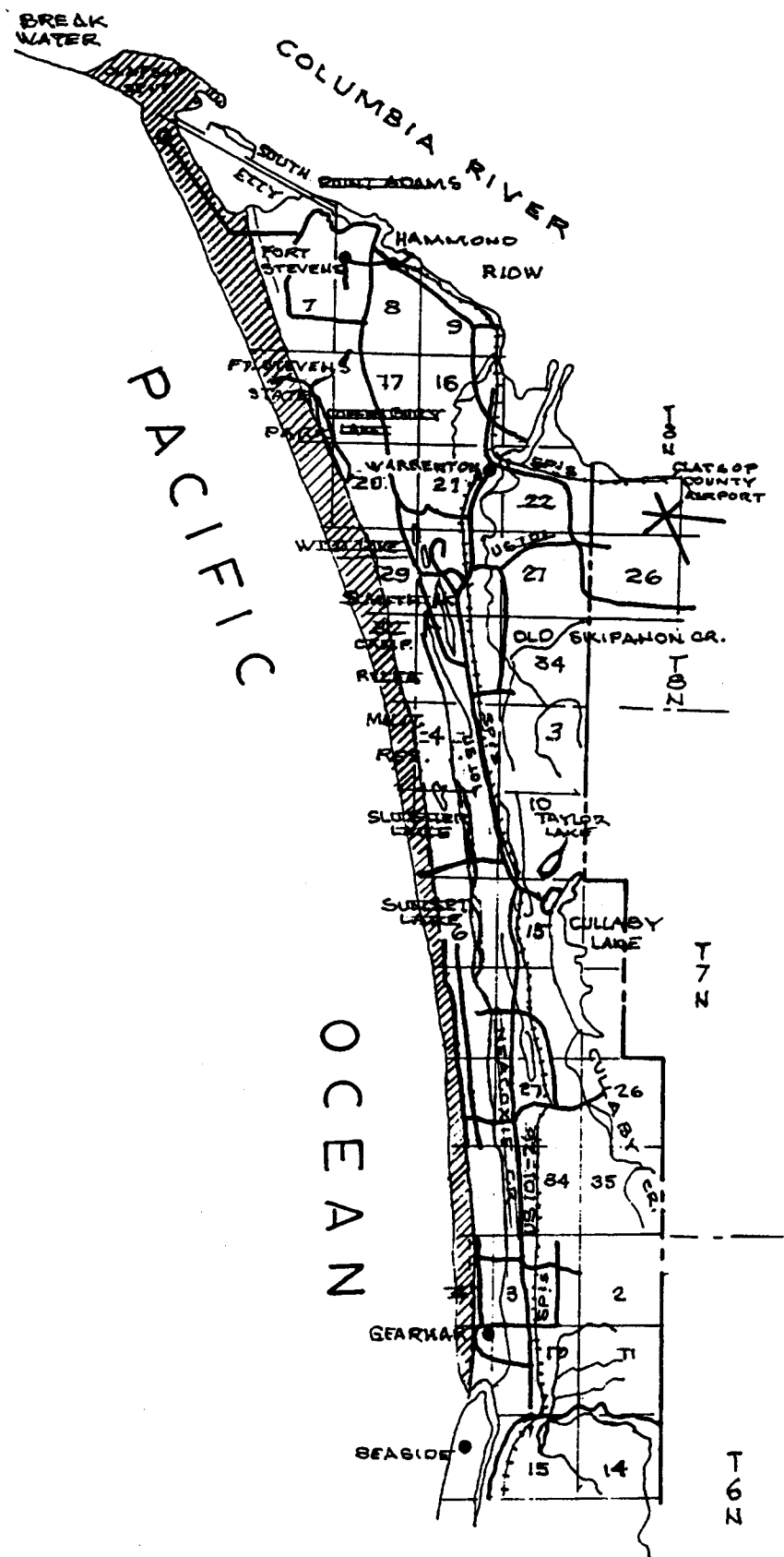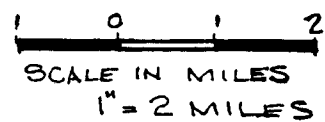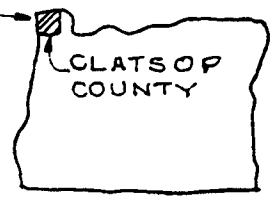
Figure 2
Sand Dune Hazard Shaded, Clatsop County, OR, January 1996

many miles of foredunes. Fortunately, the dune hazard for human use is low because most of the active high dunes and foredunes are in the U. S. Forest Service, Oregon Dunes National Recreational Area. However, these dunes have a high appeal for visitor and recreational use.

