DYNAMIC REVETMENTS FOR COASTAL EROSION STABILIZATION: A FEASIBILITY ANALYSIS FOR APPLICATION ON THE OREGON COAST

Special Paper SP-37

By

Jonathan C. Allan, Ron Geitgey, and Roger Hart

Oregon Department of Geology and Mineral Industries

Cover photograph: Cove Beach gravel berm. The size and sorting characteristics of the sediments and the steep nature of the gravel face make this one of the most impressive and dynamic gravel beaches along the Oregon coast. View is looking landward (east). Photograph by Roger Hart, July 2003.

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

Special Paper SP-37

Dynamic Revetments for Coastal Erosion Stabilization: A Feasibility Analysis for Application on the Oregon Coast

By Jonathan C. Allan[1], Ron Geitgey[2], and Roger Hart[1]

2005

[1] Oregon Department of Geology and Mineral Industries, Coastal Field Office, 313 SW 2nd Street, Suite D, Newport, OR 97365
[2] Oregon Department of Geology and Mineral Industries, 800 NE Oregon Street, Suite 965, Portland, OR 97232

Oregon Department of Geology and Mineral Industries Special Paper 37
Published in conformance with ORS 516.030

For additional information:

Administrative Offices
800 NE Oregon Street, Suite 965
Portland, OR 97232
Telephone (971) 673-1555
Fax (971) 673-1562

http://www.oregongeology.com
http://www.oregongeology.state.or.us

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

Nature of the Northwest Information Center
800 NE Oregon Street, Suite 177
Portland, OR 97232
Telephone (503) 872-2750
http://www.naturenw.org

or these DOGAMI Field Offices:

Baker City Field Office
1510 Campbell St.
Baker City, OR 97814-3442
Telephone (541) 523-3133
Fax (541) 523-5992

Grants Pass Field Office
5375 Monument Drive
Grants Pass, OR 97526
Telephone (541) 476-2496
Fax (541) 474-3158

TABLE OF CONTENTS

(Table of Contents, continued)

LIST OF FIGURES

(List of Figures, continued)

LIST OF TABLES

CONVERSION FACTORS (ENGLISH TO METRIC; METRIC TO ENGLISH)

Multiply	by	to obtain
inch (in)	25.40	millimeters (mm)
miles (mi)	1.609	kilometers (km)
cubic feet (ft^3)	0.0283	cubic meters (m^3)
millimeters (mm)	0.0394	inches (in)
kilometers (km)	0.6214	miles (mi)
cubic meters (m^3)	35.31	cubic feet (ft^3)
cubic meters (m^3)	1.308	cubic yards (yd^3)

Acknowledgements

We thank the Oregon Department of Transportation Research Unit and the Federal Highways Administration for funding this study (contract number 21019). In particular, we are grateful for the assistance (and patience) provided by Dr. Matthew Mabey. This work was also partially funded under the National Shoreline Erosion Control Development and Demonstration Program (Section 227) authorized by the Water Resources and Development Act of 1996 (Public Law 104-303, 110 Stat. 3658), under contract number W912HA-04-C-0028. We are grateful for the assistance provided by Dr. Don Ward and Mr. Bill Curtis from the Engineer Research Development Center (ERDC) of the U.S. Army Corps of Engineers. We also acknowledge the help provided by Dr. Alan Niem, who assisted us with portions of the fieldwork, and Dr. Paul Komar for his advice and comments on the study. We are grateful to the members of the Technical Advisory Panel for their comments on the draft report.

Dynamic Revetments for Coastal Erosion Stabilization: A Feasibility Analysis for Application on the Oregon Coast

By Jonathan C. Allan, Ron Geitgey, and Roger Hart

EXECUTIVE SUMMARY

Gravel beaches are one of the most efficient forms of coastal protection, exhibiting a remarkable degree of stability in the face of sustained wave attack. Because of this they have been recommended as a form of shore protection. Such structures are variously termed cobble berms, dynamic revetments, or rubble beaches. The approach essentially involves the construction of a gravel or cobble beach at the shore, in front of the property to be protected. The dynamic sloping cobble beach is effective in defending properties because the sloping, porous cobble beach is able to disrupt and dissipate wave energy. It does this by adjusting its morphology in response to prevailing wave conditions. Dynamic revetments are also significantly easier to construct than a conventional riprap revetment or seawall. This is because the particle sizes used in the construction are smaller and generally less expensive than large armor stones and placement of the gravel requires little attention.

There are few examples of dynamic revetments worldwide. In 1999, the Oregon Parks and Recreation Department constructed a dynamic revetment at Cape Lookout State Park (CLSP) following almost three decades of intensive coastal erosion. The Cape Lookout site provides the first real test of such a structure with respect to Oregon's extreme wave climate. To date, the structure has survived several major storms, including at least four events that resulted in the cobble berm and artificial dune being overtopped. Damage to the structure has been minimal, suggesting that these types of structures may be viable alternatives to "hard" engineering solutions in the Pacific Northwest. There remain, however, a number of uncertainties concerning the physical design of dynamic revetments, especially on a high-energy beach where the cobble berm is fronted by a dissipative sand beach, and in terms of acquiring sufficient gravel for construction and periodic maintenance required to maintain such structures.

This study has two key objectives. The first is to assess the geomorphology of gravel beaches along the Oregon coast, with emphasis on identifying the predominant berm crest elevations, berm widths, beach slopes, gravel volumes, and mean grain sizes, from which appropriate recommendations can be made with respect to the design of a dynamic revetment. The second is to identify potential sediment sources that may be used to construct such structures elsewhere on the Oregon coast and to evaluate methods and costs of transporting the sediment to the coast.

The study's principal findings include the following:

- Analyses of 27 profile lines at 13 gravel beach study sites along the Oregon coast revealed that the majority of the gravel beaches were stable and characterized by well-vegetated backshores. Most of the stable gravel beach sites are found on the northern Oregon coast, whereas sites exhibiting evidence of backshore erosion tend to be concentrated on the central and southern Oregon coast.
- Examination of the morphological characteristics of stable versus eroding gravel beaches revealed that in most cases the key difference was the width of the gravel beach and its associated sediment volume. In contrast, there is no clearly discernible pattern in the crest elevation of the gravel beaches and their respective slopes and grain sizes among stable versus eroding beaches.
- Analyses of the heights of the gravel beaches revealed elevations that ranged from 5.7 to 7.1 m (19 to 23 ft), we recommend that the berm crest height should be no less than 7.0 m (23 ft).
- A cumulative frequency plot of the combined wave runup superimposed on the tide (T_{WL}) revealed that T_{WL} exceeds an elevation of 6.0 m (20 ft) 5 percent of the time, while T_{WL} exceeds a 7.0 m (23 ft) height only 2 percent of the time. These results suggest that it is probably reasonable to construct a dynamic revetment to an elevation of at least 7.0 m (23 ft), acknowledging that such a structure would be periodically overtopped, as has occurred on occasion at CLSP (Komar and others, 2003; Allan and others, 2004).
- Mean grain sizes were found to range from −4.9Ø (30 mm) on the southern Oregon coast to −7.0Ø (128 mm) on the north coast; the recommended gravel size is −6Ø (64 mm).
- The preferred lithology for gravel is basalt, due to its relative abundance throughout Oregon and because basalt is more likely to undergo slower rates of abrasion.
- Gravel berm slopes were found to range from 7.7º to 14.1º, with an average slope of 10.9º. Accordingly, we recommend that the preferred designed slope should be 11º.
- Analyses of the width of the gravel berms and their volumes revealed that the north coast gravel beaches tend to exhibit wider berms (about 28 m [about 92] ft) and correspondingly

larger volumes of gravel (about 77 $m^3 \cdot m^{-1}$ [about 830 $ft^3 \cdot ft^{-1}$]) when compared with the central to south coast gravel beaches, which are characterized by widths and volumes that are, respectively, 35 percent and 57 percent lower. Furthermore, because these two variables were found to be highly correlated, a simple empirical model was developed which makes it possible to estimate appropriate gravel volumes on the basis of a design berm width.

- Design considerations should also account for any longshore drift, which has been shown to be extremely effective in the removal of sediment along the shore. We recommend that any project design include a program for periodic maintenance, which may include replacing some portion of those sediments transported out of the project area or periodically introducing additional new sediment as the gravel volume decreases. Alternatively, one could evaluate an engineering solution such as a low weir-type groyne constructed across the gravel berm, which could reduce the rate of alongshore gravel transport (at least until the gravel begins to overtop the groyne).

A major constraint that may limit the adoption of dynamic revetments as a viable engineering solution on the Oregon coast is the availability of suitable gravel sources for the construction and maintenance of such structures.

- Our review of existing gravel quarries capable of producing rounded particles supports the perception that this type of gravel is scarce in Oregon. Identified resources are more common in Washington State. Only five gravel quarry sites capable of producing "rounded" gravel in the −6ø (64 mm) range could be identified on the central to northern Oregon coast; these include Deer Island, Richold/Waterview, and Santosh located in Columbia County adjacent to the Columbia River, and the two Stayton quarries in Linn County (Figure 47). In contrast, seven sites near the southern Oregon coast could potentially provide suitable gravel for the construction of a dynamic revetment; the Elk River, Broadbent, and Umpqua sites are closest to the coast (Figure 48).
- Quarries capable of producing crushed gravel of a particular size are more common. Some of these sites are located near major towns or transportation hubs (for example, Astoria, Tillamook, Newport, and Coos Bay). As indicated in Figures 47 and 48, many of these quarries are capable of producing about 50,000 tons of crushed rock annually.
- No quarries south of Port Orford are capable of producing crushed rock.
- Production of cobble-size round rock or quarry rock may require an operator to modify procedures in excavating, blasting, quarrying, sizing, storage, and handling. The ability and willingness of a producer to effect these changes will be a function of the source's physical characteristics (jointing, fracturing, and particle size distribution), location of the active operating face at the time of need, and economic conditions at the time of need (including transportation costs, individual source economics, and the size of an ODOT contract).
- Assessments of material and transportation costs proved to be the most difficult item to estimate, as few of the quarry and transportation operators were willing to provide a cost estimate without a specific project description.
- Material costs were estimated to be about $10 per ton at the pit or quarry, an indefinite figure dependent in part on what modifications of production procedures would be required.
- Truck transportation costs were estimated to average about $0.75 per ton per mile for hauls of a few tens of miles. Actual cost is dependent on a variety of factors including travel time, distance, equipment type, and the type of road surface. For example, travel costs may increase to as much as $1.60 per ton per mile on unpaved (gravel) roads.
- A hypothetical rail haul of 10,000 tons of round rock from a Roseburg source to a siding in Coos Bay or North Bend, about 210 miles by rail, was estimated to cost about $8 per ton. This figure assumes three trips of 30 cars and includes car leasing for a month. It does not include stockpiling or storage fees, local handling and truck transport to the project site, or possible demurrage charges.
- A hypothetical barge haul of 10,000 tons of round rock from Scappoose or Tacoma, Washington, to the Port of Newport was estimated to cost about $6 per ton. This does not include port, stevedoring, stockpiling, storage, possible demurrage fees, or local handling and truck transport to the project site.

Unresolved problems in need of further study include:

- Investigation of the rate at which crushed rock rounds to the appropriate diameter under varying wave conditions.
- Investigation of alongshore transport of cobbles and crushed rock as a function wave conditions, currents, and the geomorphology of the coastline.
- Development of quantitative numerical models of erosion and deposition of cobble berms based on empirical observations.
- Development of suitable wave runup equations for gravel beaches.
- Additional detailed economic analyses based on small-scale pilot projects designed to test viability at sites with large differences in gravel movement, availability of artificial sources, geomorphology, and wave conditions. Three sites most appropriate for this type of analysis are:
    - Cape Lookout State Park, Tillamook County;
    - Spencer Creek Bridge, Lincoln County; and
    - Hooskanaden Creek, Curry County.

INTRODUCTION

Significant portions of the Oregon coastal highway system are threatened by ocean wave attack and erosion. The standard approach for mitigating erosion is through the construction of "hard" shoreline protection commonly using riprap revetments, seawalls, or bulkheads. There are concerns, however, over the likely effects of such structures due to their unnatural appearance, which mars the beauty of the coast, and to the potential for such structures to cause adverse impacts to adjacent unprotected property.

The latter concern, termed active erosion, encompasses a variety of potential impacts including enhanced toe scour due to the reflection of wave energy from the structure. The transfer of wave energy to the adjacent unprotected ends of the structures results in erosion termed end effect (Griggs and others, 1994; Kraus and McDougal, 1996). Given sufficient numbers, coastal structures may also impact the stability of beaches due to the impoundment of the sediment contained behind them, material that would otherwise have been available to the beach sediment budget. As a result, the cumulative expansion of coastal engineering structures, such as seawalls and riprap revetments, may eventually exacerbate the erosion of beaches, particularly if sea level rise continues at the present rate or accelerates over the course of the next century (Intergovernmental Panel on Climate Change [IPCC], 1995).

To minimize the negative impacts of shore protection, "soft" engineering alternatives that attempt to replicate nature are necessary to slow erosion to an acceptable rate while eliminating or reducing scour and beach sediment loss. One such approach is the use of a dynamic revetment or gravel berm, which requires the construction of a gravel beach that can dissipate the wave energy and protect shorefront properties and infrastructure while maintaining a natural appearance.

The Oregon Department of Geology and Mineral Industries (DOGAMI), in cooperation with Dr. Paul Komar of the College of Oceanic and Atmospheric Sciences at Oregon State University, the Engineer Research Development Center (ERDC) of the U.S. Army Corps of Engineers (USACE), and the Oregon Parks and Recreation Department (OPRD), is presently investigating erosion remediation in the form of a dynamic revetment that is composed of naturally occurring beach cobbles (cobble berm) backed by an artificial dune. The structure was constructed by OPRD in December 2000 at Cape Lookout State Park (CLSP) on the northern Oregon coast (Figure 1) and has thus far survived four winters and several major storms. Although the structure has experienced some erosion that has led to surficial damage to the artificial dune, the basic integrity of the dynamic revetment remains intact, suggesting that these types of structures may be a viable alternative to "hard" engineering solutions in the Pacific Northwest.

The existing engineering literature on dynamic revetment design does not address the Oregon coastal setting where a sand beach fronts a cobble structure. Instead, the design of the CLSP revetment was based primarily on the slopes, gravel sizes, and elevations of a natural gravel beach found in the park. There are many examples of natural gravel beaches along the Oregon coast, which provide protection to properties atop sea cliffs and foredunes. Additional research of those beaches would greatly facilitate the design and application of future dynamic revetments for the protection of Oregon's coastal highways. A major focus of this study is therefore to evaluate the morphology (gravel beach slopes, crest elevations and alongshore variability, grain size, and temporal and spatial patterns of the beach) and distribution of existing gravel beaches, and the processes (waves and tides that may impact the beaches) that characterize the Oregon coast.

The availability of cobble-size material to use for construction of dynamic revetments is also key to this program. An initial data search for stream gravel sources by DOGAMI in 2003 revealed significant erroneous information, demonstrating the need for a more accurate and up-to-date database of potential sources. The new database (Appendix B) provides accurate information on potential sources for gravels that may be used to construct a dynamic revetment and the estimated costs to transport the material to a particular site.

This study has two key objectives:

Objective 1: Undertake a field study devoted to the collection of geological and oceanographic information about naturally occurring gravel beaches along the Oregon coast to:

- Identify the spatial distribution of naturally occurring gravel beaches on the Oregon coast and assess the stability of these beaches with respect to erosion;
- Establish beach profile surveys at selected study sites to evaluate beach slopes and crest elevations;
- Carry out measurements of gravel sizes and sorting patterns along each beach profile; and
- Undertake model calculations of expected wave-swash runup elevations during major storms.

These data are critical to the effective design of dynamic revetment structures along both bluff- and dune-backed beaches.

Objective 2: Analyze the feasibility of obtaining and transporting naturally occurring gravel material in sufficient quantities for use along Oregon's coastal highways and roads. Examine Oregon and Washington resources. Contrast these data with the feasibility and cost effectiveness of generating cobble-size material from crushed rock. Develop an accurate spatial database of natural and man-made cobble sources that might be useful for coastal remediation.

This report synthesizes the results of this study, with emphasis on (1) the development of improved design criteria for dynamic revetments and (2) cost-benefit assessments of gravel sources for the construction of such structures on the Oregon coast to protect the State's highways.

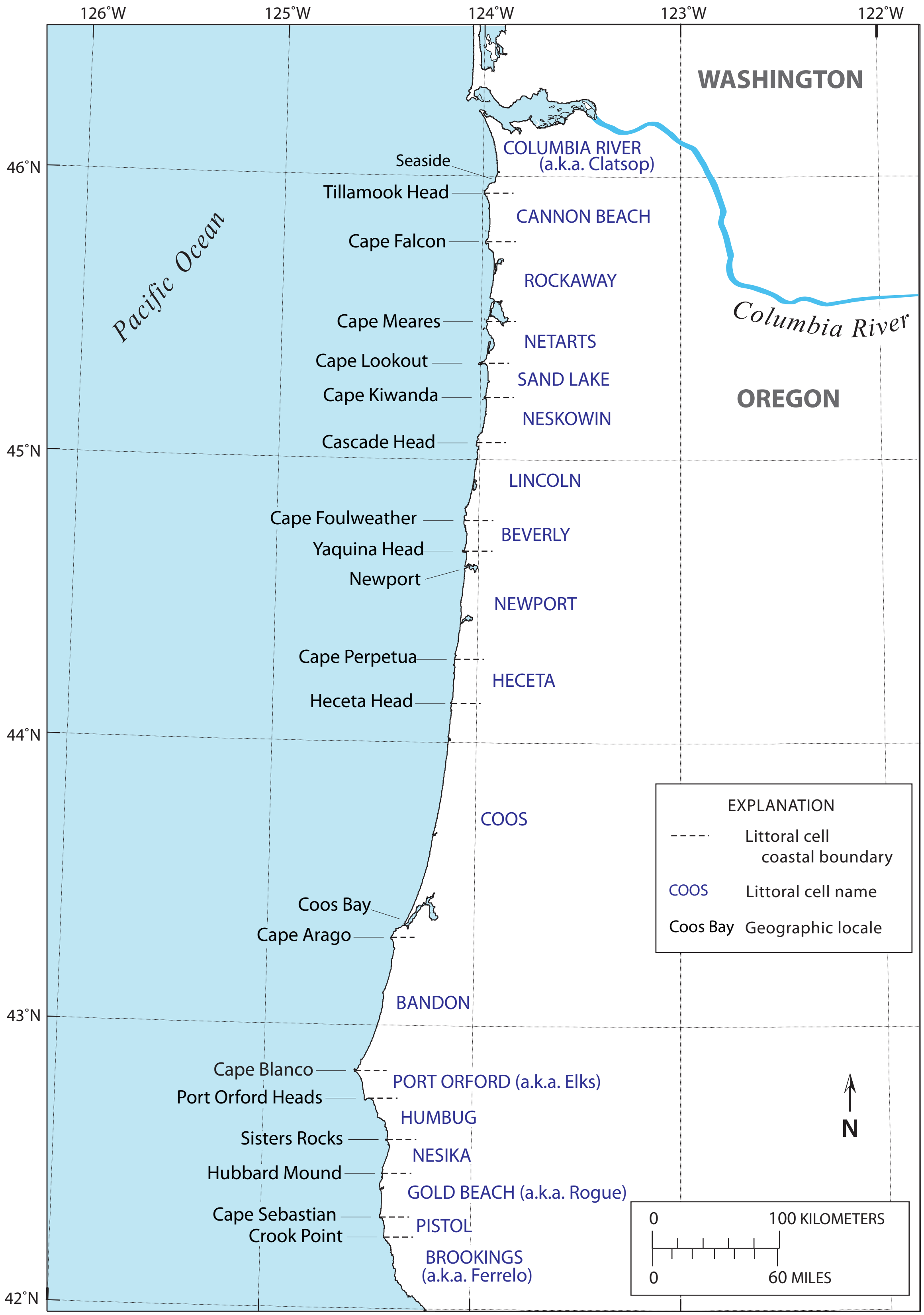


Figure 1. Map of the Oregon coast showing littoral cells.

BEACH PROCESSES ON THE OREGON COAST

Background

The Oregon coast is about 580 km (360 mi) long (Figure 1) and may be broadly characterized as consisting of long stretches of sandy beaches bounded by resistant headlands. These types of systems are referred to as littoral cells (Komar, 1997) and include both a cross-shore (littoral zone, Figure 2) and a longshore extent. At least 18 major littoral cells have been identified on the Oregon coast (Figure 1). The majority of the shoreline (72 percent) consists of dune-backed sandy beaches, while the remaining 28 percent of shore comprises a mixture of bluff-backed beaches, rocky shores, and coarse-grain (gravel) beaches. Because the headlands extend into deep water, wave processes are generally regarded as unable to transport beach sediment around the ends of the headlands. As a result, the headlands form a natural barrier for sediment transport, preventing sand exchange between adjacent littoral cells. Thus, a littoral cell is essentially a self-contained compartment, deriving all its sediment from within that cell.

Beaches composed of loose sediment are among the most dynamic and changeable of all landform types, responding to a myriad of complex variables that reflect the interaction of the processes that drive coastal change (waves, currents, and tides) and the underlying geological and geomorphological characteristics of the beaches (for example, sediment grain size, shoreline orientation, beach width, sand supply and losses).

Coastal processes (waves, currents, and tides) have a threefold role in contributing to the morphology and position of the beach. These include:

1) Promoting the supply of sediment to the beach system for beach construction,
2) Transporting sediment through the system, and
3) Removing sediment through the process of erosion.