The fourth region lies between Cape Arago in Coos County and the California border. The only significant active dunes occur in the 12-mile coastal strip bisected by the Coquille River. About two-thirds of the older stabilized dunes mapping unit, mapped on the Oregon Coast occur in this region.

The relationship between the Columbia River and the Clatsop Plains on the north Coast and the Siuslaw and Umpqua Rivers and the Coos Bay dune sheet on the south coast emphasizes the importance of coastal rivers as a sand source. In the case of these two regions, the sediment deposited so exceeded the amount removed by longshore transport that beach deposition and associated dune formation has been extensive.

Dune Hazards
WIND EROSION
On May 10, 1792, Captain Gray on the ship Columbia Redevia crossed the Columbia River bar for the first time with a sailing ship (State of Oregon, 1994). This discovery of the Columbia River for large-ship use essentially opened up the Columbia River area to shipping and trading. However, the sediment bars within the mouth and offshore of the Columbia River made navigation precarious, as the Columbia River bar is one of the most treacherous in the world. To improve the navigation access to the Columbia River, construction of the south jetty started in 1885, with the north jetty to follow a few years later.

Essentially, the human intervention into the Oregon coastal dune process, and associated vegetation changes, started at the time of construction of the south jetty. This and other jetties caused the embayments at the mouth of rivers to fill in with sand (i.e., the beach prograded rapidly seaward). This accreted sand blew eastward across prior dunes, lakes, rivers, and wetlands, as well as the road and railroad infrastructure and associated development. In the early 1900's there was also a destruction of the natural grass, shrub, and forest vegetation by fire and overgrazing, which caused extensive sand blowing (Reckendorf et al., 1985). This was especially true in the Clatsop plains (Figure 2).

The combination of the jetty effects and the damage to the native vegetation created extensive sand blowing areas by the early 1900's in the Clatsop Plains. For example, a sand dune area of about 3000 acres was moving eastward in the early 1930's, burying roads, limited development, forests, rivers, estuaries, wetlands, and lakes (such as Coffenbury and Slusher Lakes). Most people today take for granted that lakes such as Coffenbury Lake in Fort Stevens State Park has always been there as viewed today. However, without massive sand stabilization work this lake would have been severely altered. In fact, a vegetated Fort Stevens State Park might not exist today if not for the extensive stabilization work.

Local officials, agencies, and corporations were very concerned with the lost resources because of sand accumulation, so stabilization work started. The O. N. & R Railroad was responsible between 1897 and 1899 for some of the earliest dune stabilization work of the west coast, which was done at the northern end of Seaside, Oregon (Reckendorf et al., 1985). A few years later, between 1910 and 1916, the U.S. Forest Service directed the planting of trees, shrubs, and European beachgrass on 47 acres of dunes, between Florence and Coos Bay, Oregon. In 1935 the USDA Soil Conservation Service in cooperation with the Warrenton Dune Soil Conservation District, Clatsop County, and the Civilian Conservation Corps, started the Warrenton Dune Demonstration Project to test various species for dune stabilization (Reckendorf et al., 1985, 1987).

European beachgrass, American dunegrass, and American beachgrass were the primary grasses tested. Based on the field trials, European beachgrass was recommended as the primary grass for use in stabilization because it transplants better as culms and has more vigorous growth (can grow up through as much as three feet of winter sand burial) than the other grasses (McLaughlin, and Brown, 1942; Carlson et al, 1991).

American dunegrass (the only native dunegrass on the Pacific Coast) was likely the grass that stabilized the higher, older foredunes (parallel ridges on Clatsop Plains), but that occurred by natural spreading of the dunegrass and with a much lower rate of sand accumulation. However, the field trials on active foredunes, as well as on active oblique and parabola dunes, showed that American dunegrass did not transplant well if other than dormant stock is used. Usually transplant survival was 25%, where 99% survival is essential (McLaughlin and Brown, 1942). Because the sand accumulation associated with jetty construction created such a high wind hazard, by the early 1930's it was essential to reduce wind damages as fast as possible. Therefore, a grass was needed that transplanted well for dune stabilization—especially in foredune stabilization that occurred in a very high wind energy and sand supply environment—so European Beachgrass was selected as the primary grass to plant. This causes some concern today because it is a non-native grass. However, in the past several years, planted American dunegrass has been outcompeting previously planted European beachgrass along the foredune in the Clatsop County, from about Fort Stevens to the Sunset Beach area (Reckendorf,, 1996). The American dunegrass is mostly on the top and on the leeward side of the foredune (i.e., further from the beach). American dunegrass has also been extensively planted in Lane, Douglas, and Coos counties in the USFS Oregon Dunes National Recreation Area, in a backdune position. Further planting of the native dunegrass under this site condition may help to spread its distribution along the entire coast, and to replace European beachgrass in many areas.