The depletion of beaches along the Oregon coast is largely dependent on the occurrence of high-magnitude events such as occurred during the March 2-3, 1999, storm (Allan and Komar, 2002a) or in response to enhanced periods of storm activity such as the 1982-1983 and 1997-1998 El Niños and 1998-99 winter. Collectively, these events resulted in some of the most significant examples of coastal retreat observed during the past three decades. For example, during the late 1990s dune erosion averaged about 11.5 to 15.6 m (38 to 49 ft) along the Neskowin and Netarts littoral cells respectively, and as much as 55 m (180 ft) in some locations, damaging adjacent properties (Allan and others, 2004). Further south, the erosion along the Garrison Lake shoreline near Port Orford was especially acute, resulting in the retreat of beaches there by 100 to 120 m (328 to 394 ft). Much of the erosion during the 1998-1999 winter was likely caused by the occurrence of four

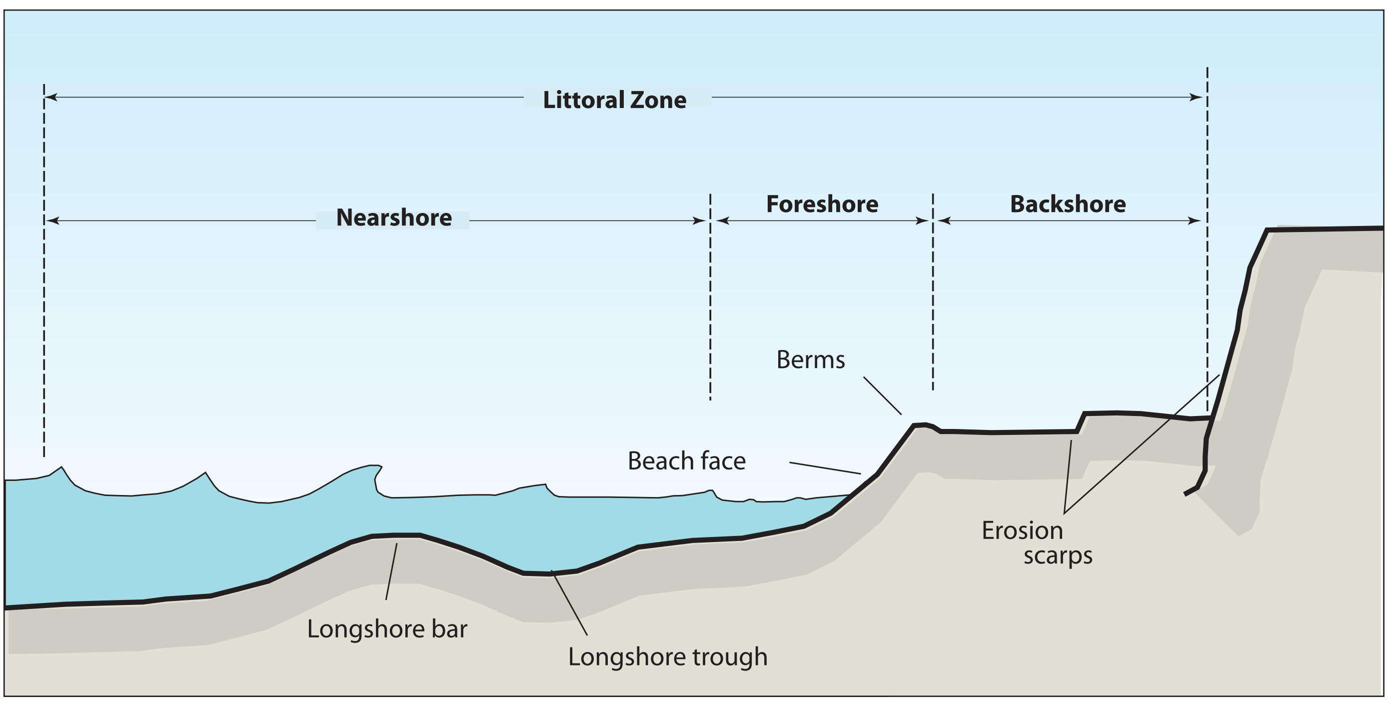


Figure 2. Terminology used to define aspects of the beach (Komar, 1998). The backshore is composed of some combination of a foredune, a foredune backed by a dune field, or a bluff. The erosion scarp typically lies on the seaward edge of the foredune or bluff.

100-year storms that generated significant wave heights in excess of 10 m (33 ft). Longer-term adjustments may also be recognized on the beaches and may be related to a change in sea level. Existing attempts to quantify this last process, however, suggest that erosion due to sea level rise is probably minimal (Allan and others, 2003a).

Terminology used to describe the form of a beach is shown in Figure 2. A typical beach cross-section comprises both a subaerial component (the beach foreshore and backshore) and an underwater component that includes the nearshore and offshore zones. Furthermore, the visible sandy foreshore comprises only a small portion of an onshore-offshore sand exchange system that extends seaward. Thus, the cross-shore extent of the littoral zone extends from the backshore (which may encompass a dune field, beach ridge, sea cliffs) seaward to some limiting depth where underwater bed changes tend to be minimal. The seaward limit of onshore-offshore sand exchange can be estimated empirically using formulas developed by coastal engineers on the basis of the offshore wave climate. These calculations suggest that the seaward limit of the littoral zone calculated for the Oregon coast extends out to a depth that ranges from 10 to 14 m (33 to 46 ft).

Longshore Sediment Transport

Within the littoral zone, a distinction is made between the movement of sediment that is directed in primarily onshore-offshore directions (cross-shore sediment transport) and the movement of sediment parallel to the beach (longshore transport). The latter process can be especially significant and is dependent on the angle at which waves approach the shore. Longshore currents are formed when waves approach the shore at oblique angles. These currents are confined to a narrow zone landward of the breaker zone and can be responsible for the movement of substantial volumes of sediment along the shore.

Longshore currents play an important role in sediment transport along the Oregon coast due to seasonal variations in the direction of wave approach between summer and winter (Figure 3A). During a typical year, summer waves approach the coast from the northwest, driving sediment toward the southern ends of the littoral cells. This process is aided by strong north to northwesterly summer winds that are capable of transporting large volumes of sand and fine gravel toward the south ends of the cells and also landward to form dunes. In contrast, the arrival of large waves from the southwest during the winter results in a reversal in the net sediment transport direction; it is now directed toward the north, and can erode the beaches. Thus, over several normal years there is a net equilibrium so that the net sediment transport is close to zero; that is, there is no net long-term buildup (accretion) of sediment at either end of the littoral cells (Komar, 1986). However, although the net balance of longshore sediment transport for sand-size particles is likely to be zero, that is unlikely the case for gravel. This is because the energy flux required to transport gravel and cobbles is significantly greater and because the waves may reach the cobbles only during the winter. As a result, gravels and cobbles on the Oregon coast may move in one direction during the winter months, but they are unlikely to move back in the direction they originally came from.

Periodically, the volume and direction of sand transported along Oregon's littoral cells may be augmented due to the occurrence of an El Niño. El Niños typically occur at intervals of 5 to 6 years but may recur on 2- to 7-year cycles. In the past two decades there have been seven El Niños, with the 1982-1983 and 1997-1998 events the strongest on record, while the period between 1990 and 1995 was characterized by persistent El Niño conditions, the longest on record (Trenberth, 1999). The 1982-1983 and 1997-1998 El Niños were particularly significant events, producing some of the most extreme erosion occurrences on the Oregon coast (Komar, 1986, 1998; Allan and Komar, 2002a; Revell and others, 2002; Allan and others, 2003a).

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

In addition to changes in the mean water levels along the coast, during an El Niño there is also a southward displacement of storm tracks toward the coast of central California (Seymour, 1996). As a result, storm waves reach the Oregon coast from a more southwesterly quadrant, creating an abnormally large northward transport of sand within littoral cells. This results in hotspot[1] erosion at the southern ends of the cells, north of the bounding headlands and also north of migrating inlets (Figure 3B). The opposite response is found south of the headlands, where the northward-displaced sand accumulates, causing the coast there to locally advance seaward (Figure 3B).

Detailed documentation of this northward sand displacement and hotspot erosion became possible during the 1997-1998 El Niño using Light Detection and Ranging (LIDAR) data, a remote sensing technology developed by the U.S. Geological Survey (USGS) and the National Aeronautics and Space Administra-

[1]Hotspots are areas of focused erosion; that is, areas that erode significantly more rapidly than the adjacent beaches.

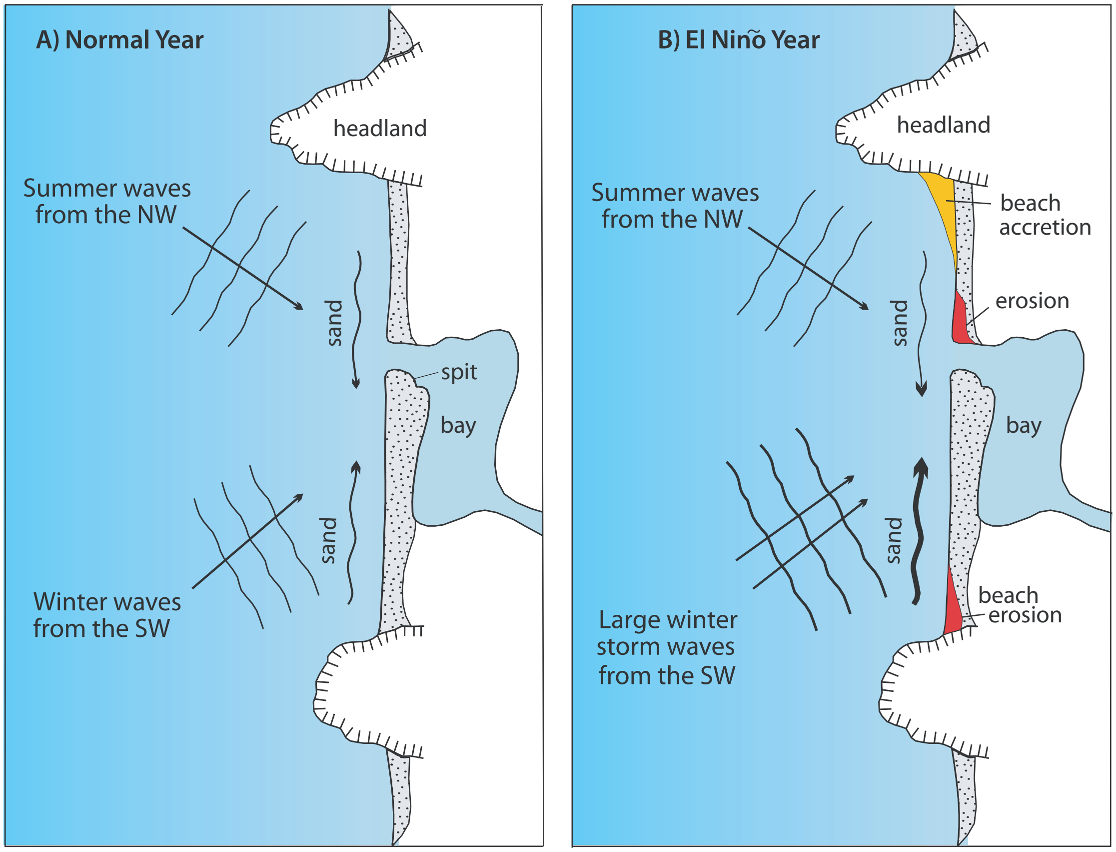


Figure 3. The alongshore seasonal movement of beach sediment on the Oregon coast for (**A**) a typical year and (**B**) an El Niño year (Komar, 1998).

tion (NASA) to collect topographic data of the beach. Additional information on LIDAR and its application can be found at the NOAA Coastal Service Center website (http://www.csc.noaa.gov/crs/tcm/index.html) and is discussed in detail by Brock and others (2002) and Stockdon and others (2002). Analyses by Revell and others (2002) used the fall-1997 versus spring-1998 LIDAR data to measure the vertical and volumetric changes in the beach that occurred during the El Niño winter along the length of the Netarts littoral cell in Tillamook County, documenting a clear pattern of northward sand transport in response to the southwest approach of El Niño storm waves. Allan and others (2003a) undertook additional analyses of the LIDAR data in the Netarts cell, quantifying the hotspot erosion effect along the south end of the cell (Figure 4). Apparent in the figure is the concentrated zone of erosion along the southern 3 km (1.9 mi) of shoreline, where negative values indicate erosion and positive values indicate accretion. The hotspot erosion effect is greatest along the southern 1–2 km (0.6–1.2 mi) of the coast where it reaches about −20 m (−65 ft) and progressively decreases northward along the spit. Figure 4 also demonstrates the northward transport of sediment along the cell, as conceptualized in Figure 3, with the shoreline having prograded seaward by 10 m (33 ft) along the northern extent of the spit and by several meters north of the mouth of Netarts Bay.

Pacific Northwest Wave Climate

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

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

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

Wave Climate Characteristics

Wave heights and periods and some meteorological phenomena have been measured in the North Pacific using wave buoys and sensor arrays since the mid 1970s. These data have been collected by the National Oceanic and Atmospheric Administration (NOAA), which operates the National Data Buoy Center (NDBC), and by the Coastal Data Information Program (CDIP) of Scripps Institution of Oceanography. The buoys cover the region between the Gulf of Alaska and Southern California and are located in both deep and shallow water. The NDBC operates some 30 stations along the west coast of North America, while CDIP has, at various times, carried out wave measurements at 80 stations. Presently, CDIP has only one buoy, located near Coos Bay, operating offshore from the Oregon coast. The CDIP data sets tend to be characterized by short bursts of project-specific sampling and long durations of no measurements, so that the data record tends to have significant gaps. Because of this the CDIP data sets have not been used for this report.

Wave measurements by NDBC are obtained hourly and are transmitted via satellite to the laboratory for analysis of the wave energy spectra, significant wave heights, and peak spectral wave periods. These data can be obtained directly from the NDBC through their website (http://seaboard.ndbc.noaa.gov/Maps/Northwest.shtml).

There are currently three buoys stationed within about 32 to 48 km (20 to 30 mi) from the Oregon coast (Figure 5). A fourth buoy was recently installed by NOAA about 142 km (88 mi) west of Cannon Beach. Table 1 describes the general characteristics of each wave buoy site: World Meteorological Organization station name, location, water depth, period of operation, and system.

Previous analyses of the significant wave heights along the central and southern Oregon coast have revealed that there is little difference in the measured wave heights between the Newport and Port Orford buoys (Allan, 2004), with a slight decrease in wave height northward to the Columbia River buoy (Allan and Komar, 2000a). As a result, an assessment of the wave-swash runup elevations during major storms will be based on wave statistics derived from the Newport buoy. These latter calculations will be used to compare the crest elevations of the gravel beaches with the swash elevations and are discussed in more detail in the "Results" section.

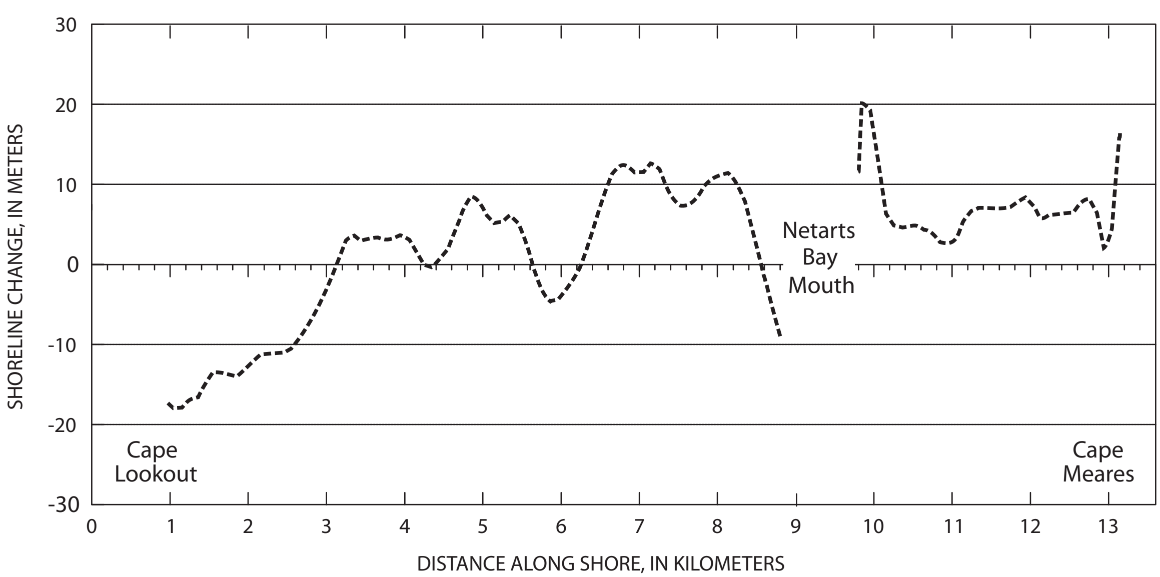


Figure 4. Example of the hotspot erosion effect identified in the Netarts littoral cell in Tillamook County (after Allan and others, [2003a]). Changes occurred between fall 1997 and spring 1998.

Table 1. Wave buoy site characteristics.

Station Name	Location	Water Depth (m)	Period of Operation	System
46029	Columbia River Bar (lat 46°07′00″N, long 124°30′36″W)	128	1984–present	3-m discus buoy
46089	Tillamook (lat 45°52′53″N, long 125°45′59″W)	2,230	Nov 2004–present	3-m discus buoy
46050	Newport (lat 44°37′16″N, long 124°31′42″W)	130	1987–present	3-m discus buoy
46015	Port Orford (lat 42°44′00″N, long 124°50′30″W)	448	2002–present	3-m discus buoy

The wave climate along the Oregon coast is seasonal, with the strongest storms and largest waves occurring in the winter months (Tillotson and Komar, 1997; Allan and Komar, 2000a). Figures 6 and 7 present the monthly average deep-water significant wave heights (H_S) and peak spectral wave periods (T_P) for the Newport buoy (NDBC #46050). The graphs show a prominent cycle in the mean monthly wave heights and peak wave periods. Waves are characteristically smallest (<2.0 m [6.6 ft]) between May and September, reaching a minimum in August (Figure 6). The range (±1 standard deviation) of wave heights during July and August is generally less than 0.17 m (0.6 ft). This suggests that during the summer, the West Coast is characterized by relatively similar conditions for wave generation, likely by local winds that blow over short fetches. During the winter, wave heights typically range from 3 to 4 m (9.8 to 13.1 ft). During major winter storms, however, wave heights in excess of 7 m (23 ft) are not uncommon, with the most extreme storms producing deep-water significant waves 14 to 15 m (45.9 to 49.2 ft) high (Allan and Komar, 2002a). A similar pattern can be seen for the peak wave periods, such that during the summer the periods are typically less than about 10 s, reaching a minimum of 8.4 s in July (Figure 7). Wave periods tend to be longest in December and January and range from 12 to 14 s on average and may reach as much as 25 s during major storms.

Beginning with the 1997-1998 El Niño winter, the Oregon coast experienced over 20 large storms in which deep-water significant wave heights exceeded 6 m (20 ft) for 9 hours or longer (Allan and Komar, 2000b). These storms affected shipping and produced considerable beach and property erosion along the coasts of Oregon and Washington. Prior to that the maximum number of storms experienced using the above criteria was 10 to 12 and occurred in the early 1980s (Figure 8).

On the basis of wave data through 1996, Ruggiero and others (1996) calculated the 100-year-storm wave to be around 10 m (33 ft) for the Oregon coast. A storm on November 19-20, 1997 exceeded that projection. Wave conditions were substantially worse during the following 1998-1999 La Niña winter (Figure 8), when 17 to 22 major storms occurred off the PNW coast, with four having generated deep-water significant wave heights equal to or greater than the 10 m (33 ft) projected 100-year occurrence. The largest storm developed on March 2-4, 1999, generating 14.1 m (46 ft) deep-water significant wave heights. Thus, the PNW received a "one-two punch" from the successive El Niño and La Niña winters, with severe cumulative erosion of the coast (Allan and Komar, 2002a). Between major storms, the reduced wave energies permitted beach rebuilding, with the shoreline prograding (advancing) seaward and with foredunes rebuilding (Komar, 1997; Allan and Priest, 2001; Allan and others, 2003a). This latter process, however, is much slower, so that the foredunes may take several years to a few decades to rebuild.

We are less confident about the wave-direction information as there are fewer data on wave direction offshore from Oregon, mainly because these data have only recently begun to be compiled, but also because of a dearth in instrumentation sites along the U.S. West Coast. Nevertheless, as a general rule, during the winter waves typically arrive from the west or southwest, while in the summer the predominant wave direction is from the northwest (Komar, 1997). This response is highlighted in Figure 9, which is based on an analysis of both summer and winter directional data measured by the Columbia River buoy (#46029, Figure 5). Figure 9 shows that the summer months are characterized by waves predominantly from the west to northwesterly quadrant (83.7%), with fewer waves out of the southwest quadrant (14.6%). The bulk of these reflect waves with amplitudes that are predominantly less than 3 m (9.8 ft). In contrast, the winter months are dominated by much larger wave heights (up to 12 m [39.4 ft]) out of the southwest, which make up about 25% of the wave spectrum. Waves from the west are also important, increasing from about 20% in the summer to around 33% in the winter.

Tides

Tidal measurements of tides on the Oregon coast are available from gauges at four locations: the Columbia River (Astoria), Yaquina Bay (Newport), Charleston (Coos Bay), and Port Orford (Figure 1). The long-term record from Crescent City, California, 56 km (35 mi) south of Brookings, is also useful in tidal analysis for southern Oregon. Tides along the Oregon coast are classified as moderate, with a maximum range of up to 4.3 m (14 ft) and an average range of about 1.8 m (6 ft) (Komar, 1997). There are two highs and two lows each day, with successive highs (or lows) usually having markedly different levels (Figure 10). Tidal elevations are given in reference to the mean of the lower low water levels (MLLW). As a result, most tidal elevations are positive numbers with only the most extreme lower lows having negative values. Figure 10 shows the daily tidal elevations derived from the Newport tide gauge (#9435380). Tides at Newport have a mean range[2] of 1.9 m (6.27 ft) and a diurnal range[3] of 2.54 m (8.3 ft). The highest tide measured at Newport reached 3.73 m (12.2 ft) and was recorded in November 1969.

The actual level of the measured tide can be considerably higher than the predicted level provided in standard tide tables and is a function of a variety of atmospheric and oceanographic forces, which 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. During the summer months, however, these processes can be ignored due to the absence of major storm systems. The El Niño climate phenomena may also superelevate mean water levels for a period of a few months as described below.

On the Oregon coast, tides tend to be enhanced during the winter months due to warmer water temperatures, which result from the breakdown of cooler summer upwelling, and the presence of northward-flowing ocean currents that raise water levels along the shore. This effect can be seen in the monthly averaged water levels (Figure 11), derived from the Newport tide gauge, with the averaging process removing the water-level variations of the tides, yielding a mean water level for the entire month. Thirty-six years of data show monthly mean-water levels during the winter (Figure 11) nearly 0.22 m (0.7 ft) higher than in the summer. Water levels are most extreme during El Niño events, due to an intensification of the processes, and are largely due to enhanced ocean sea surface temperatures offshore from the Oregon coast. This was particularly evident during the unusually strong 1982-1983 and 1997-1998 El Niños. Water levels during those climate events (Figure 11) were approximately 0.5 m (1.6 ft) higher in the winter than during the preceding summer. The importance of this is that all tides — low tides as well as high tides — were elevated by that amount, enabling wave swash processes to reach much higher elevations on the beach.

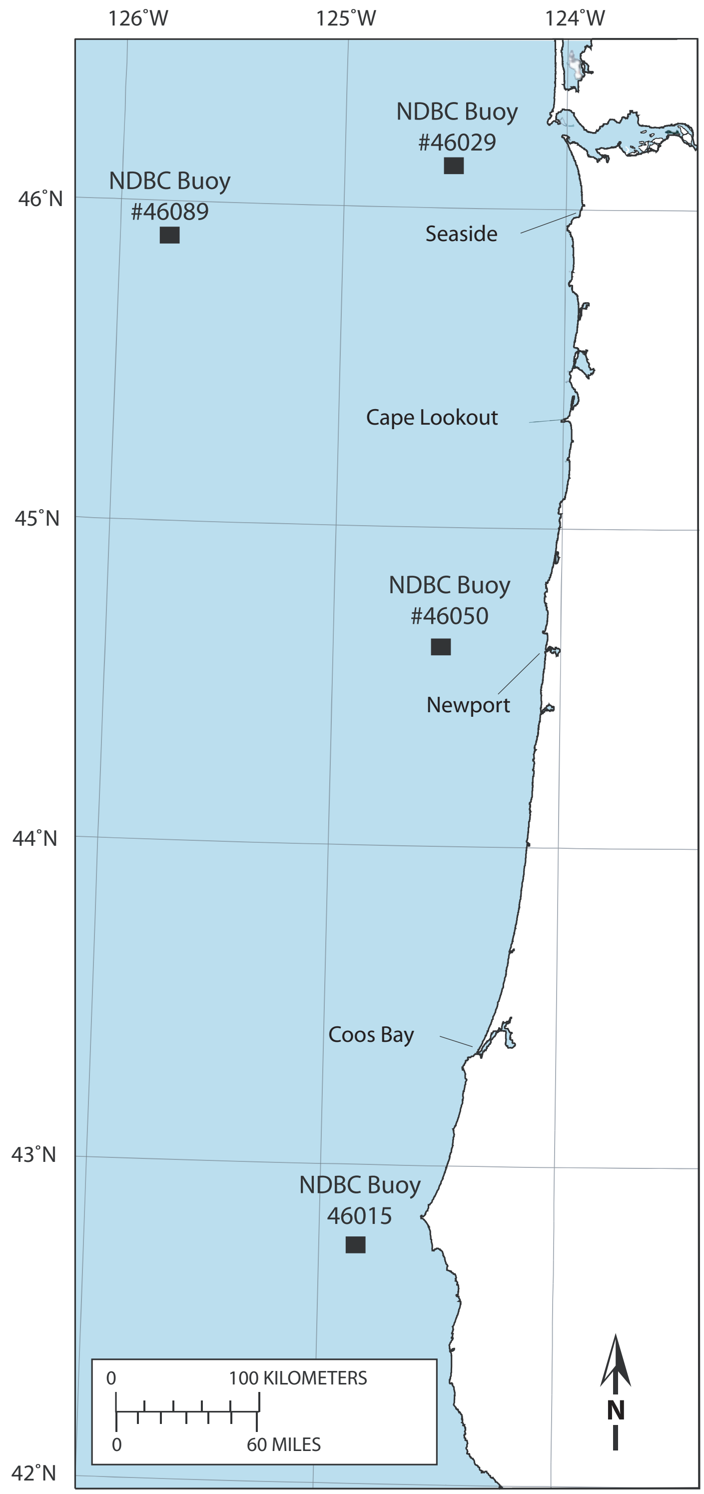


Figure 5. Locations of National Data Buoy Center (NDBC) wave buoys.

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

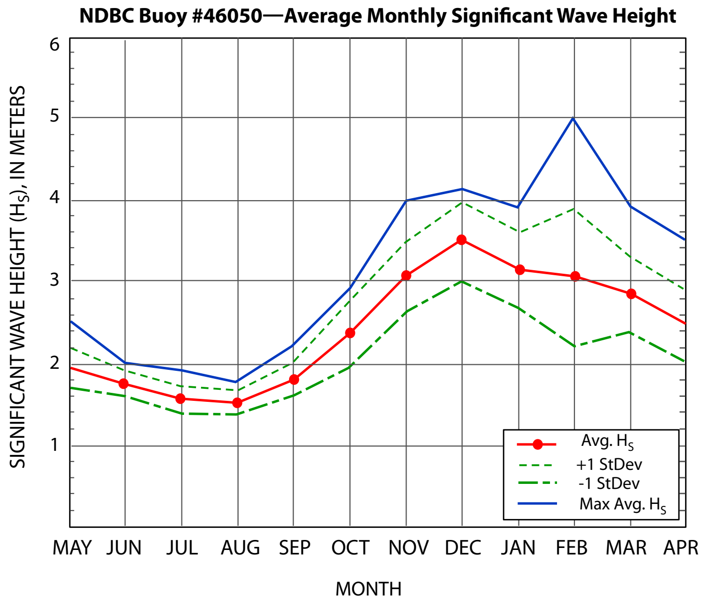


Figure 6. Monthly averages of the significant wave height at NDBC Buoy 46050 (1987–2004). The graph shows the average monthly significant wave height, the monthly average maximum significant wave height, and the range (±1 standard deviation) for each month.

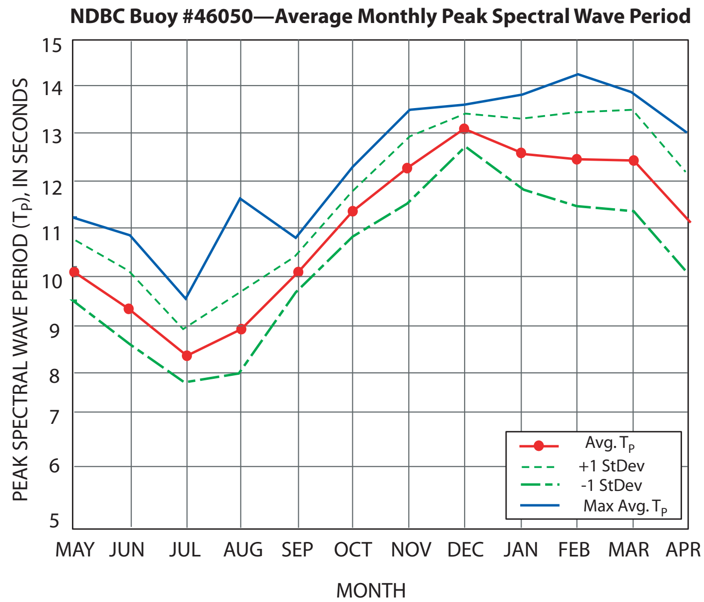


Figure 7. Monthly averages of the peak spectral wave period at NDBC Buoy 46050 (1987–2004). The graph shows the average peak spectral wave period, the monthly average maximum peak spectral wave period, and the range (±1 standard deviation) for each month.

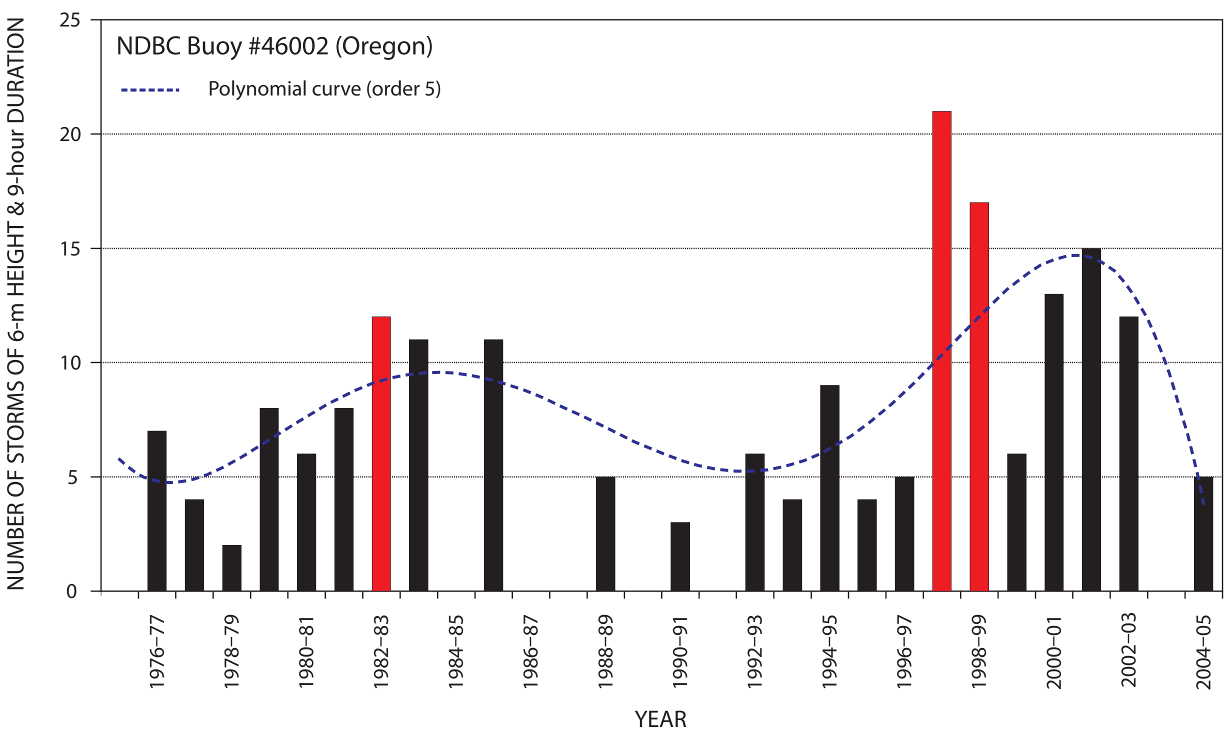


Figure 8. Incidence of storms between 1976 and 2005 that generated significant wave heights greater than 6 m (19.7 ft) for a duration of 9 hours or more. Data are based on the Oregon NDBC buoy (#46002). Note the unusually large number of storms that occurred during the late 1990s. The blue dashed line is an order 5 polynomial regression that has been fit to the data to highlight longer cycles in storm periodicity (extended from Allan and Komar [2000b]).

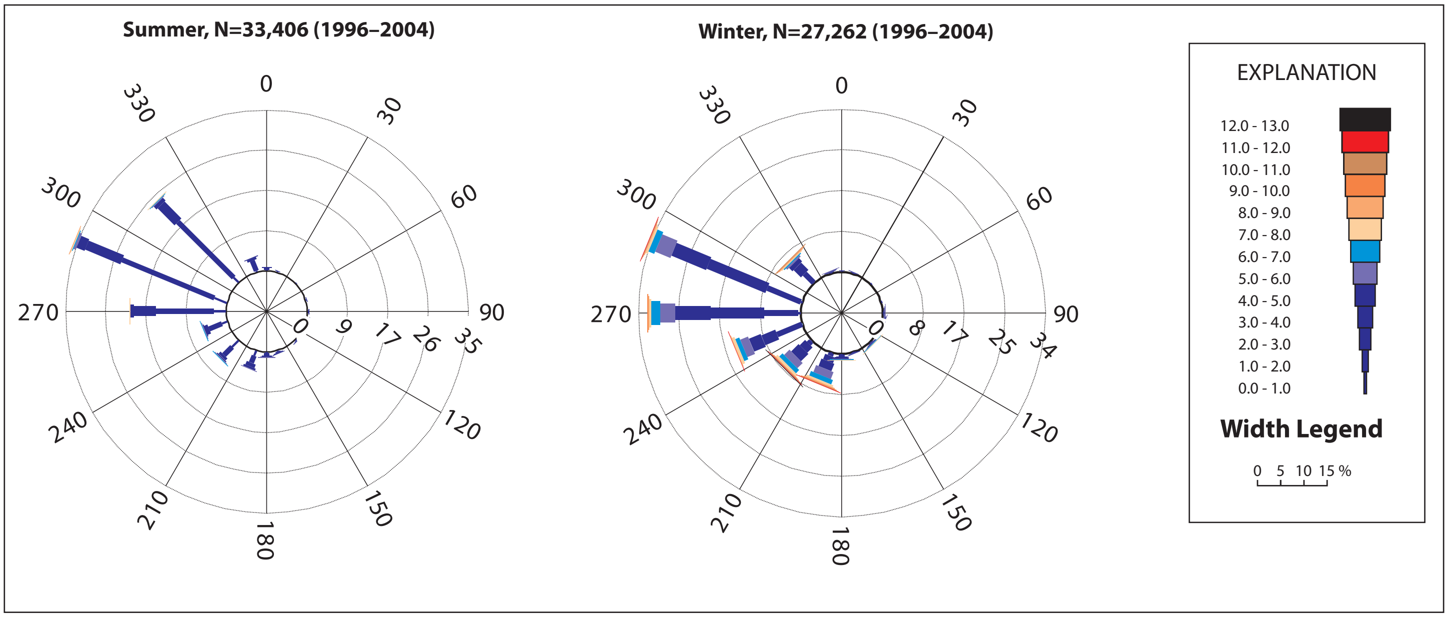


Figure 9. Wave directional information derived from the Columbia River (#46029) buoy for the period 1996–2004.

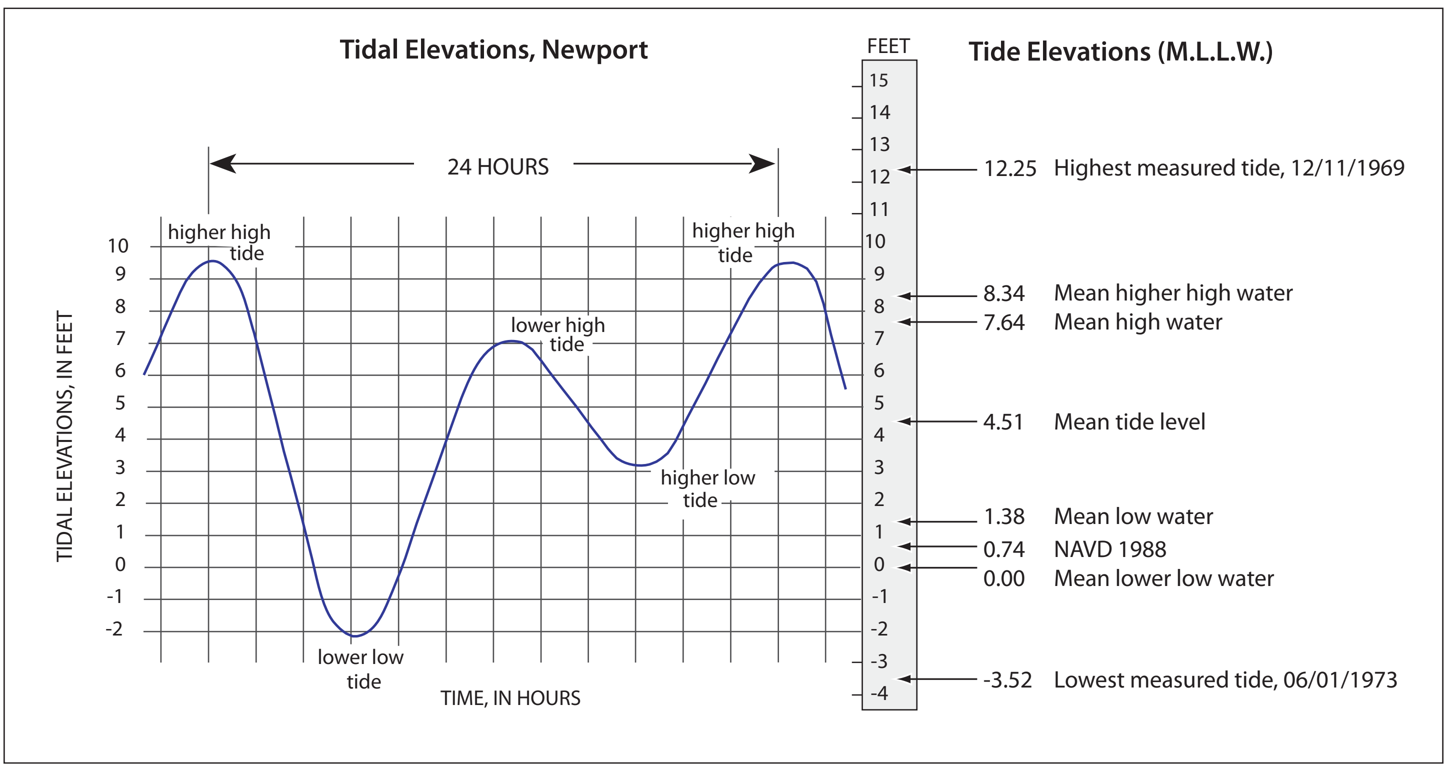


Figure 10. Daily tidal elevations for a normal day measured at Newport on the central Oregon coast. Data are from the NOAA National Ocean Service (http://www.co-ops.nos.noaa.gov/).

GRAVEL BEACHES, COBBLE BERMS, AND DYNAMIC REVETMENTS

The previous section described the general characteristics and responses of sand beaches on the Oregon coast. This section focuses on the science and engineering of coarse "gravel" beaches and the concept of dynamic revetments as a form of "soft" engineering. In contrast to pure sand beaches, less research has been directed at coarse beaches to understand the effects of coastal processes on morphology.

The composition of a beach depends ultimately on the sources of its sediment. The majority of beaches throughout the world consist primarily of sand, derived from the weathering and erosion of rocks such as granite, schist, and gneiss. Other rock sources supply coarse-grained material ranging from pebbles to cobbles, and some boulders, to the beach.

Coarse-grained beaches, variously termed pebble, shingle, gravel or cobble beaches, are found in many parts of the world (Marshall, 1927; Bluck, 1967; McLean, 1970; Carr, 1974; Carter and Orford, 1984; Nicholls and Webber, 1988; Jennings and Shulmeister, 2002). Typically, the sediment on coarse beaches is partly rounded and has been sorted by marine processes, so that the grain sizes fall within the range of 4 mm (–2ø) to 256 mm (−8ø) as measured along their intermediate (B) axis (Carr, 1974; Sherman, 1991) (note that $ø = –\log_2 D$, where D = grain size in millimeters). However, as the proportion of sand volume increases on coarse beaches (typically ranging from 15 percent to 68 percent by volume), the beaches are then termed mixed sand and gravel (Mason and Coates, 2001). For purposes of this study, the term gravel beach will be used to describe those beaches containing sediment between 4 mm and 256 mm (0.15–10.1 in).

We divide beaches into five categories on the basis of grain size (Figure 12). Jennings and Shulmeister (2002) described three predominant categories; Horn and Walton (in review) and Komar (2005) noted two additional categories, dependent on grain-size mixtures.

A) **Pure coarse-grained beaches:** Beaches composed of particle sizes ranging from pebbles to cobbles and boulders, with minimal sand, and no fronting sand beach.

B) **Mixed sand-and-gravel beaches:** Beaches consisting of high proportions of both coarse particles and sand, with intimate mixing of the two size fractions in the beach deposit.

C) **Composite beaches — mixed sand and gravel:** Beaches having a higher proportion of sand, sorted by the waves and nearshore currents, so the beach consists of an upper foreshore or backshore ridge composed of mixed sand and gravel, fronted by a flat dissipative sand low-tide terrace that is exposed at mid to low tides. These are characterized by a distinct boundary at the junction of the two predominant sediment groups.

D) **Composite beaches — pure gravel:** Pure gravel beach fronted by a sand beach. This beach has a higher proportion of sand, which has been sorted by waves and nearshore currents, so the beach consists of an upper foreshore or backshore ridge composed of pure gravels but is fronted by a lower foreshore of sand, generally with a distinct boundary between them.

E) **Pure sand beaches:** Composed almost entirely of sand.

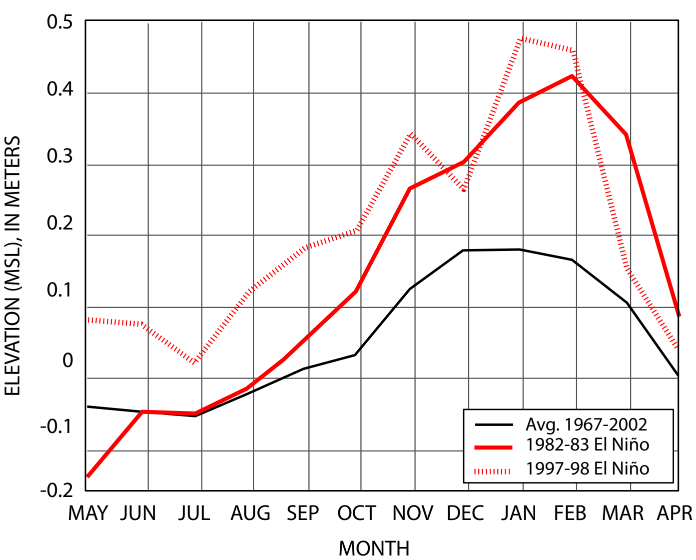


Figure 11. Mean monthly tides determined from the Newport, Oregon, tide gauge, expressed as a long-term average and as monthly averages for the 1982-1983 and 1997-1998 El Niños.

The Oregon coast exhibits examples of each of the above beach types. Pure sand beaches (E) predominantly make up the shoreline morphology, followed by a smaller component of mixed sand and gravel beaches (B and C) (Figure 13). Of greatest interest for the purposes of this study are composite beaches that exhibit a gravel berm or beach ridge composed of pure gravel that is fronted by a sand beach (D) (Figure 14). Along the U.S. West Coast, the latter are characterized by a steeply sloping gravel berm or ridge (average slope about 9.8º [1-on-5.8] but may reach as much as 23º [1-on-2.3]) that is fronted by a wide, gently sloping sand beach (average slope about 2.3º [1-on-25]). The gently sloping sand beach therefore provides the first line of defense to the backshore by dissipating the incident incoming wave energy. In these cases, the sandy beach face is exposed at all tidal stages during the summer, only to become submerged in the winter when storms occur and much of the sand is transported to offshore bars, allowing the waves to reach the gravel ridge at mid to high tides (Allan and Komar, 2002b; Everts and others, 2002; Allan and Komar, 2004).