In 1937-1938, the extensive area of blowing sand in the Clatsop Plains was stabilized with a combination of sand fences and planted and fertilized European beachgrass. Herbaceous and woody vegetation was established one to two years after European beachgrass was planted. This type of planting sequence was

followed at many other locations along the Oregon, Washington, and California coasts (Reckendorf et al., 1987). The European beachgrass spread naturally from the planted locations. This resulted in beachgrass creating active or conditionally stable foredunes along much of the Oregon Coast. By the early 1970's about 76 miles of conditionally stable foredune had developed (Reckendorf, 1975). In other words, most of the modern foredune on the Oregon Coast can be attributed to the introduction of European beachgrass. Thus, the introduction of European beachgrass on the Oregon Coast has had a profound effect on land use. The European beachgrass allowed a low dune above the beach to form in a short period of time, and people saw the foredune as a landscape to develop so they could be near the beach. Minimal consideration was given to the potential wind erosion, water erosion, or ocean flood hazard that might be associated with the development on the foredune.

On the positive side, from a land-use perspective, dune stabilization has allowed road access near the beach and reduced damage to lakes, rivers, estuaries, wetlands, recreation areas, and development. To control the human damage to the wind-stabilized areas, two local units of government (Warrenton Dune Soil and Water Conservation District and Clatsop County), implemented regulations in 1948 to limit land-use activities and development in dune hazard areas (Warrenton SWCD, 1948). This was followed much later by the Oregon Coastal Conservation and Development Commission (Reckendorf, 1975) and later the Land Conservation and Development Commission, which implemented Beaches and Dune Goal 18, which applied coastwide.

There are several important requirements in Goal 18 that local governments are expected to implement. One of the most important is No 2, which states, " Local governments and federal and state agencies shall prohibit residential developments and commercial and industrial buildings on beaches, active foredunes, or other foredunes that are conditionally stable and that are subject to ocean undercutting or wave overtopping, and on interdune areas (deflation plains) that are subject to ocean flooding" (LCDC, 1995). There are some exceptions given in the provisions, but the intent is to prevent development if there is a wind erosion, or water erosion and ocean flooding hazard.

Recently for the Clatsop Plains, a study of the extent of dune hazard that should be most regulated by Goal 18 was revised (Reckendorf, 1996). The approximate boundary for the dune hazard area in the new study is shown in Figure 2. However, because of local development politics, this study has yet to be officially adopted for land-use implementation in Clatsop County.

Goal 18 required local governments to control and limit access, use, and development in identified dune types which I previously discussed. However, existing development, or areas already approved for development, were excluded. For example, the developments on the foredunes on Nestucca, Siletz, and Alsea spits were excluded. This excluded over one hundred existing homes and lots. In addition, the developments on the open dune sand conditional stable mapping unit in southern Lincoln County north

of the Alsea River and in the city of Florence in Lane County were excluded. In other words, some oblique and parabola high dunes that had been mapped as temporarily stabilized (open dune sand, conditionally stable mapping unit), were essentially excluded from the regulations. Fortunately, most of the development on sand dunes on the Oregon Coast has occurred in the Older Stabilized Dune mapping unit (Reckendorf, 1975), which covers 80,955 acres. Goal 18 restrictions on this mapping unit are minimal because to reach open dune sand that would start blowing would require deep excavation.

Because of the interest in development close to the ocean, for the view and other amenities, some development has occurred right where the active foredune growth was taking place. The development along the active foredune south of Cape Kiwanda in Pacific City is a case in point. The sand accumulation and dune growth around the houses was graded away for about 40 years. However, the south end of the Pacific City active foredune is in a state park. The active foredune in the park has grown to about 30 feet in elevation, to become a conditionally stable foredune. One can stand on top of the north end of the foredune and project a level line to the north. The projected top of the foredune projects over the tops of the peaks of most of the houses immediately to the north. In other words the houses' foundations are setting about 15 to 20 feet below the height that the foredune is trying to grow. Obviously this provides these landowners with a substantial wind deposition hazard.

WATER EROSION HAZARD
The effect of storm waves has been to periodically create a significant erosion hazard along the foredune. The impacts of storm waves are occasionally combined with the erosion effects of rip currents which hollow out troughs into the beach, over a short stretch of beach. Twenty-three-foot, significant waves have been recorded (Komar, 1992) along the Oregon Coast. Associated with these significant waves are individual waves as high as 41 feet. Waves of this magnitude (23–41 feet) with run-up can essentially overtop the modern foredune along the coast of Oregon (Reckendorf, 1996). Some storm events have been associated with El Niño events.

Over the past 27 years that the author has monitored beach and dune processes along the Oregon Coast, he has observed or monitored significant foredune erosion in every county at various times. The likely causes of some of the past foredune erosion because of storm waves appear to be: (1) reduced sand supply (Fort Stevens area); (2) jetty construction, which reduced sand supply (Tillamook Spit); (3) poor jetty maintenance (Nedona beach along Nehalem Spit); (4) rip currents (Netarts, Siletz, and Alsea Spits); and (5) significant waves (Nestucca and Yaquinna River Spits).

The Oregon Department of Geology and Mineral Industry has done some modeling of water erosion hazard from tsunami run-up associated with subduction zone earthquakes (Charland and Priest, 1995; Priest 1995a; 1995b, and 1995c). The most recent work describes the tsunami run-up effects from an evaluation of three models which provide a range of values as to the potential effects.

The results reflect differences in the width and location of the locked portion of the theoretical subduction zone fault. It is the locked portion of the fault that builds up strain that is catastrophically released during the subduction zone earthquakes (Priest, 1995c). The present modeling does reflect the attenuation effects of crossing the landscape, but the landscape is based on the 7.5-minute topographic maps with 25-foot contours. The maps resulting from the modeling have just been released (Priest, 1995c). There is such a large coastwide variation that only only the northern coast shown in Figure 2 will be used as an example of the potential tsunami water hazard on the modern foredunes or older foredunes.

According to Priest (personal communication, 1995), the particular model that shows the highest run-up shows run-up elevations to 49 feet at Seaside, 33-38 feet along the Gearhart Quadrangle, and 29 to 35 feet across the Warrenton Quadrangle. The average foredune height along the three areas mentioned is 30 to 35 feet at Seaside and along the Gearhart Quadrangle and 25 to 30 feet along the Warrenton Quadrangle. Therefore, flood run-up with these elevations would essentially overtop the modern foredune. Since the pre-jetty 1885 foredune has about the same height as the modern foredune, this dune could also be overtopped if tsunami flood heights have minimal attenuation by the time they reach that far inland. The east boundary of the projected flood run-up, based on the data given, would lie east of the sand dune hazard line shown in Figure 2.

The Priest modeling (1995a, 1995b and 1995c) takes into consideration a general land subsidence after a subduction zone earthquake. However the sand dunes, particularly the modern foredune above the beach, may show some additional subsidence effects not reflected in the modeling. During a magnitude 8.8 subduction zone earthquake, the dry sand on the foredune is likely to compact and to increase the pore pressure on the underlying wet sand. This scenario of increased pore pressure could lead to sand liquefaction and a blowout of the beach side of the foredunes where there is minimal lateral pressure. Because liquefied sand has minimal strength, the structures on the dunes are likely to settle and tilt. There are no Oregon data on foredune subsidence associated with liquefaction. However, there is evidence of coeseismic marsh subsidence of one to two meters, which is reflected in the run-up values previously presented. Therefore, it would not be unreasonable to assume that subsidence would substantially exceed the one to two meters indicated and that the overtopping of the foredune figures noted is conservative.

There is only minimal development on the foredune in Clatsop County, and that occurs in Gearhart. However, there is considerable development on the pre-1885 foredune from the town of Gearhart north to Sunset Beach Road. In other words, if the tsunami run-up wave heights are not attenuated much below the values noted for the heighest predicting model, there will likely be extensive development damage and potential loss of life, on the pre-1885 foredune on the Clatsop Plains.

Water Seepage Hazard
A third hazard exists associated with development in the dunes on the Oregon coast: contaminating freshwater dune aquifers and for providing pollutants to the beach. Since sand dunes by their very nature tend to be permeable, septic tank effluent from development on all dune types has locally become a significant problem along the Oregon Coast. Various freshwater dune aquifer contamination problems have been identified by the Oregon Department of Water Resources, and by the Oregon Department of Environmental Quality from Clatsop to Curry Counties. The freshwater contamination is from both private development and state parks. Unfortunately, many of the potential freshwater contamination problems have been dealt with only by finding alternate sources of fresh water, rather than by a more comprehensive transition from septic tanks to sewers. In the meantime, the pollution from the septic tanks frequently reaches the beaches and river mouths where unsuspecting children and adults play in the polluted water.