It is well recognized in the coastal engineering literature that gravel beaches are one of the most efficient forms of coastal protection, exhibiting a remarkable degree of stability (Nicholls and Webber, 1988; Powell, 1988; Sherman, 1991; Everts and others, 2002), and as a result have been suggested as a form of shore protection or breakwater (van Hijum, 1974). Carter and Orford (1984) noted that gravel-dominated barrier beaches remain rela-

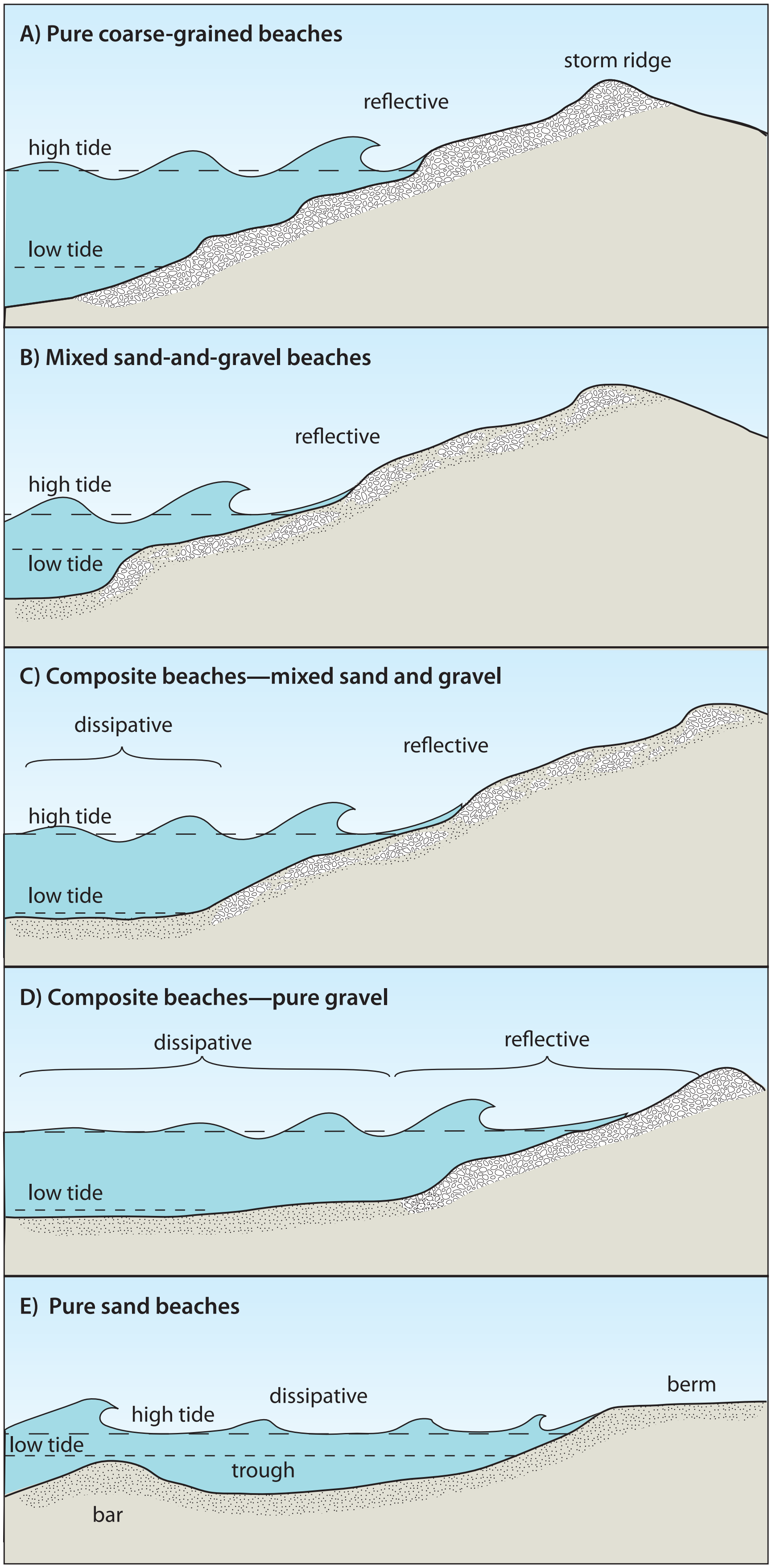


Figure 12. Classification of beaches based on their proportions of coarse sediments (gravel and cobbles) versus sand, with the resulting differences in their morphologies (extended from Jennings and Shulmeister [2002], Horn and Walton [in review], and Komar [2005]).

tively stable in the face of sustained wave attack, in part due to the inability of particles within a gravel mass to become entrained except under high-energy events. In fact, Carter and Orford observed the buildup of gravel beaches in southeast Ireland during storms, a finding consistent with observations by Allan and others (2003a) at Cape Lookout State Park on the northern Oregon coast. Furthermore, analysis of LIDAR data presented by Allan and others (2004) revealed that Netarts cell dunes fronted by composite gravel beaches (type D) experienced erosion rates that were typically 20 to 40 percent lower than erosion rates experienced along adjacent pure-sand beaches, highlighting the level of protection offered by a gravel beach compared to a sand beach.

Gravel beaches in Southern California have also been observed to gain material and increase their crest elevations during severe storms, while neighboring sand beaches eroded so significantly that the sand berms present on those beaches disappeared (Lorang and others, 1999; Everts and others, 2002). Horn and Walton (in review) noted that coarse coastal beaches in the United Kingdom are likely to become increasingly important in practical terms as many of these beach types constitute an important defense against erosion and flooding. They further observed that these beaches form effective barriers in front of low-lying marshes, supply toe protection along eroding cliffs, and help protect urban areas and high value agricultural, recreational, and environmental assets around the United Kingdom. As a result, the importance of understanding the morphodynamics of coarse beaches is now being recognized in part due to the increasing need for fundamental understanding of gravel beaches, how they might be nourished, and if gravel beaches could be used in some situations instead of more conventional, statically stable riprap revetments. Much of this work is being driven by research now being undertaken in the Netherlands and England and to a lesser extent in the United States.

Beach Morphodynamics

The range of beach categories described in the previous section encompasses contrasting morphologies with different degrees of stability when assaulted by storms. This can be illustrated by placing the categories in the morphodynamics classification developed by Wright and Short (1983). Morphodynamics is the adjustment of coastal areas due to the interaction between the morphology of the beach and fluid hydrodynamic processes. The "morpho" portion of the classification refers to the geometry of the beach, both its two-dimensional profile and the three-dimensional topography of bars and troughs, while the "dynamics" part refers to how that morphology changes in response to varying wave conditions. Figure 15 shows modified version of the Wright and Short model, which has dissipative beaches (Figure 15A) at one end of the spectrum and reflective beaches (Figure 15C) at the other. There are four stages of intermediate categories, only one of which is shown (Figure 15B). The average beach slope is seen to steepen progressively from the dissipative to the reflective condition, with the intermediate profiles tending to be more irregular due to the presence of offshore bars and troughs or rip-current embayments.

Dissipative beaches are characterized by low slopes and wide surf zones. Thus, on dissipative beaches the waves tend to break well offshore from the dry beach. The bores formed from broken waves cross a wide surf zone and lose most of their energy before they reach the shore and swash up the beach face. In the opposite extreme, the profile slope of reflective beaches is so steep that waves break very close to the shore, often on a plunge step, and they immediately develop into a strong swash up the beach face. As a result, reflective beaches lose very little wave energy during shoaling, so that the bulk of the energy is expended during the wave-breaking process. These beaches are reflective in that, because of their steep slopes, they can reflect a significant portion

Figure 13. Example of a mixed sand and gravel beach. The backshore consists of a gravel and transitions to a wide, gently sloping, dissipative sand beach exposed primarily at low tide.

Figure 14. Composite beaches on the northern Oregon coast in Tillamook County. These beaches include a backshore consisting of a steep-faced gravel berm, which transitions to a wide, gently sloping, dissipative sand beach exposed at all tidal levels (Short Beach) or at low tide (Cove Beach).

of the wave energy, sending waves seaward after being reflected from the beach face. The Oregon coast exhibits examples of each of the beach states in the Wright and Short (1983) morphodynamic model, although the dissipative beach is the most common beach type. As noted previously, reflective beaches are also found along the Oregon coast (Figures 13 and 14), but they are not as common as dissipative sand beaches.

The position of a specific beach within this morphodynamics classification depends on its sediment grain size and the energy level of the waves (also affected to a degree by the range of tides). In general, the coarser the grain size the steeper the beach profile, so that gravel and cobble beaches usually have steep faces and are reflective. A pure sand beach tends to be intermediate at times of low waves and dissipative under high wave conditions, although a coarse-sand beach may be sufficiently steep to become reflective under low waves. As the heights of the waves increase during a storm, the sand beach morphology shifts very quickly toward the dissipative end of the spectrum (Wright and Short, 1983; Lippmann and Holman, 1990). The dissipative response of sand beaches to storms at the height of the storm helps reduce the energy of waves at the shore, thereby limiting the extent of storm-induced erosion to the beach and backshore. After a storm, with a return of reduced wave energies, the beach morphology shifts from the dissipative end into the intermediate state, tending to follow the sequence of beach forms diagrammed in Figure 12, perhaps eventually reaching the reflective condition. Unlike the rapid shift of the beach category during the storm, this progression following the storm may take many days to weeks.

Beaches that are at the extremes, either dissipative or reflective, tend to show the least variability in either their three-dimensional morphologies or in a simple set of beach profiles. Significantly, it is the intermediate beaches that are most dynamic in their responses to storms and that therefore tend to be the most hazardous in terms of potential erosion of shorefront properties (Wright and Short, 1983). For example, on the Oregon coast, repeated beach-profile surveys show that the finer-grained dissipative beaches change in elevations by about 1 to 2 m (3.3 to 6.6 ft) between the summer and winter (Aguilar-Tunon and Komar, 1978; Shih and Komar, 1994; Allan and others, 2003a) or at the time of a major storm, while the somewhat steeper, coarser-grained beaches that are intermediate in the morphodynamics classification experience elevation changes that are on the order of 1 to 3 m (3.3 to 9.8 ft), typically with a much greater extent of property erosion in both foredunes and sea cliffs backing those beaches.

Pure coarse-grained beaches that consist of coarser gravels tend to always remain reflective due to their persistent, steep seaward slopes (Wright and Short, 1983). This imparts a degree of stability to the beach by virtue of the large sizes of the particles and perhaps also because a significant portion of the wave energy is reflected; they are less dynamic in profile changes during storms than are the intermediate beaches. Composite beaches are interesting in that if the fronting sand deposit is sufficient, it provides a dissipative sand beach backed by a reflective coarse-grained ridge (for example, Figure 14), the two most stable end members in the morphodynamics classification of Wright and Short (1983).

Because of the relative stability of pure coarse-grained beaches, some mixed beaches, and particularly composite beaches with both dissipative and reflective elements, a ridge of coarse gravels constructed at the back of a sand beach may be used to further mitigate incoming wave energy. If constructed properly, this ridge can provide the same degree of protection to shorefront properties as does a large volume of sand added in a beach nourishment project and, in some cases, can even substitute for a hard engineering structure such as a riprap revetment or seawall that is more expensive to construct.

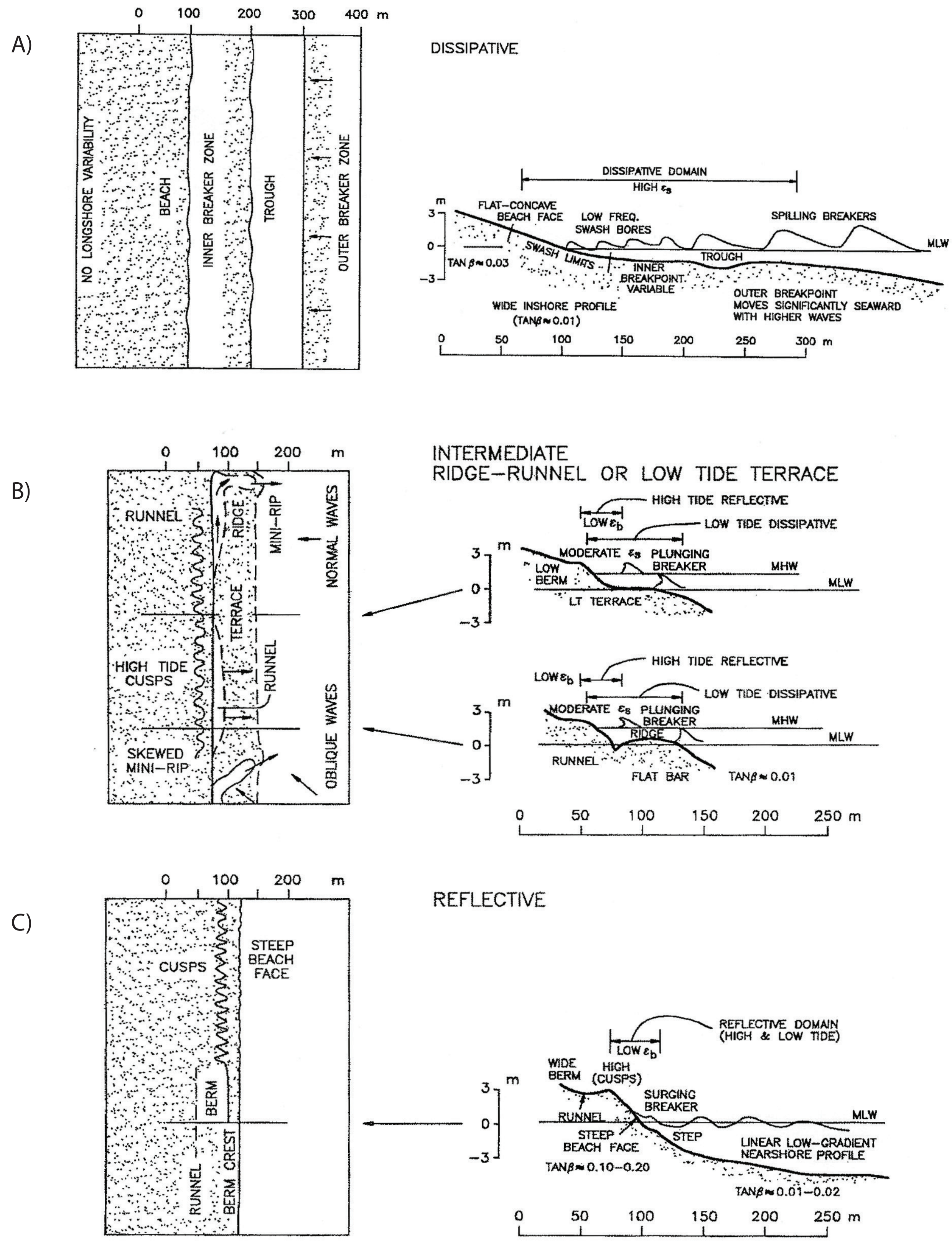


Figure 15. The morphodynamic classification of sand beaches (after Wright and Short [1983]). Four intermediate categories exist between (**A**) dissipative beaches and (**C**) reflective beaches; only one (**B**) is shown in this figure.

The Dynamic Revetment Concept

A strategy for shore protection using what has been variously termed cobble berms, dynamic revetments, or rubble beaches is of relatively recent origin. The construction of a gravel (shingle) or cobble beach at the shore in front of the property to be protected represents a transitional strategy between a conventional riprap revetment of large stones and a beach nourishment project. The term dynamic revetment highlights this transition in that the gravel and cobbles are expected to be moved by waves and nearshore currents — the system is dynamic. This contrasts with a conventional "static" riprap revetment where boulder-size quarry stone is designed not to move under the expected forces of waves during extreme storms (Ahrens, 1990; Ward and Ahrens, 1991). A dynamic revetment is designed for the wave action to rearrange the gravel into an equilibrium profile. In this regard, the cobble berm is constructed to provide protection to coastal developments while remaining more flexible than a conventional riprap revetment, adjusting rather than failing when movement occurs.

The constructed dynamic revetment either fronts directly into the water or is located landward of a sandy beach that is providing inadequate buffer protection from erosion by waves and currents. Such morphologies are relatively common on some coasts, so the placement of a cobble berm constitutes a more natural and aesthetic solution than a conventional revetment or seawall. The objective is to construct the cobble berm to be as close as possible in form and behavior to natural cobble beaches in order to be compatible with the natural environment and to insure stability (Komar and others, 2003).

The origin of the use of dynamic revetments for shore protection is uncertain. Early papers on the artificial nourishment of gravel beaches (for example, Muir Wood [1970]), have aspects that are similar to those for a cobble berm. The concept of a structure having a dynamic response to wave attack on a larger scale has also been applied to rubble-mound breakwaters (Bruun and Johannesson, 1976; Willis and others, 1988). The earliest published paper that considers the design of an artificial gravel beach is that of van Hijum (1974) who described the applicationof gravel along the bank of the entrance to Rotterdam Harbor, Netherlands, more to dissipate wave energy rather than to serve as shore protection. A similar engineering application is that of Ahrens (1990), who studied the use of a constructed cobble berm to protect a bulkhead located in shallow water.

The use of dynamic revetments for shore protection has been particularly advanced by observations that natural gravel beaches often protect the backshore from erosion (Nicholls and Webber, 1988; Powell, 1988; Everts and others, 2002). Such occurrences are common along the Oregon coast, where natural gravel beaches served as the basis for the design of a dynamic revetment to protect Cape Lookout State Park (Allan and Komar, 2002b; Allan and others, 2003b; Komar and others, 2003).

Regardless of the origin of the concept, the basic strategy has evolved into one of building a gravel or cobble beach for shore protection (Figure 16). The dynamic structure is effective in defending properties because the sloping, porous cobble beach is able to disrupt and dissipate the wave energy (Ahrens, 1990; Ward and Ahrens, 1991), even during intense storms.

There are a number of practical advantages in using a cobble berm for property protection (Ahrens, 1990; Ward and Ahrens, 1991):

- Smaller stone size and typically less expensive than the large armor stones used in a conventional riprap revetment.
- Placement of the material does not require special care. As a result, the boulders may be dumped at the site rather than individually placed, making the construction process much simpler.
- Movement of the gravels by ocean processes does not constitute failure but is desirable in that the gravel berm adjusts its shape to reflect the predominant storm wave conditions.
- Dynamic revetments are more aesthetically acceptable when compared with a conventional seawall or riprap revetment because they conform with the coastal setting, being indistinguishable from natural gravel beaches. This may make construction more acceptable by management authorities, even on coasts that do not permit the use of conventional "hard" structures.

Constructing a dynamic revetment requires more material than does a riprap revetment, but the dynamic revetment is generally less expensive than "hard" engineering structures. However, it cannot be expected that a dynamic revetment will provide the same level of shore protection as a conventional riprap revetment or seawall. The gravels can be moved by the waves, and the placed material may be transported alongshore or offshore by extreme storm waves (Allan and others, 2003b). Thus maintenance requirements can be expected to be more frequent than for static structures.

The dynamic revetment itself may also become a hazard to shorefront properties if the gravels become projectiles during a storm and are flung by the waves against houses. Because of this, the use of dynamic revetments is safest where backed by a bluff or substantial sand dune or if developments are set sufficiently back beyond the reach of wave-flung gravels. Another issue that may limit dynamic revetment feasibility as a form of soft engineering is the identification of suitable gravel sources and the cost of transporting materials.

Design of Cobble Berms/Dynamic Revetments

The design of cobble berms/dynamic revetments has been based largely on experiments undertaken by engineers in laboratory wave basins and on observations and measurements made by coastal geologists during many years of studying gravel beaches.

The initial experimental research on the design of cobble berms was done by engineers at the Delft Hydraulics Laboratory, Netherlands (van Hijum, 1974; van der Meer and Pilarczyk, 1986; van der Meer, 1987; van der Meer and Stam, 1992; van

Figure 16. Comparison of a dynamic revetment constructed at Cape Lookout State Park (left) versus a conventional riprap revetment constructed at Neskowin (right).

der Meer and others, 1996). Most of their laboratory work was conducted with relatively deep water at the toe of the structure. The results were more applicable to the design of a dynamic breakwater than a cobble berm/dynamic revetment to be used in shore protection on a beach. Ahrens (1990) and Ward and Ahrens (1991) elaborated on the Dutch research through additional laboratory investigations conducted with shallow water fronting the rubble mound. The completed laboratory experiments focused on a range of design criteria, including the stability of rock on a sloping beach and the geometry of an equilibrium beach under different wave conditions, with derived empirical relationships for the crest height, slope angle, and horizontal distance from the still-water shoreline to the crest position. The results of the studies provide guidance on the quantity of stone needed to provide adequate protection from wave attack. However, a shortcoming of these experimental studies is that they have not included the composite beach condition (Figure 12, type D) where a sand beach fronts the gravel berm, which is the more common setting for protecting shorefront properties along the Oregon coast.

There is extensive literature derived from study of natural gravel beaches. Of relevance to the design of dynamic revetments are studies of gravel movement by waves, how clasts are sorted by size and shape across the beach profile, and how clasts are transported alongshore at different rates (Carr, 1971; Hattori and Suzuki, 1978). Also relevant are studies of beach responses and how beach profiles change under varying wave conditions, especially at times of major storms. A full review of this literature is beyond the capacity of this report, so only a few representative references are provided.

Threshold equations have been developed for boulder entrainment by waves on beaches (for example, Lorang [2000]), but there are few data from natural beaches to test such relationships. Geologists have been particularly interested in the sorting of gravel particles across the profile (Bluck, 1967; Orford, 1975; Williams and Caldwell, 1988) and have found a variety of patterns. However, the general pattern is characterized by an onshore, upslope decrease in grain size that reflects the decreasing competence of the wave swash. In addition to size sorting, there exist distinctive patterns of sorting on the basis of particle shape, with the extent of departure from a spherical shape governing the tendency of the particle to be swept up the beach by the wave surge versus the tendency to roll back down the beach under the backwash. Sorting can also occur along the length of the beach, caused by different rates of transport by the waves or longshore variations in wave-energy levels as can occur within a pocket beach (Carr, 1969, 1974).

Laboratory and field research have also been undertaken to measure processes affecting the morphologic responses of gravel beaches. Because of the difficulty of process measurements on natural gravel beaches, the majority of this research was done in controlled conditions in laboratory wave basins. For example, Deguchi and others (1996) provided wave-flume measurements of wave-height variations and swash runup elevations. Powell (1988) and Bradbury and Powell (1992) examined the dynamic responses of shingle beaches to random waves, with measurements of swash runup and wave reflection. Although this laboratory work generally used scaled-down grain sizes of material of lower density (for example, coal particles), the resulting empirical relationships compare positively with the limited data from the field. Kirk (1975) provided one of the few attempts to measure the velocity and excursions (including runup elevations) of the wave swash on mixed sand and gravel beaches. Kirk identified a correlation between the breaker heights and the length of swash, but the correlation with the runup elevations was not so good. Nevertheless, the work by Kirk demonstrated a dependence of the runup elevation on the wave period, consistent with recent research undertaken more recently by Holman (1986) and Ruggiero and others (2001). Other studies have used aluminum pebbles as tracers to measure the longshore transport and sorting of shingle by waves on English beaches (Nicholls and Webber, 1988; Nicholls and Wright, 1991).

A particularly relevant field study of natural cobble beaches is that of Everts and others (2002) in Southern California, which focused on providing improved design criteria for constructing dynamic revetments on that coast. At the study sites, natural cobble accumulations are found at the backs of otherwise sandy beaches, a configuration that dissipates much of the wave energy. Repeated profiles showed that in the winter the cobble deposits were accreted, whereas in the summer cobbles dispersed into the sand portion of the beach. This was opposite to the response of the fronting sand beach and what is normally found in beaches. During times of storms, the cobble beaches steepened, again opposite to the response of sand beaches, which typically decrease in average slope as sand is transported offshore. This response, important to the stability of beaches, has also been observed by Lorang and others (1999) on natural cobble beaches and by Allan and others (2003a) on a constructed cobble berm on the Oregon coast.

Existing Dynamic Revetment Applications

Until recently most of the construction of dynamic revetments for shore protection has been limited to relatively low-wave-energy environments. Downie and Saaltink (1983) describe a dynamic revetment installation on the shore of Vancouver, British Columbia, within the fetch-restricted Strait of Georgia. The site, a pocket beach adjacent to the campus of the University of British Columbia, is backed by a 61-m-high (200 ft) cliff that has been eroding at a rate of about 0.4 m (1.3 ft) per year. The causes of erosion were excess surface runoff, groundwater-induced piping, and storm wave erosion of the bluff toe. The decision to use a dynamic revetment was a compromise between engineers, who wanted to protect the university's engineering building from the threat of bluff erosion, and beach users.

An interesting component to the construction of the dynamic revetment was the inclusion of drift sills installed parallel to the incoming wave crests and used to control the alongshore migration of the cobbles once the structure was built. The sills consisted of a central core of boulders that was covered with cobbles and designed to blend in with the morphology of the adjacent beaches. The design crest (the height required to minimize wave overtopping) of the structure was established at 6.4 m (21 ft). However, no information was provided on how the berm crest elevation was derived. Sediment material sources were located locally, within about 32 km (20 mi) of the structure. The cost of the structure was estimated to be around $500,000.

The Vancouver dynamic revetment has performed relatively well, with the cobbles tending to move up the beach face to form a steep profile (about 18º or 1-on-3). However, Downie and Saaltink noted that the sills did not perform as effectively due in part to their lower elevations, so that significant quantities of material were transported over the sills and along the beach.

Johnson (1987) documented several examples in the Great Lakes of North America where dynamic revetments proved to be cost effective solutions for shore protection. Initially, revetment creation was inadvertent — gravel beaches formed from copper mine tailings that had been disposed of on the beach or where a beach nourishment project used a mixture of sand and gravel, with the sand subsequently being lost while the waves concentrated the gravel into a revetmentlike deposit at the back of the beach. On the basis of those serendipitous examples, dynamic revetments have been intentionally constructed at Great Lakes sites.

Lorang (1991) described the construction of a perched gravel beach used for shore protection in Flathead Lake, Montana. The completed structure was about 60 m (197 ft) long and consisted of a base formed of boulders and cobbles, which was then backfilled with cobbles to form a sloping cobble beach face. Particle sizes ranged widely due to the glacial origins of the lake, with the median grain sizes ranging from 5 to 25 mm (0.2 to 0.9 in; classified as pebble). Following construction of the dynamic revetment, the structure effectively reduced the erosion to the adjacent backshore. However, the site did experience some loss of gravel due to oblique wave approach that caused the sediment to be transported to the north.

An extension of this approach for shore protection is a gravel-beach accumulation at the Port of Timaru, on the east coast of the South Island of New Zealand (Kirk, 1992a). The breakwater of the port had degraded owing to direct assault by high-energy waves. In response, a protective beach was established along the length of the breakwater by constructing a short groyne at its end, which partially blocked longshore gravel transport that had previously bypassed the breakwater. The accumulated gravel beach was so successful in dissipating the wave energy that large rocks of the breakwater have been mined for use in structures elsewhere.

At Washdyke beach, located in South Canterbury, New Zealand, Kirk (1992b) described a novel experimental solution to a very severe erosion and inundation hazard that is analogous to the construction of a dynamic revetment. This particular beach had been eroding naturally since historic record-keeping began, but erosion increased significantly after construction of a harbor at the Port of Timaru. The harbor effectively cut off the supply of gravels that are normally transported northward along this section of coast. The erosion became especially acute adjacent to an ocean outfall. In order to protect the outfall and to buy time for a new outfall to be constructed, a 300-m-long (1000 ft) section of beach centered on the outfall was "rebuilt" in 1980. The construction consisted of two phases. The first phase used gravel that had rolled over to the backshore by storm wave overwash. These sediments were used to raise the barrier beach by 2.0 to 2.5 m (6.6 to 8.2 ft). The second phase involved the introduction of approximately 9,800 m^3 (12,818 yd^3) of coarser gravels that would be more resistant to erosion and were placed on top of the reconstructed barrier, effectively "capping" it. In many respects, this type of beach reconstruction is analogous to the building of a dynamic revetment. The total cost of the project was $40,000 (New Zealand dollars). The effort proved highly successful with a 55% reduction in the overall erosion rate over a period of 5 years (the project design life) with no crest retreat, no overtopping, and no sediment washover (Kirk 1992b). In contrast, the neighboring untreated coasts retreated 11 to 22 m (36 to 72 ft) during the project period. The project was so successful that the structure was still protecting its portion of beach in 1991 and was eventually reshaped to conform to the adjacent eroding coast. This was completed when the old outfall was eventually demolished in the early 1990s.

Large-scale dynamic revetments have only recently been constructed on U.S. ocean shores for erosion control. A 300-m-long (985 ft) cobble berm, backed by an artificial dune containing sand-filled geotextile bags, was constructed at Cape Lookout State Park, Oregon in 1999, following several years of extreme erosion (Allan and Komar, 2002b; Allan and others, 2003b; Komar and others, 2003; Allan and Komar, 2004). The selection of a dynamic revetment to prevent further erosion and flooding of the park's campground was based primarily on the desire to maintain the park in as natural a condition as possible, as opposed to a large-scale "hard" structure separating the park from its main attraction, the beach. An extensive monitoring program currently underway includes periodic measurements of beach cross-sections, measurements of cobble movement and the progressive development of particle sorting patterns, and a video data collection of swash runup on the berm. Another U.S. West Coast installation of a cobble berm is located at Surfers Point, Ventura, California. A test site was designed and constructed there in 2000 by Coastal Frontiers Corporation to protect eroding park lands and a bicycle path (Noble Consultants, 2000). The choice of a cobble berm rather than a conventional structure was influenced in part by an important surfing site along this stretch of shore.

METHODS

Techniques used for documenting the coastal geomorphology of cobble beaches on the Oregon coast include:

- Creating a beach-profile monitoring network at selected cobble beaches along the full length of the Oregon coast;
- Undertaking beach profile surveys of the morphology of the gravel beach study sites, including assessments of their beach slopes, berm crest elevations, and where possible an assessment of their temporal responses to wave and current processes;
- Analyzing the response of the cobble berms and their temporal and spatial responses based on 1997, 1998, and 2002 LIDAR beach-topography data;
- Obtaining measurements of the grain sizes and sorting characteristics at each of the study sites; and
- Analyzing the potential for wave runup and overtopping of the cobble beaches.

Morphology Surveys

Beach-Profile Surveys

A reconnaissance trip along the northern Oregon coast was taken in April 2003 to determine appropriate locations to establish a series of beach-profile monitoring sites. On the basis of this trip it was determined that monitoring suitable gravel beaches could be undertaken at six locations: Short Beach, Cape Meares, Neahkahnie, Cove Beach, Arch Cape, and Seaside (Figure 17). Additional gravel beach study sites were later established on the central Oregon coast, north of Heceta Head, and on the south coast adjacent to Brookings (Figure 17). Gravel beach monitoring is also underway at Cape Lookout State Park and at Oceanside as part of an ongoing study to examine the performance of the dynamic revetment that was constructed in the park in 2000 (Allan and others, 2003b; Allan and Komar, 2004). These latter data sets are also used here.

The cobble beach monitoring network consists of a total of 27 profile lines (cross-sections) at 13 gravel beach study sites, with multiple lines at most of the cobble beach locations, to measure the beach morphology. Beach surveys provide a snapshot of the shape of the beach for an individual survey that includes the height of the dune crest, beach slope, presence or absence of any erosion scarps, volume of sand, and information on swash runup limits. Subsequent resurveys of the profiles will provide insight into the spatial and temporal behavior of the beach as it responds to variations in waves and tides.

Initial surveying of the beach profiles was accomplished using a Sokkia "Set 500" Total Station theodolite. Those surveys were undertaken in July 2003 for the north coast beach profile sites, in April 2004 for the south coast, and in August 2004 for the central coast sites. Each profile site has been referenced to a benchmark (a survey monument having a known location and elevation, serving as a reference point for subsequent resurveys) installed in stable locations adjacent to the beach. The benchmarks consist of wooden stakes or magnetized "pk" surveyor nails. Elevations of the benchmarks were initially established relative to the height of the tide at the time of the survey. During the latter half of 2004, a cooperative venture was begun between DOGAMI, OPRD, and the Department of Land Conservation Development to purchase a Trimble 5700/5800 Global Positioning System (GPS). As a result, we have since been able to locate precisely the coordinates and elevations of each of the benchmarks with the exception of those sites established on the south coast and benchmarks that were lost at Seaside and at Arch Cape.

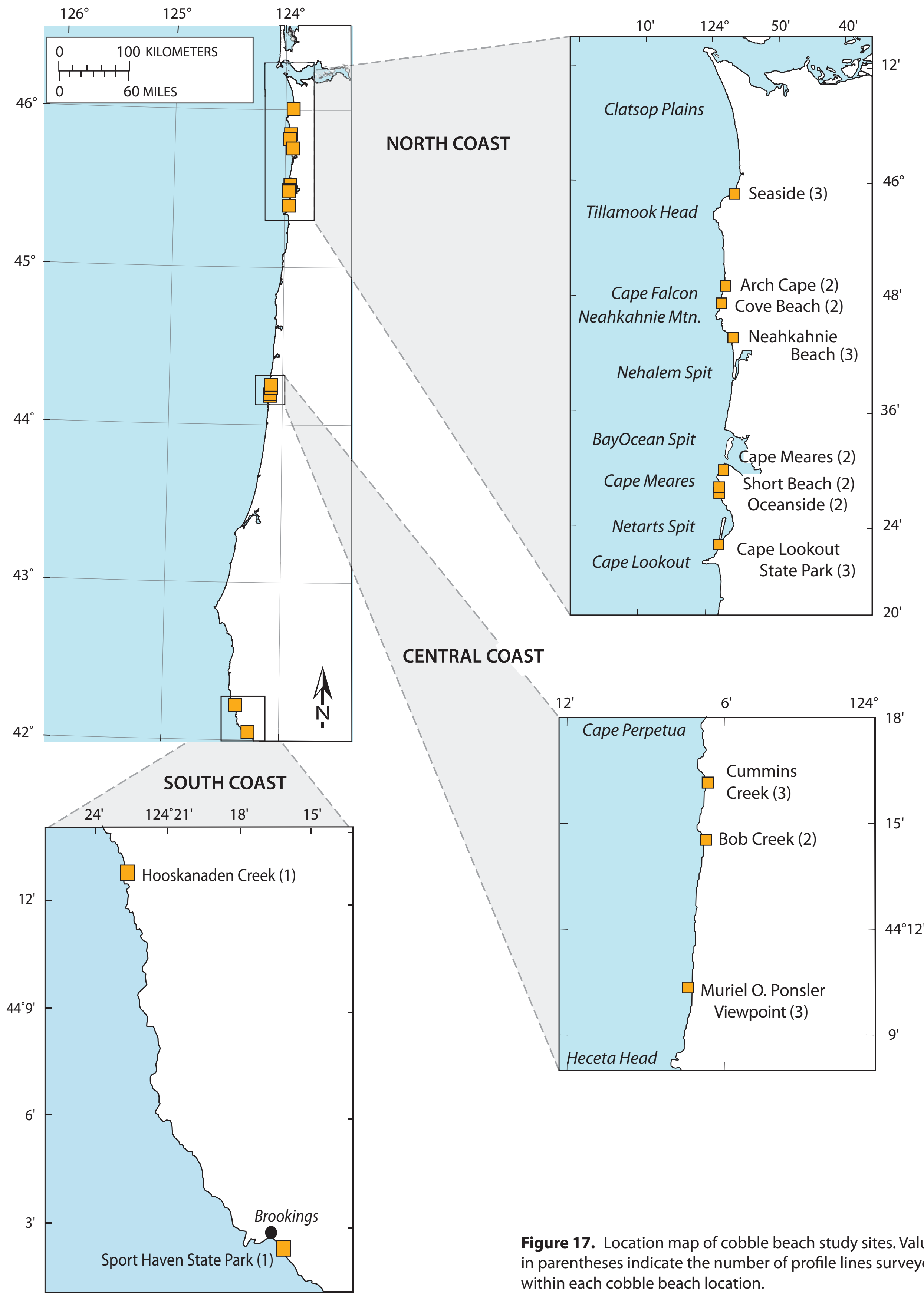


Figure 17. Location map of cobble beach study sites. Values in parentheses indicate the number of profile lines surveyed within each cobble beach location.

Light Detection and Ranging (LIDAR) Data

Additional information on the spatial and temporal variability of gravel beaches was obtained from an analysis of 1997, 1998, and 2002 LIDAR topographic beach data measured by the USGS and NASA. LIDAR is a remote sensing approach consisting of *x*, *y*, and *z* values of land topography derived using a laser ranging system mounted onboard a De Havilland Twin Otter aircraft. The LIDAR data were obtained from the National Oceanic and Atmospheric Administration's (NOAA) Coastal Service Center (CSC) operated in tandem with the USGS and NASA. Detailed information on how the beach topography measurements are derived and processed are covered by Brock and others (2002). The LIDAR data have a vertical accuracy of approximately 0.15 m (0.5 ft), while the horizontal accuracy of these measurements is about 0.8 m (2.6 ft) (Sallenger and others, 1999). All LIDAR data obtained from the CSC are in the 1983 Oregon State Plane Coordinate system, while the elevations are relative to the North American Vertical Datum of 1988 (NAVD 88).

The LIDAR data were analyzed using a triangulation approach to generate a grid data set. This process was accomplished using Vertical Mapper™ (contour modeling and display software), which operates seamlessly within the geographical information system (GIS) software by MapInfo®. After generating a grid data set, cross-sections of the beach morphology were constructed at 100-m (328 ft) intervals along selected gravel beach shores (for example, Cape Meares, Neahkahnie, Cove Beach, Arch Cape, and Seaside). The transects were then used to extract various beach and dune morphological features (for example, berm crest elevations and beach slopes) for the 1997, 1998, and 2002 LIDAR flights.

Grain-Size Analyses

Assessments of the mean grain sizes and sorting characteristics of Oregon's gravel beaches are important to provide guidance on identifying the appropriate gravel size to use in dynamic-revetment construction. Grain-size analyses were done at each of the 27 profile sites. Because of the coarse nature of the particles, existing techniques of grain-size measurement (for example, sieving) cannot be used. An alternative to this approach is the use of a "gravelometer" to measure the size of the particles (Figure 18). The gravelometer is a 5-mm (0.2 in) thick aluminum template with square holes cut out at 0.5ø intervals and is used to measure the B (intermediate) axis of the particles. The template is capable of measuring sediment ranging from –1ø to –7.5ø (2 to 180 mm). To operate the gravelometer, the user simply passes the B axis of a particle through the various holes until the appropriate size is found.

Prior to measuring particle sizes, a 20-ft-ling (6-m) tape measure was extended across the gravel face, parallel with the ocean. Sediments were then sampled at one-foot (0.3 m) intervals along the tape. Once the end of the tape was reached, the tape was moved 2 feet (0.61 m) down the gravel face where the sampling process was repeated. The process continued until at least 100 samples were measured. At most sites we attempted to measure the upper, middle, and lower sections of the gravel face, which provided as many as 300 samples per profile location. However, if the sediment was of a relatively uniform size or the gravel beach face was narrow in width, sediment sampling was confined to the midsection of the gravel slope. The number of particles retained in each size category of the gravelometer was logged accordingly. Cumulative totals of the grain sizes were then tabulated, and these data were eventually plotted on log probability paper in accordance with existing procedures for grain-size calculations.

Grain-size statistics were calculated using procedures established by Folk and Ward (1957). The most commonly specified descriptive parameter in the examination of sediment is the mean value ($M_z ø$). Mean grain size reflects the overall average size of the sample and is a measure of the central tendency of the sample. Calculation of the inclusive graphic mean is as follows:

$$M_z ø = \frac{ø16 + ø50 + ø84}{3} \tag{1}$$

where ø16, ø50, and ø84 represent the cumulative percentiles 16, 50, and 84 percent, respectively, measured from the log probability plot. Folk (1965) noted that mean grain size is a function of two variables. First, it is dependant on the range of sediments that are available. Second, it is a function of the amount of energy that is exerted on the sediment and is therefore further dependant on the current velocity and the degree of turbulence. Other parameters also calculated include grain-size sorting (akin to the standard deviation) and median (D_{50}) grain size.

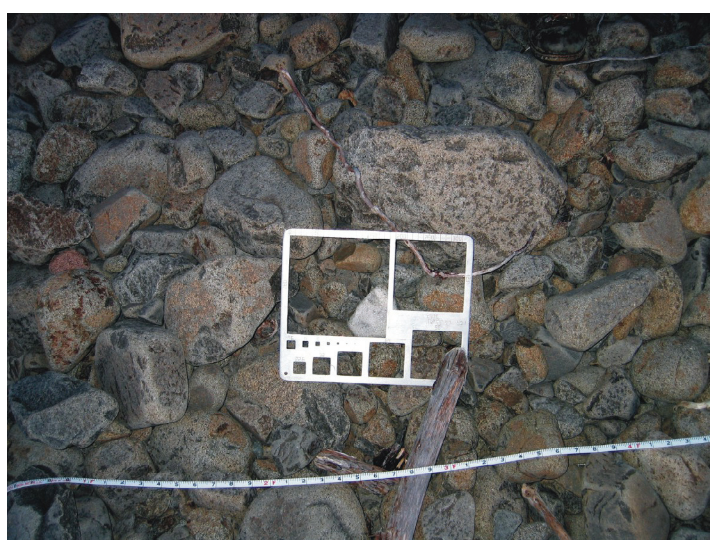


Figure 18. Example of a "gravelometer" being used at Neahkahnie to determine grain-size statistics on the beach.

Wave-Runup Assessments on Gravel Beaches

The crest of the beach face is generally formed at a level that is just below the maximum level of wave runup (Bradbury and Powell, 1992). It is unclear, however, whether the maximum wave runup level is associated with a 1 percent event or some other recurrence event (for example, an annual average wave runup). Nevertheless, it is well established that the beach crest (Figure 19) is generally a function of some combination of wave conditions and water levels as well as size, sorting, and grading characteristics of the sediment. As the total water level (T_{WL}), produced by the combined effect of wave runup (R) plus the tidal elevation (E_T), reaches and begins to exceed the foredune or berm crest ($E_{J\ HIGH}$), overwash occurs, which may result in erosion of the beach and backshore. These concepts are analogous to those applied to the erosion of beaches and dunes on the Oregon coast (Shih and Komar, 1994; Komar and others, 1999) and on barrier beaches on the U.S. East Coast (Sallenger, 2000).

Gravel beaches are capable of dissipating much of the incident wave energy when the swash of the wave passes over the steep gravel face due to the high infiltration rates characteristic of coarse beaches and from friction effects exerted by the gravel. Under low to moderate storm conditions, sediment carried up the gravel face is often deposited as a gravel ridge (Figure 19A), which may continue to aggrade vertically for some time depending on sediment supply rates and the wave climate. However, under extreme storm conditions when high wave energy levels are combined with extreme water levels, the gravel beaches become susceptible to very high swash excursions, which results in frequent overtopping of the crest of the beach face (that is, $T_{WL} > E_{J\ HIGH}$, Figure 19B). It is under these latter conditions that erosion occurs along both dunes and bluffs, as the waves are able to reach the toe of these backshore features. Thus, it is apparent that a relationship exists between the total water levels (the wave runup superimposed on the tide) achieved during some interval and the crest of the beach. As a result, in the absence of measured beach morphology information, it may be possible to estimate the height of the cobble berm/dynamic revetment from an understanding of the total water levels achieved during a winter season or seasons.

The conceptual model portrayed in Figure 19 is akin to the storm impact scale developed by Sallenger (2000), which couples the forcing processes associated with a major storm with the geomorphological characteristics of the coast and has been used to measure the likely impact of tropical and extra-tropical storms along the barrier islands of the U.S. East Coast. The model defines four regimes on the basis of variations in the upper and lower limits of the total water levels produced during a storm (R_{HIGH} and R_{LOW}) relative to the dune crest elevation (D_{HIGH}) and the beach-dune junction (termed D_{LOW} by Sallenger). Sallenger (2000) identified four regimes, termed swash, collision, overwash, and inundation, derived from the ratios of these variables. During storms, the beaches of Oregon typically fall under the collision regime, which reflects conditions when the wave runup collides directly with the toe of the dune or bluff (the $E_{J\ HIGH}$), forcing dune erosion. However, at some locations, including on gravel beaches, these same conditions may result in R_{HIGH} exceeding D_{HIGH} (the berm crest), producing overwash (Figure 19B). Along the U.S. East Coast, overwash of barrier islands has often resulted in landward migration of the barrier. Such migration could occur at a few sites on the Oregon coast, but in the majority of cases migration will not occur, as most of Oregon's gravel beaches are backed by either a dune or sea cliff, limiting landward movement.

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

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

for estimating the 2 percent exceedence runup (R) elevation, where S is the beach slope (tan ß), H_{SO} is the deep-water significant wave height, and L_O is the deep-water wave length given by

$$L_O = (g/2\pi°T)^2 \tag{3}$$

where T is the wave period and g is acceleration due to gravity (9.81 m/s^2). Therefore, estimates of wave runup elevations depend on an availability of data for wave heights and periods and surveys of the beach profile. However, it is important to appreciate that this relationship is from empirical observations of sandy beaches and does not take into account measurements of wave runup on gravel beaches; hence, runup calculations in this paper for gravel beaches are somewhat uncertain. Development of new empirical relationships to more accurately estimate runup for gravel beaches is beyond the scope of this investigation.