Goal 18 does provide that "Local, state and federal plans implementing actions and permit reviews shall protect the groundwater from drawdown which would lead to loss of stabilizing vegetation, loss of water quality, or intrusion of salt water into water supplies" (LCDC, 1995). However, building permits for single-family dwellings are exempt from this requirement if appropriate findings are provided in the comprehensive plan or at the time of subdivision approval.

The water contamination problems caused by septic tanks is complex in that the source of pollution may not be directly over the polluted area. Discontinuous soils and iron bands, such as those reflected in Figure 1, frequently control the direction of subsurface flow, along with the stratigraphy of the coastal terraces and underlying rock units. However, the impermeable soils in the coastal terraces and the less permeable underlying rock units tend to direct the pollutant loads laterally to the closest sea cliff or drainageway. Seepage at this boundary is common along the coast, even in the dry months, because of the pollution load.

The largest area of dunes that provides the potential for groundwater and beach contamination problems are the open dune sand conditionally stable mapping unit (4,970 acres), younger stabilized dunes mapping unit (14,945 acres), and the older stabilized dunes mapping unit (80,955 acres) (Reckendorf, 1975). These dunes are spread throughout the coast, so any local evaluation needs to review the specific county maps in the baseline study used in developing Goal 18 (Reckendorf, 1975).

Conclusions
There are many geologic hazards associated with development on sand dunes. These include wind erosion and deposition, water erosion and flooding from storm waves and rip currents, water erosion and flooding from tsunamis, and contamination of freshwater aquifers with associated pollution of beaches and rivers. Current wind erosion hazards for development vary from extreme on active foredunes where dune grading has taken place, to severe for development built into or on top of active foredunes, to moderate on conditionally stable foredunes. These conditionally stable foredunes still have a reasonably high dune hazard because

fire can suddenly destabilize the area for wind erosion and deposition to occur.

There has been some controversy over the years because European beachgrass has displaced the native American dunegrass on many of the coastal dunes of Oregon. This has been somewhat reversed in recent years in many areas, especially where American dunegrass has been planted in site conditions where it can out compete the European beachgrass. Therefore, there is a potential to increase the presence of American dunegrass.

Along with the positive effects of reduced wind erosion damage and increased access that European beachgrass has allowed, European beachgrass has created a problem that is much more detrimental from a land-use point of view than the reduced distribution of a native grass species. The vigorous nature of European beachgrass allowed a modern foredune to form quickly above the beach line. People interested in being close to the beach developed on this foredune. In other words, there was very limited natural foredune area along the Oregon Coast, except in Clatsop County, where the parallel ridge dunes formed. The European beachgrass allowed for the modern foredune, and much of the development occurred before land-use regulations prevented or slowed development on the vulnerable fordune area.

The wind erosion hazard that applies to high dunes—such as parabola and oblique dunes—is supplemented by a water erosion and flooding hazard on active and conditionally stable foredunes. In other words, the foredune can be stabilized with grasses, shrubs and trees, to decrease the wind erosion hazard, but these dunes provide only limited protection against water erosion and flooding. The dune stabilization can be used to increase the bulk (i.e., width and height) of the foredune, which provides some indirect protection for development placed behind the foredune. However, there has been no comprehensive attempt by builders to place structures behind foredunes so they benefit from the limited protection from erosion and ocean flooding provided by the bulk of the foredune.

There are several hundred homes or businesses on active or conditionally stable foredunes on the Oregon coast that are vulnerable to ocean flooding from significant waves, as well as tsunami hazards. Communities or unincorporated areas with high potential hazard are: (1) Gearhart and Seaside in Clatsop County; (2) Nedona Beach and Pacific City in Tillamook County; (3) the developments along Siletz, Yaquina, and Alsea spits in Lincoln County; (4) Florence in Lane County; (5) Coquille River spit in Coos County; and (6) Rogue River spit and Gold Beach in Curry County.

The long-term outlook is for increased beach and foredune erosion and flooding from ocean storms and waves. A major part of the problem is likely to be reduced sand supply to rebuild beaches during the summers, after they have been eroded and steepened during winter storms. The impact of reduced sand supply might be difficult to establish but includes: (1) reduced sediment supply because of dam entrapment; (2) the lack of flushing flows in the lower rivers because of flood control; (3) increased storm and El Niño events since foredune establishment; (4) riprap and concrete protection of shorelines that used to provide a sand supply to the beach; and (5) reduced sand supply in the beach because of the increased sand supply being tied up in the foredune.

The long-term trend is also for erosion and flooding because of tsunamis. Certainly both the recurrence interval and the height of the flood wave are debatable based on the available data. However, because of the large amount of development on the vulnerable foredune position, it is reasonable to conclude that there will be future damage and potential loss of life from megathrust, earthquake-caused tsunamis.

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