To calculate the total water levels (T_{WL}), all hourly wave data (derived from the Newport buoy for the period July 1987 to March 2003) and tide statistics (for example, Newport) were compiled in a spreadsheet. The data were eventually analyzed in MATLAB™ to yield a frequency distribution of all hourly total water levels. Additional analyses included:

- Assessing the calculated total water levels for the winter months (October to March); and
- Using standard techniques of extreme value analyses to determine the 10- through 100-year extreme total water levels. The extreme value analysis was undertaken using the Coastal Engineering Design and Analysis System (CEDAS) software developed by the U.S. Army Corps of Engineers.

RESULTS

Cobble beach development on the Oregon coast results from a balance between the supply of suitable quantities of coarse material to the beach face and the coastal processes, primarily waves and currents. These processes act to transport and sort the gravel laterally along the beach and in cross-shore directions to form gravel beaches. The gravel and boulders are derived from a variety of sources including mass wasting of rocky headlands and other rock bluffs, from fluvial sources (for example, small mountain streams that encroach onto the beach), and from the erosion and undermining of coastal bluffs containing Quaternary alluvial or marine terrace deposits. In the majority of cases the predominant source of sediment to the gravel beaches is likely from mass movement such as debris flows, landslides (Figure 20), or rock falls. Once introduced into the littoral zone, the sediment is rapidly reworked by waves and currents and is redistributed across the beaches.

Most of the cobble and boulder material introduced to the coastal zone in Oregon is from crystalline volcanic or metamorphic rocks. Tertiary basalt is the main source on the northern and central Oregon coast. The most common unit is the Columbia River Basalt (Schlicker and others, 1972). On the southern Oregon coast many coastal bluffs have Mesozoic volcanic and metamorphic rocks that provide ready sources of gravel to the beach. In some areas of the north coast, such as around Cove Beach and along the Arch Cape shore, basaltic gravel may be mixed with Tertiary sandstones. Once introduced, the gravels may form extensive beaches that span several thousand meters along the shore (for example, at Netarts Spit, Figure 21A), smaller accumulations within shoreline reentrants (for example, near Bob Creek on the central Oregon coast, Figure 21B), or a thin veneer on the landward edge of shore platforms (for example, Bob Creek, Figure 21C). Invariably though, the best examples of gravel beaches can

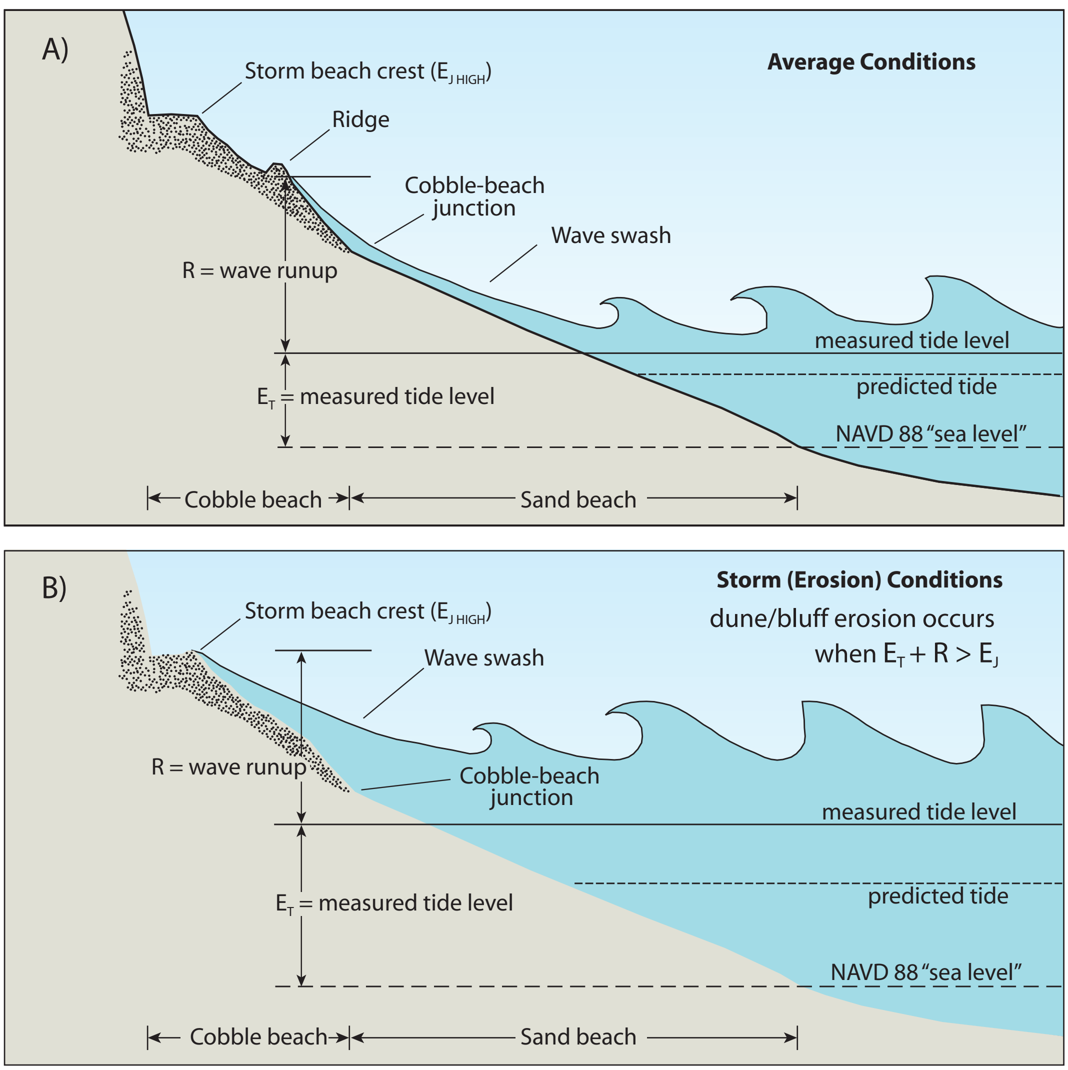


Figure 19. Graphic depiction of wave runup during typical and storm conditions. (**A**) Typical composite gravel-sand beach exposed to wave runup (R) and tidal (E_T) conditions, which may result in erosion of the cobble foredune toe (E_J) and/or berm development. (**B**) During large storms and elevated water levels, wave runup is able to reach much higher elevations on the backshore (> $E_{J\ HIGH}$) eroding a bluff or dune that may back the beach. Furthermore, waves may also occasionally overtop the berm crest depositing material on its crest raising the elevation of the crest and leeward face (after Komar and others [1999]).

be found on the north and south sides of prominent headlands, especially on the northern Oregon coast.
At many of these sites, the presence of the gravel beach has been an important form of natural shoreline protection, effectively slowing the erosion of the backshore.

The southern Oregon coast gravel beaches are similar to those in the north, with the distinction that the gravel may include larger proportions of sedimentary rocks such as sandstones and siltstones and especially metamorphic rocks from the Klamath Mountains. The supply of these materials to the coast is again dominated by the occurrence of rock falls and landslides, although in some locations the gravel is probably predominantly fluvial in origin (for example, adjacent to Brookings and at Gold Beach).

In most cases, the gravel tends to be well rounded and exhibits a wide range of sizes from fine gravel to boulders. The beaches may exhibit some evidence of cross-shore sorting, with the coarsest sediment tending to accumulate in the lower portion of the gravel face and an upward fining in the sediment size up the gravel face. However, on those beaches that contain smaller gravel volumes, there tends to be little evidence of cross-shore sorting so that the sediment is highly mixed.

Beach Surveys and Grain-Size Measurements

The 27 profile lines located at 13 gravel beach study sites along the Oregon coast (Figure 17) were selected for assessments of their beach morphologies and grain-size characteristics. This section presents results of the beach surveys and grain-size measurements undertaken at each of the study sites. A general description and the main findings for each of the study areas are presented. A discussion of the overall results is then provided. In each example the morphology of the gravel berm and its general effectiveness in limiting erosion are described. Indicators of low erosion in the backshore are vegetation, colluvial slopes at the angle of repose of the colluvial material, and fixed position of topographic features on historic photos and topographic surveys.

Clatsop County

Columbia River Littoral Cell

The Columbia River littoral cell (CRLC) extends from Tillamook Head, Oregon to Point Grenville, Washington. The coastline is 165 km (102 mi) long and consists of beaches and spits that have prograded seaward over the past 4000–5000 years as the rate of sea level rise slowed following the end of the last glaciation. The CRLC is subdivided by three large depositional estuaries: Grays Harbor, Willapa Bay, and the lower Columbia River estuary. The estuaries and two headlands divide the CRLC into four coastal subcells that include the Clatsop Plains on the Oregon coast in the south and Long Beach Peninsula, Grayland Plains, and North Beach on the Washington coast. Although the bulk of the shore is characterized by pure sand beaches (Figure 12, type E), a section of the shore adjacent to Seaside, located at the extreme south end of the littoral cell, is characterized by a composite gravel-sand beach (Figure 12, type C).

Seaside

An extensive gravel beach has developed on the north side of Tillamook Head, with the sediment having been transported north toward the town of Seaside, located at the south end of the Clatsop Plains (Figure 17). The gravel beach is about 3.3 km (2 mi) long and in some places attains a crest elevation of up to 8 m (26.3 ft) NAVD 88 high. However, it is likely that the gravel beach is much longer, probably extending as far north as Gearhart

Figure 20. Photograph of landslide on the north side of Cape Lookout. The landslide occurred early in 2003 adjacent to Cape Lookout State Park. Such events periodically introduce significant quantities of coarse material to the coastal zone where the material is then redistributed along the shore to form cobble berms.

(Tom Horning, personal communication, 2005), with the gravel to the north buried by sand.

The Seaside gravel beach forms an "L" shape, trending north-south at Seaside and east-west on the south flank of Tillamook Head (Figure 22). In this region there is evidence for several older beach deposits, demonstrating the occurrence of previous aggradational phases that may be related to influxes of sediment in response to landslides along the northern flank of Tillamook Head. One such event occurred early in 1987 and released an estimated 230,000 m^3 (300,000 yd^3) of material onto the beach (Tom Horning, personal communication, 2005). The landslide debris was rapidly redistributed along the shore, moving at an estimated 3.2 km (2 mi) per month. By July 1987 it had formed a barrier spit across the beach near where the berm curves again to the north (Figure 22). By September 1987, the sediment had migrated onto the existing gravel beach but continued to travel to the north, eventually causing the beach at U Avenue (Figure 22) to prograde seaward by 45 m (150 ft).

Three transect lines were established at Seaside (Figure 22). Results from our surveys of the gravel beach and from analyses of LIDAR data are presented in Figure 23. Apparent in Figure 23 is that the crest elevation of the gravel beach is uniform between profiles 1 and 2, with the height of the beach located at an elevation of 6.6 m (22 ft), but decreases in the north at profile

Figure 21. Examples of gravel beach types identified along the central and northern Oregon coast. (**A**) Netarts Spit gravel beach spans several thousand meters; (**B**) Bob Creek is characterized by smaller accumulations within a shoreline reentrant; (**C**) Bob Creek (view to the south) has a thin veneer on the landward edge of the shore platforms.

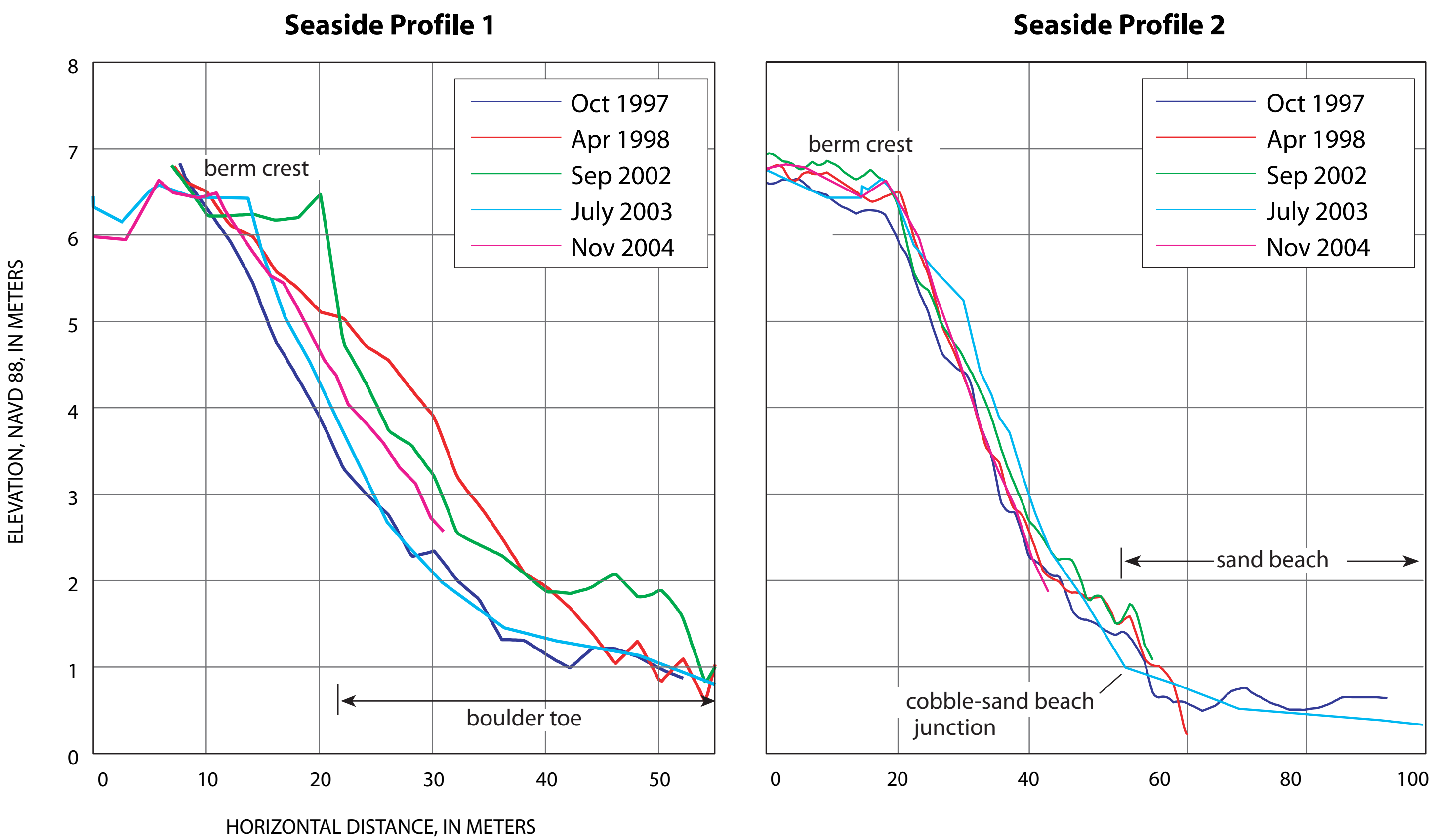
Figure 22. Seaside gravel beach showing locations of beach profile sites and grain-size sampling.

3 to about 5.5 m (18 ft). Of greater significance is the dramatic increase in the width of the beach to the north, increasing from about 54 m (177 ft) at profile 1 to around 130 m (427 ft) at profile 3. This equates to an increase in the volume of gravel on the beach from about 130 cubic meters per meter (1400 $ft^3 \cdot ft^{-1}$) of beach at profiles 1 and 2 to about 430 $m^3 \cdot m^{-1}$ (4627 $ft^3 \cdot ft^{-1}$) at profile 3.

Measurements of the mean grain size and sediment sorting characteristics at each of the study sites revealed very little difference along the gravel beach. However, as can be seen in Figure 21, the gravel berm adjacent to profile 1 is characterized by an extensive boulder toe, which provides additional protection to the beach. In all cases the backshore slopes were well vegetated, indicating that the gravel beach was likely dissipating much of the incident wave energy. The beach gravel is classified as "moderately well sorted," and the mean grain sizes ranged from −5.7 to −6.1ø (52–69 mm), with some suggestion of a slight coarsening to the north at profile 3. This last finding is surprising. One might expect to see the reverse pattern occurring because the finer particles tend to be more easily moved. However, such reversals can occur due to the trapping of finer particles along the shore, particularly if there are large cobbles and boulders present as is the case at Seaside. In addition, it is possible for significant volumes of sediment containing larger clasts to be moved en mass as a gravel "slug"; such an event might occur with the introduction of a large volume of sediment, as from the landslide that occurred in 1987.

The Seaside gravel beach is dynamic (Figure 24), especially at profiles 1 and 3, and is subject to periods of both erosion and rebuilding. At profile 1, the beach was in its most landward phase in 1997 just prior to the onset of the 1997-1998 El Niño. By the end of the winter, however, the beach had prograded seaward by some 10 to 20 m (33 to 66 ft), likely due to the arrival of higher storm waves from the southwest, typical of El Niño conditions. This pattern caused a strong longshore transport gradient to develop around Tillamook Head, eroding gravel downdrift of profile 1 and redistributing the gravel along the shore. Since winter 1997-1998 the gravel beach has eroded back 5 to 10 m (16 to 33 ft).

In contrast, profile 2 shows much smaller lateral changes. This is possibly due to the extensive sand beach that fronts this section of shore and that helps buffer the incoming wave energy. In the north, the gravel beach at profile 3 has retreated landward by some 20 m (66 ft) since October 1997, although the most up-to-date surveys indicate a recent phase of seaward advance. Erosion at profile 3 is probably less of a concern as the shore there is characterized by an extremely wide gravel beach (about 130 m wide [427 ft]) and by the presence of a sand beach in front of the gravel face. Despite these changes, it is clear from our field visits that there is little to no evidence of recent erosion along this particular stretch of shore, as exhibited by the well-vegetated backshore (Figure 21), despite periodic wave overtopping.



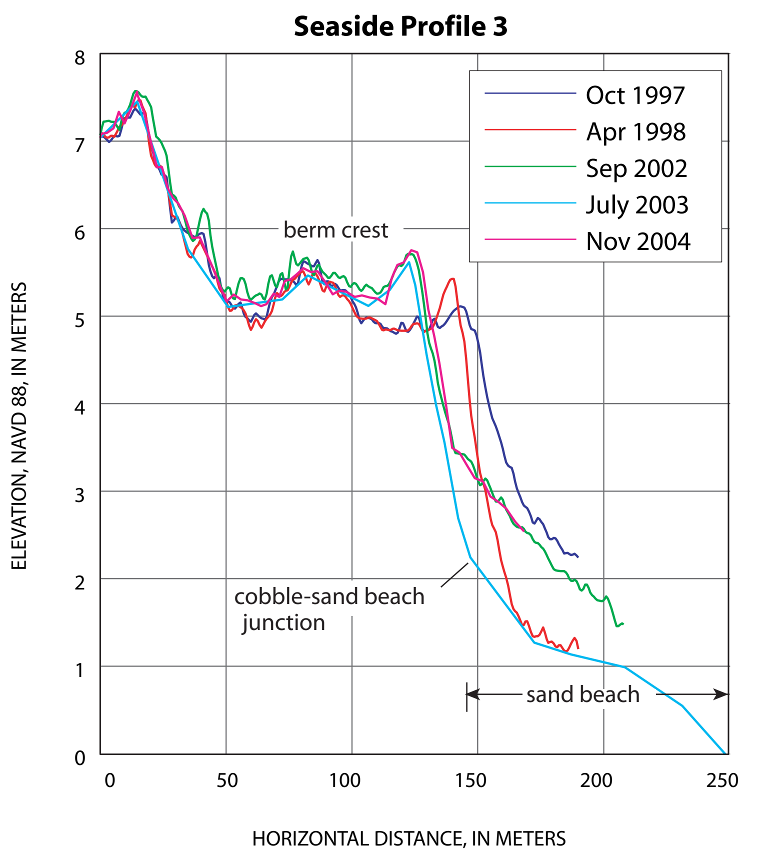


Figure 23. Seaside beach profile surveys 1, 2, and 3 undertaken along the gravel berm. The locations of the transect sites are shown in Figure 22.

Figure 24. Gravel beach at Seaside. (**A**) Adjacent to profile 2. The presence of logs at the beach crest indicates the maximum wave runup height (about 6 m [19.6 ft]) achieved during the most recent storm event. (**B**) At profile 1, the lower portion of the gravel beach is protected by a boulder toe, with the finer gravels having been pushed up the cobble face to form the crest of the beach. Note the well-vegetated backshore and marine cliff landward of the cobble beach. The survey staff near the bottom of the photo shows 0.3-m (1-ft) graduations and indicates the size of the boulder toe at profile 1.

Cannon Beach Littoral Cell

The Cannon Beach littoral cell is about 17.8 km (11 mi) long and extends from Cape Falcon in the south to Tillamook Head in the north. The cell may be further divided into two sub-cells: the shoreline between Tillamook Head and Arch Cape, and Cove Beach located between Cape Falcon and Arch Cape (Figures 17 and 25). The southern third of the shoreline, which includes the Arch Cape and Cove Beach study sites, is characterized by a composite beach that includes a gravel beach fronted by a wide sandy beach (Figure 12, type D); the northern portion of the shore is composed entirely of sand (Figure 12, type E).

Arch Cape

A 2.3-km-long (1.4 mi) gravel beach is present along the Arch Cape shoreline (Figure 25). The gravel beach is about 20 m (60 ft) wide (12 m [39 ft] wide at the berm crest) and provides protection along the toe of a low bluff composed of Pleistocene marine terrace deposits that backs the beach. The seaward face of the bluff is well vegetated and has a slope angle of 30º–40º, close to the 1-on-1.5 vertical to horizontal slope that typifies these colluvial aprons at their angle of repose. This suggests that the bluff face is generally stable. However, the area has been subject to phases of wave erosion, as shown by the presence of a large seawall and an old riprap revetment north of profile 1 and a wooden bulkhead and riprap wall north of profile 2. Despite these few engineered sites, much of the Arch Cape shoreline remains pristine and appears to be fairly well protected by the gravel berm.

Gravels in the beach tend to be well sorted, and their sizes are slightly smaller compared with the Seaside gravel beaches. Mean grain sizes (M_zØ) ranged from –5.96Ø (62 mm) in the south to –5.44Ø (43 mm) in the north. This sediment is classified as very coarse gravel. Although only two sample locations were measured at Arch Cape, the results imply a northward fining in the mean grain sizes that is probably correct given that there is an overall decrease in gravel volume and berm width to the north. The gravel beaches are again characterized by high crest elevations that vary from 6.5 m to 6.8 m (21 to 22 ft). Despite the high crest elevations the volume of gravel contained along the Arch Cape shore is noticeably lower per linear meter of shoreline when compared with the Seaside gravel beaches. For example, the two sites we measured indicate a gravel volume that ranges from 46 $m^3 \cdot m^{-1}$ (495 $ft^3 \cdot ft^{-1}$) at profile 1 to 53 $m^3 \cdot m^{-1}$ (4570 $ft^3 \cdot ft^{-1}$) at profile 2. Given these low gravel volumes, we speculate that the degree of protection offered by the gravel beach at Arch Cape is probably strongly aided by the more prominent sand beach component present in front of the gravel.

Analyses of beach profile data measured at Arch Cape reveal that the gravel beach has been subjected to both erosion and rebuilding phases. At both study sites, the beach was in a gener-

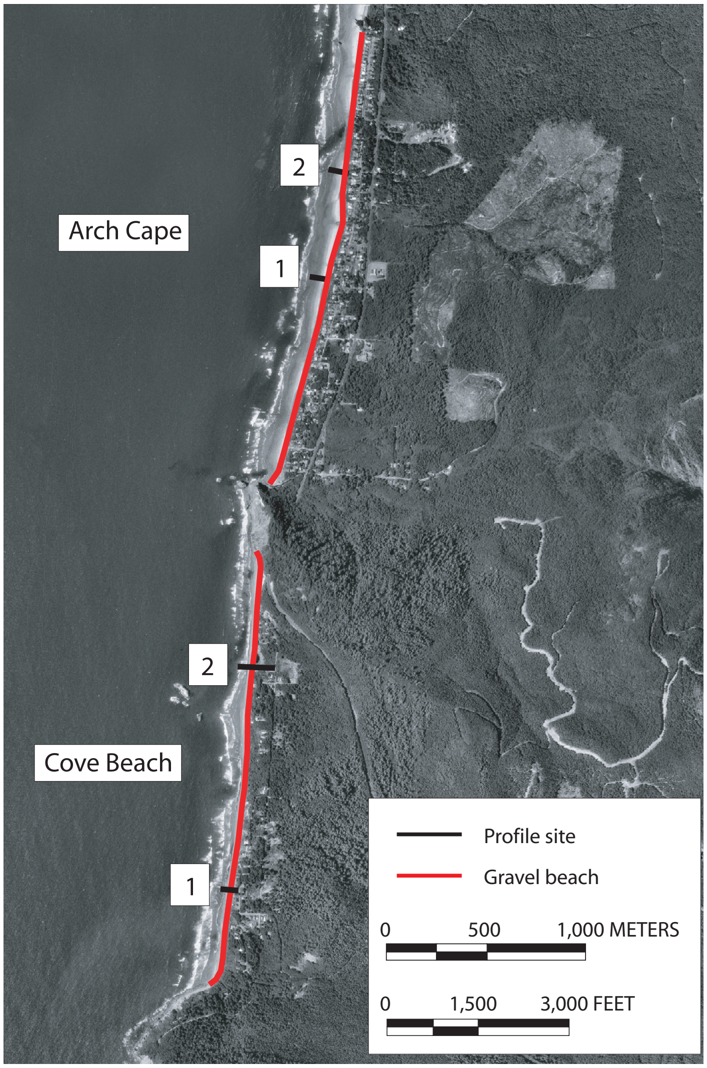


Figure 25. Arch Cape and Cove Beach cobble berm showing locations of beach profile sites and grain-size sampling.

ally degraded state following the end of the 1997-1998 El Niño (Figure 26). However, since then the berm crest has aggraded vertically by almost 2 m (6.6 ft) at profile 1 and about 1 m (3.3 ft) in the north at profile 2, which has caused the gravel face to move seaward by up to 10 m (33 ft). Apart from profile 2, the survey results reinforce the view that the bluff has been stable for at least the past several years. In contrast, results from profile 2 indicate that the bluff has eroded by about 0.5 m (1.6 ft) since 1997. This response is likely to be erroneous and is probably related to the LIDAR survey having captured the vegetation on the terrace slope and the gridding that has subsequently been undertaken to derive a digital elevation model for each LIDAR flight.

Cove Beach

The gravel beach at Cove Beach is without doubt the most dramatic example of erosion identified on the Oregon coast. Along much of its length the gravel beach fronts an actively eroding bluff At least two homes have had to be moved landward, and several other homes are now threatened (Figure 27A). This suggests that the gravel beach does not provide significant protection to the backshore, and raises the question as to why. At the north end of the beach, the gravel forms a barrier beach that has impounded a lake behind it. However, the site is subject to frequent overtopping, as evidenced by the many logs and debris along the crest of the berm and on its landward side leading into the lake (Figure 27B).

The beach is actively being fed by gravel and boulders from the south end of the cell in the form of landslides off Cape Falcon (Figure 28A), while the south-central portion of Cove Beach is primarily supplying sand and colluvial material to the system. As material is released from Cape Falcon, the sediment is rapidly transported northward along the beach where it is assimilated into the gravel beach (Figure 28A). One interesting feature that makes the gravel beach at Cove Beach different from other sites identified on the Oregon coast is the absence of a significant sand beach component in front of the gravel. This feature of Cove Beach may be a function of the most recent major El Niño that occurred in 1997-1998 and that resulted in hotspot erosion at the south end of the Cannon Beach cell; the sand may have moved to the north (toward Arch Cape and Cannon Beach) and has simply not returned.

The gravel beach is characterized by a wide range of grain sizes, from coarse sand and granules to large cobbles. (See cover page for an example of cross-shore sorting of sediment at Cove Beach.) The sediment is classified as "well sorted," which indicates a uniform mixing of the predominant grain sizes present on the beach. Mean grain sizes (M_zØ) ranged from –5.74Ø (53 mm) in the south to –6.19Ø (73 mm) in the north.

On the basis of our two surveys of the area, the mean crest elevation of the gravel beach reaches about 7.0 m (23 ft), and the width of the gravel beach ranges from 33 m (108 ft) at profile 1 to about 45 m (148 ft) at profile 2. The volume of gravel contained in the beach averages 104 m^3 per linear meter (1119 $ft^3 \cdot ft^{-1}$) of shoreline at profile 1, increasing to 160 $m^3 \cdot m^{-1}$ (1722 $ft^3 \cdot ft^{-1}$) at profile 2. These volumes are comparable to parts of the Seaside gravel beach. Another interesting feature at Cove Beach is the steepness of the beach profiles. The gravel slope at Cove Beach is extremely steep and ranges from 12.6º at profile 1 to 23.8º at profile 2 (Figure 28B).

Figure 26 shows the results of our recent surveys of the beach, including analyses of the 1997, 1998, and 2002 LIDAR surveys. The profiles reveal several interesting characteris-

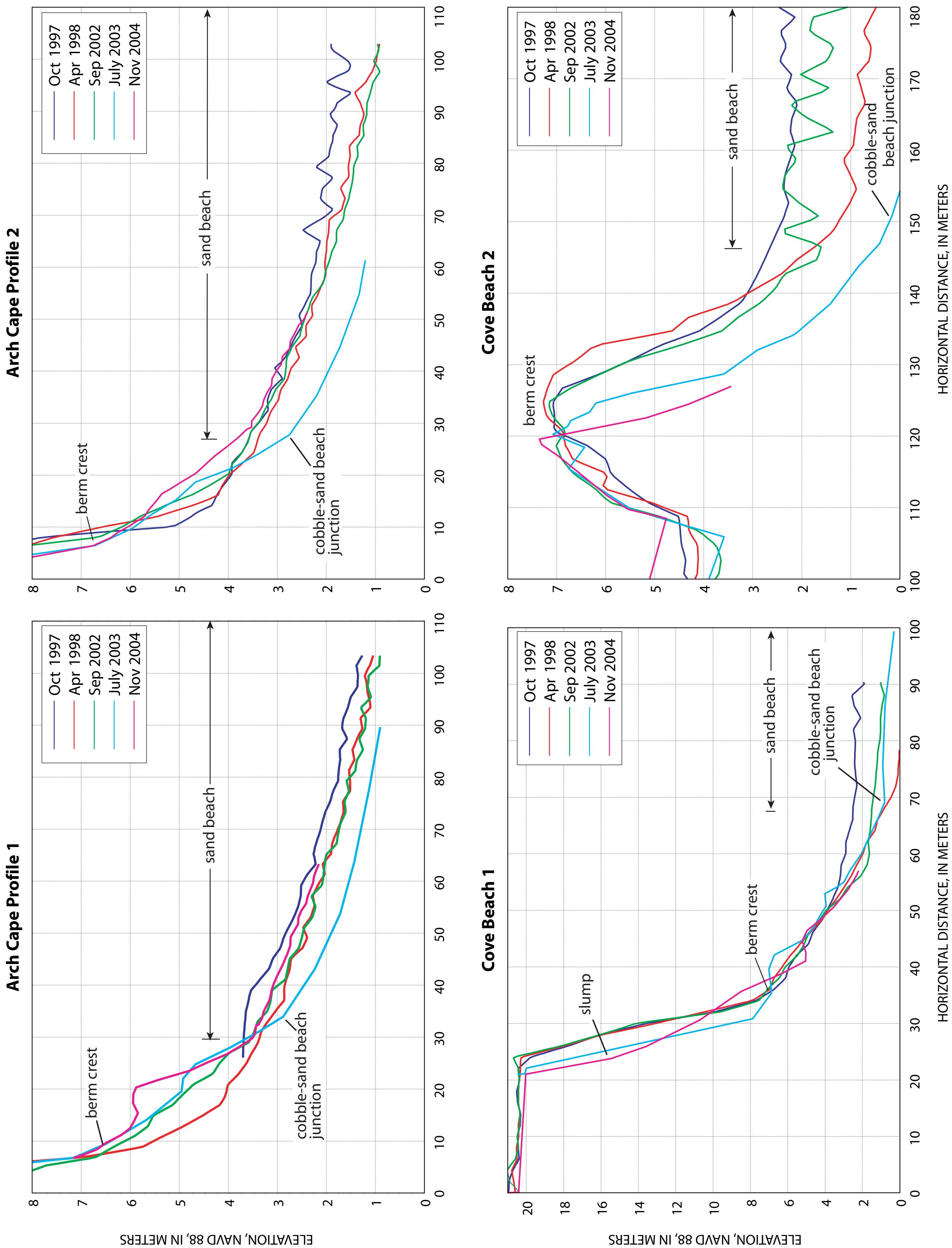


Figure 26. Beach profile surveys undertaken along Arch Cape and Cove Beach gravel beaches. The locations of the transect sites are shown in Figure 25.

tics. First, both sites are characterized by significant temporal and spatial variability on the lower portion of the profile. This response reflects the seasonal sand beach variability, which vertically erodes and aggrades by some 2 m (6.6 ft) in response to the changes in wave energy between summer and winter. Second, our surveys of profile 1 between July 2003 and November 2004 captures a slump and runout zone that probably occurred during the 2003-2004 winter. The surveys also indicate that the bluff has eroded by about 3 to 5 m (10 to 16 ft) since the 2002 LIDAR flight. Third, our most recent survey of the gravel beach at profile 2 indicates that the barrier in the north has eroded landward by 12 m (39 ft) since 1998 (Figure 26). Much of this reflects the wave overtopping and carrying sediment over the barrier during storms, with wave runup depositing sediment along the back edge of the ridge.

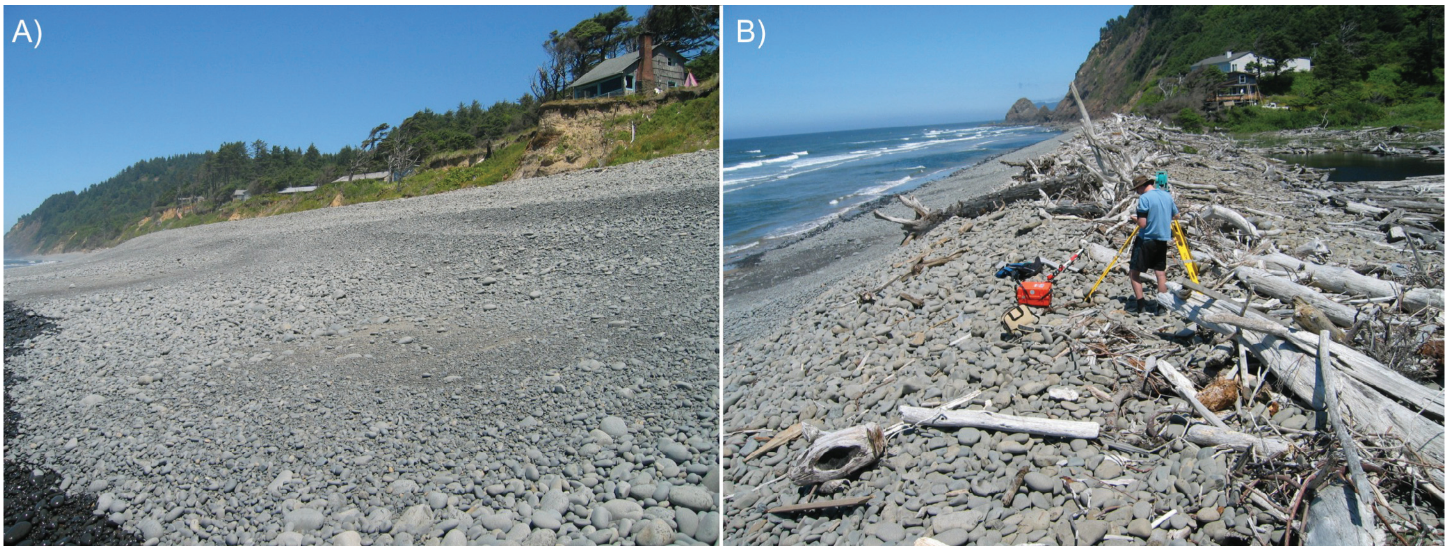


Figure 27. The gravel beach at Cove Beach in July 2003. (**A**) The bluffs that back the gravel beach are subject to active erosion to the extent that several homes are in imminent danger of falling onto the beach. (**B**) The gravel barrier at the north end of Cove Beach. Note the numerous logs that have been carried over the crest of the barrier.

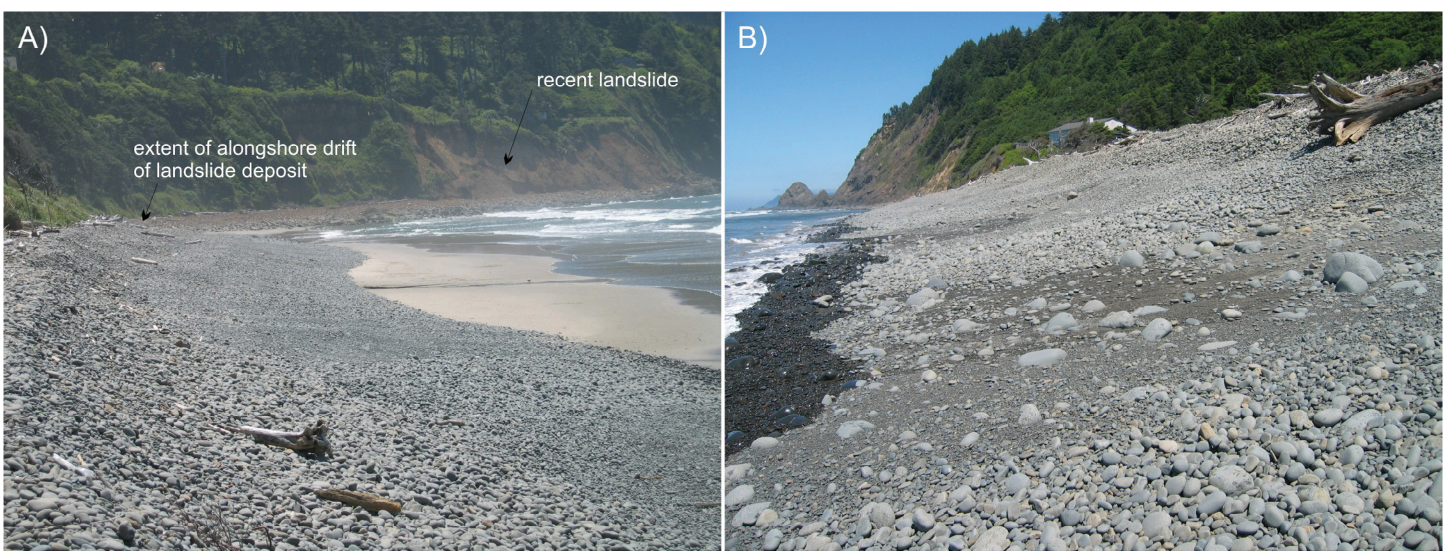


Figure 28. Cape Falson beach morphology. (**A**) Sediments from a recent landslide (probably occurred during the 2002-2003 winter) off of Cape Falcon have moved some 100–150 m (328–492 ft) along the beach. (**B**) Photo showing the extremely steep nature of the gravel beach at the north end of the shore.

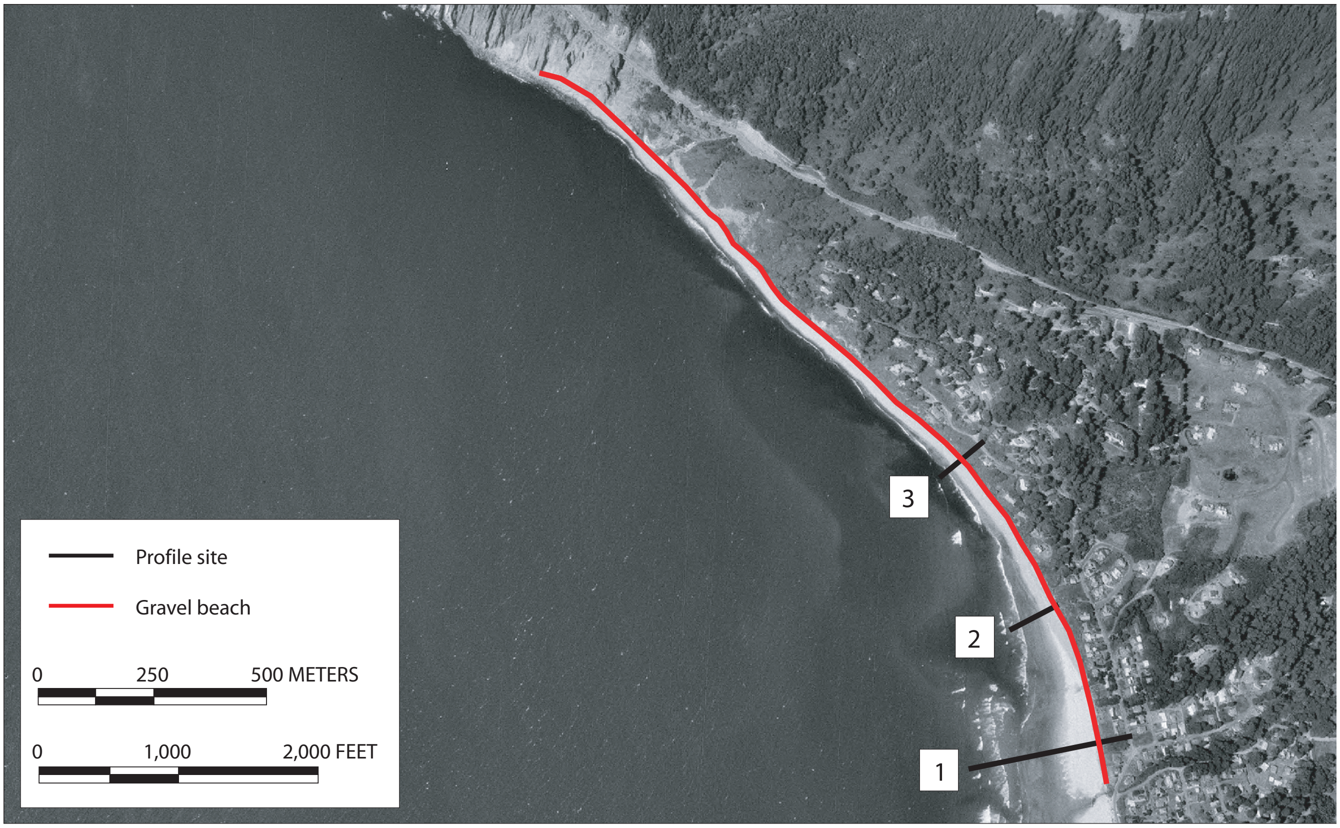


Figure 29. The Neahkahnie gravel beach, in the Rockaway littoral cell, showing the shoreline configuration, locations of beach profile sites, and grain-size sampling transects.

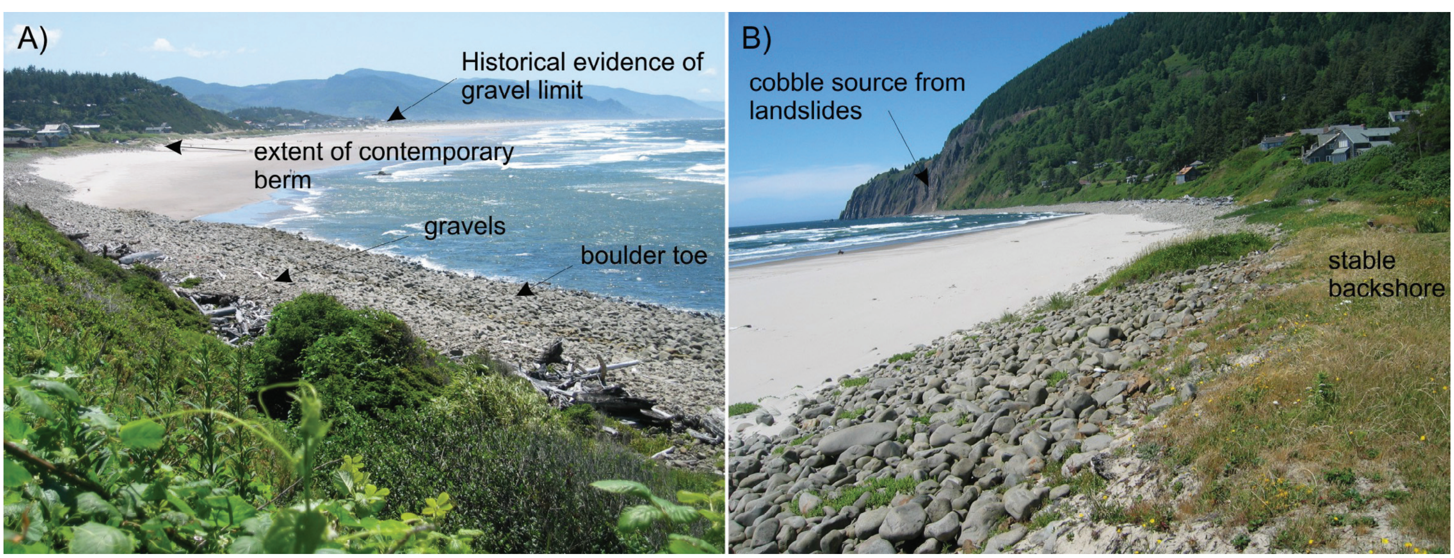


Figure 30. (**A**) Much of the Neahkahnie gravel berm gains significant additional protection and stability from having a toe composed of boulders. Photo was taken overlooking profile 3 and is looking toward the south. Note the historical limit of gravels identified adjacent to the town of Manzanita. (**B**) A well-vegetated backshore provides evidence of the stability of the gravel berm.

Tillamook County

Rockaway Littoral Cell

The Rockaway littoral cell is bounded by Neahkahnie Mountain in the north and by Cape Meares to the south. The 28-km-long (17.4 mi) shoreline is composed chiefly of sand beaches. However, the shoreline also contains two short gravel beach sections located along the toe of Neahkahnie Mountain in the north and adjacent to the community of Cape Meares in the south.

Neahkahnie Beach

The Neahkahnie gravel beach (Figure 29) is approximately 1.5 km (0.9 mi) long. It is highest in the north adjacent to the headland and decreases progressively in elevation to the south. In July 2003, three survey transects were established along the southern half of the beach (Figure 29). Beach surveys were undertaken in July 2003 and in November 2004, providing a measure of summer and winter conditions. The gravel beach is typically widest in the north at profile 3 (about 50 m [164 ft]) and decreases in width to the south; it is 27 m (88.6 ft) wide at profile 2 and 12 m (39 ft) wide at profile 1. South of profile 1 there is no obvious evidence of the gravel migrating further to the south (Figure 30). This would imply that gravel transport, which is to the south, diminishes rapidly by the time one reaches the southernmost beach profile.

Historical photos indicate that the gravel beach at Neahkahnie was once far more extensive, reaching south of the city of Manzanita. Although some gravel materials may have been extracted, it is believed that most of the gravel probably still remains on the beach, having been either buried by sand or built upon. In any case, the well-vegetated backshore indicates that the existing gravel berm has been effective in preventing wave erosion (Figure 30).

Grain-size measurements at Neahkahnie reveal that the beach is characterized by some of the coarsest gravel identified along the Oregon coast. This is due in part to the inclusion of a much higher proportion of boulders in the beach, evidence of the size of the landslides that have been occurring off of Neahkahnie Mountain (Figure 30). Mean grain sizes (M_zø) are coarsest in the north at profile 3 (–7.0ø [128 mm]), decreasing to –6.26ø (76 mm) at profile 2, before increasing slightly in the south at profile 1 (–6.44ø [87 mm]). In the north, at profile 3, the cobbles are classified as poorly sorted due to the inclusion of a higher proportion of boulders in the gravel, whereas the material at the southern two profile sites tended to be better sorted due to fewer boulders in the sediment matrix.

Results from the beach survey are shown in Figure 31. The largest morphodynamic response on the beach profiles is consistent with other beach gravel sites and is due to the seasonal variability in the elevation of the sand

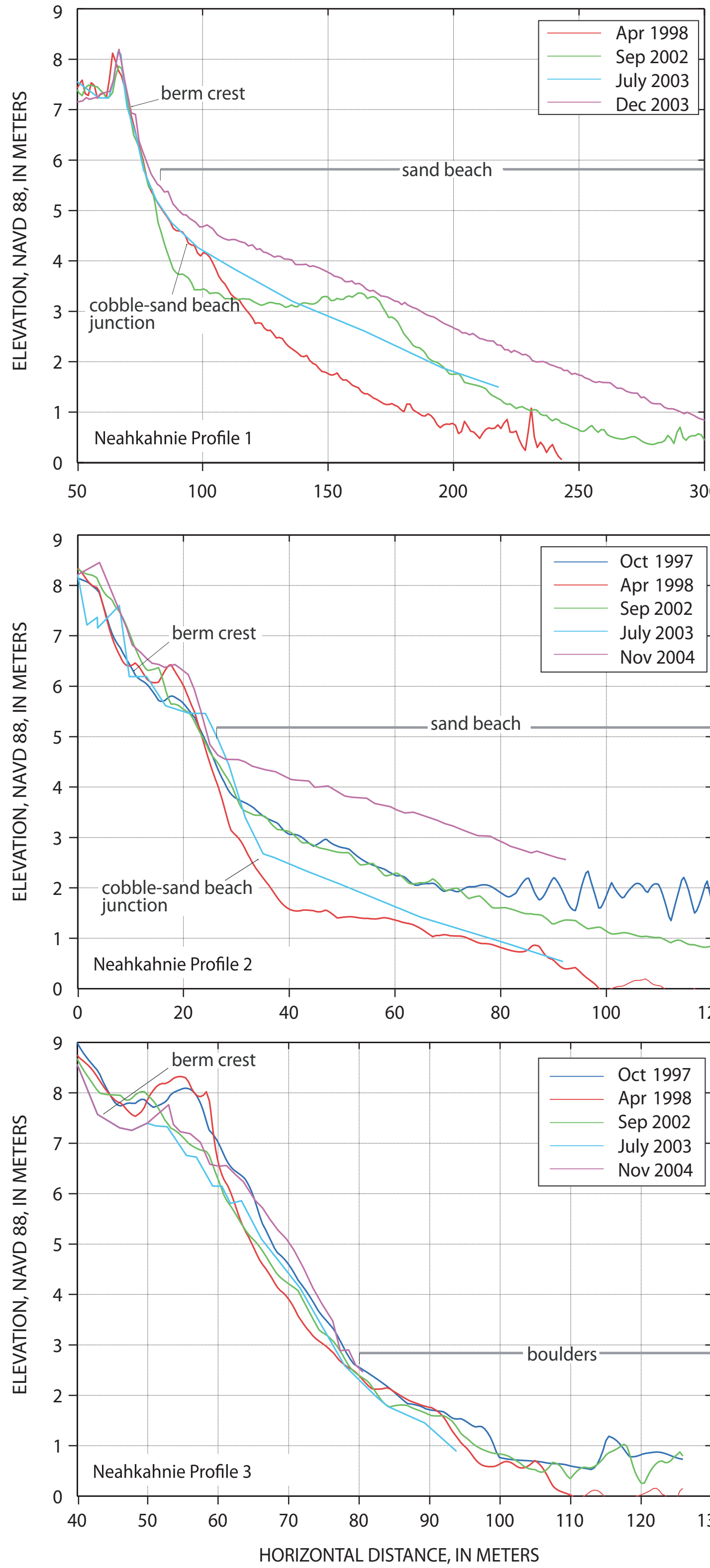


Figure 31. Beach profile surveys undertaken along the Neahkahnie gravel beach. The locations of the transect sites are shown in Figure 29. Horizontal scale varies between charts.

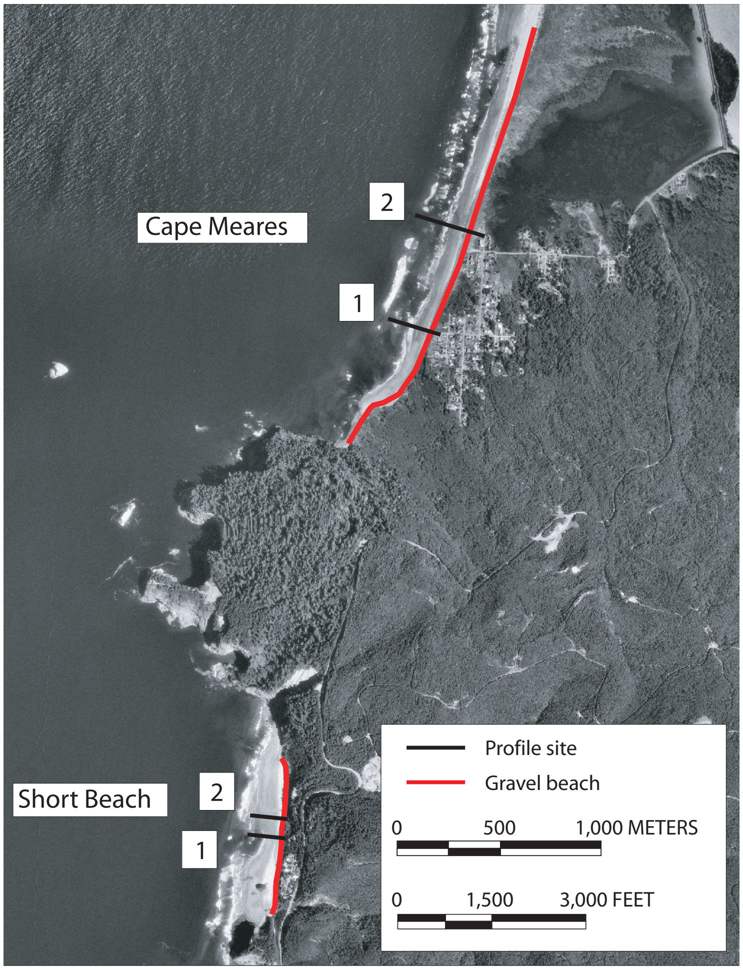


Figure 32. The Cape Meares and Short Beach gravel beaches showing the shoreline configuration, locations of beach profile sites, and grain-size sampling.

beach, which varies by some 1 to 2 m (3 to 6 ft), whereas the gravel beach typically varies by less than 1 m (3 ft) in elevation. Horizontal variability by erosion or accretion is much less at Neahkahnie when compared with the other sites — most of the variability is no more than a few meters. Of importance, though, is that the gravel beach is stable with no evidence of long-term shoreline retreat. This is particularly apparent in Figure 30B, which reveals a well-vegetated backshore and Tertiary bluff that has not been subject to recent erosion events. Gravel crest elevations ranged from 6.2 m (20 ft) at profile 2 to as high as 7.3 m (24 ft) at profile 1. However, much higher elevations were identified north of profile 3; this will be addressed later in the discussion section. Beach slopes are again consistent with the other sites, varying between 7.5º and 9.0º. The volume of gravel in the beach is greatest at profile 3, with 177 m^3 per linear meter (1905 $ft^3 \cdot ft^{-1}$) of beach, and decreases substantially to 40 $m^3 \cdot m^{-1}$ (430 $ft^3 \cdot ft^{-1}$) at profile 2 and 51 $m^3 \cdot m^{-1}$ (549 $ft^3 \cdot ft^{-1}$) at profile 1.

Cape Meares

The Cape Meares gravel beach is about 2.3 km (1.4 mi) long and is located on the north side of the headland, adjacent to the community of Cape Meares (Figure 32). The southern portion of the beach is being fed by sediment from a large active landslide that crosses the southern portion of the town (Allan and Priest, 2001), while hard-rock sediment is also derived from the headland. Although the berm extends 2.3 km (1.4 mi) along the beach, gravel can be identified up to several kilometers from the main berm, evidence for the large northward transport of gravel along the shore.

Results from the beach surveys are shown in the top two plots of Figure 33. The southern profile (Meares profile 1, MP1) crosses a small erosional scarp that is about 1.5 m (5 ft) high, while the northern profile (Meares profile 2, MP2) crosses a gravel barrier spit. Although the scarp indicates that the south end of the gravel beach has been subjected to erosion, the backshore receives significant additional protection from the accumulation of logs along the crest of the beach.This accumulation is likely serving an important role in mitigating much of the incident wave energy across the gravel beach. The beach crest elevation (Figure 33) is highest in the south at MP1, reaching 6.8 m (22 ft), but decreases significantly to 5.8 m (19 ft) to the north at MP2. Furthermore, the slope of the gravel face is steepest in the south (about 8.8º) and decreases to 6.9º at MP2. Interestingly, MP2 exhibits one of the more gently sloping morphologies of all the gravel profile sites examined in this study. This is surprising given the extremely course nature of the gravel on the beach. For example, the sediment is classified as “small cobble” with mean grain sizes that range from –6.4ø (87 mm) to –6.7ø (100 mm), and is typically well sorted to moderately sorted. It is probable that the lower beach crest and more gently sloping morphology is related to this portion of the beach, having been subjected to more persistent overtopping. Evidence for this includes many logs along the crest of the beach and landward and debris from a recent storm. In addition, it is apparent from Figure 33 that the gravel beach initially eroded landward between 1997 and 1998 in response to the El Niño. Throughout this process the elevation of the gravel beach was maintained, while the gravel face simply receded landward by a few meters.

However, during the ensuing 1998-1999 winter, which was characterized by the most severe wave conditions observed in the North Pacific in the past three decades, the beach was subject to an intensive period of erosion that caused the crest to be lowered by almost 1 m (3 ft), with the bulk of the sediment transported inland. Apart from lowering of the berm crest, the beach did not recede landward. This supports the concept that natural gravel beaches provide a positive level of resistance. Since September 2002 the crest of the gravel beach has been slowly aggrading, increasing by 0.25 m (0.8 ft).

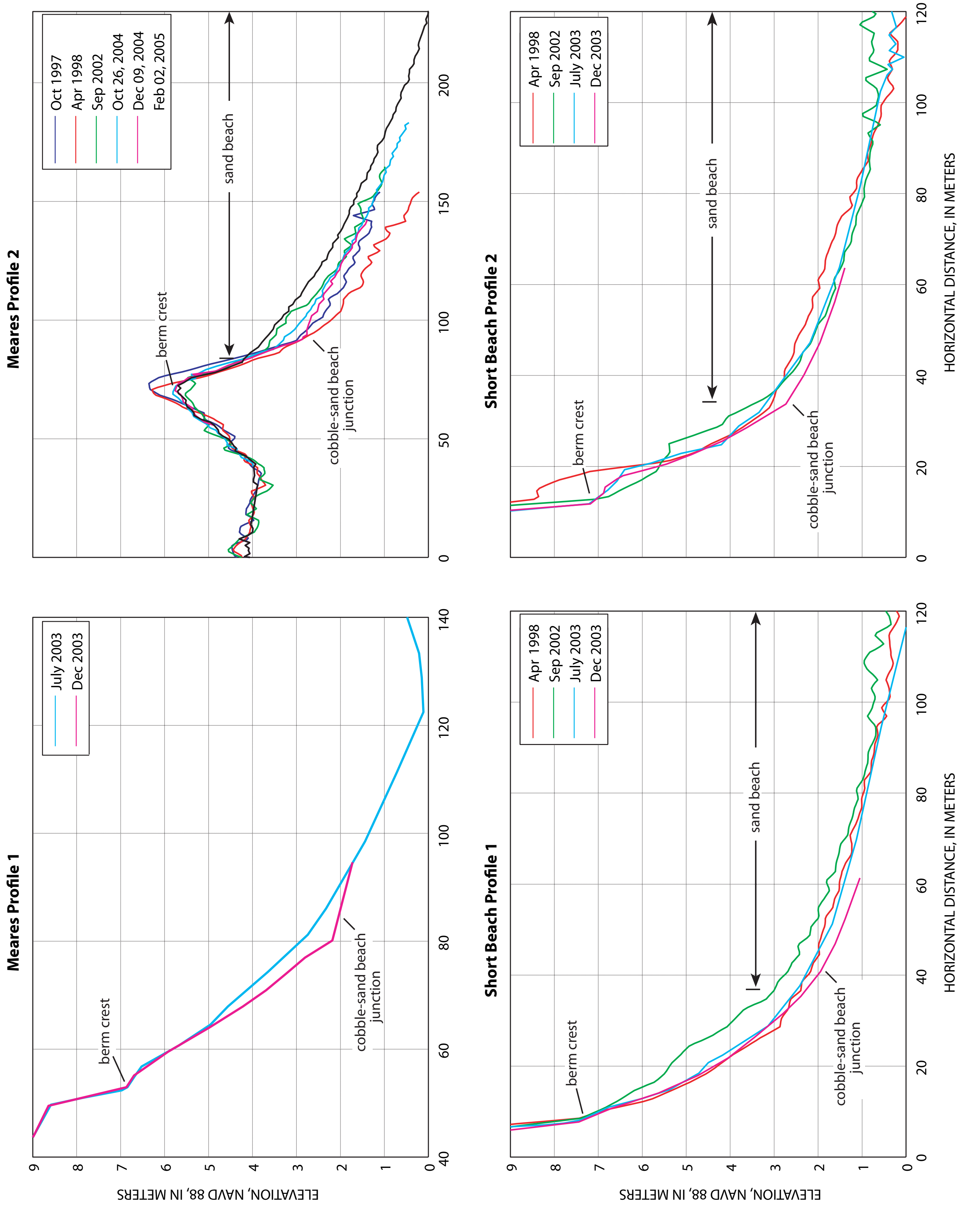


Figure 33. Beach profile surveys undertaken at Cape Meares and Short Beach. The locations of the transect sites are shown in Figure 32.

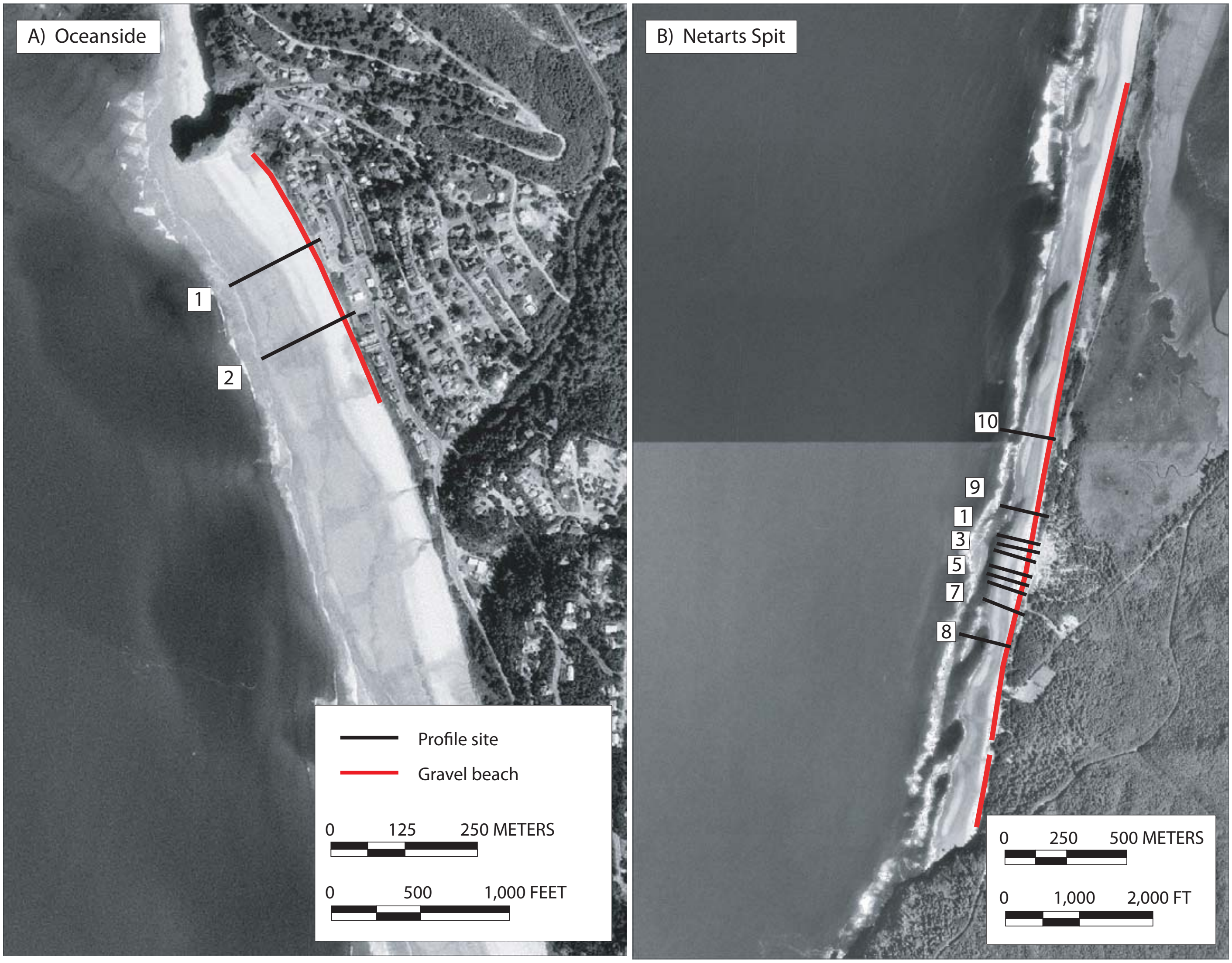


Figure 34. Aerial photographs of (**A**) Oceanside and (**B**) Cape Lookout (on Netarts Spit) gravel beaches showing the shoreline configuration, locations of beach profile, and grain-size sampling sites.

Netarts Littoral Cell

The Netarts littoral cell is about 12 km (7.5 mi) long and is located between Cape Meares in the north and Cape Lookout in the south. Gravel beach deposits exist at a number of locations including Short Beach (Figure 32) and Oceanside in the north and Cape Lookout State Park (CLSP) at the south end of the cell (Figure 34). All three beaches are characterized as composite beaches (Figure 12, type D). The response of the two gravel beaches, however, is markedly different between Oceanside and CLSP. For example, the gravel beach at Oceanside has a well-vegetated backshore and has been stable for at least several decades (based on historical photos of the area going back to the 1920s). In contrast, the beach at CLSP has experienced significant erosion and shoreline retreat during the past 30 years.

Despite the high rates of shoreline retreat observed on Netarts Spit (Figure 34), it is worth noting that erosion of the dune fronted by a gravel beach was typically some 20 to 40 percent lower when compared with the pure sand beaches further north on the spit, reinforcing the view that gravel beaches can be effective at mitigating incoming wave energy and can provide protection to foredunes. In response to the high rates of erosion experienced at CLSP, the Oregon Parks and Recreation Department constructed an artificial dune and dynamic revetment in 1999-2000 along 300 m (1000 ft) of the shore, where the erosion has been highest. The dynamic revetment has performed extremely well (Allan and others, 2003b; Komar and others, 2003;

Allan and Komar, 2004) and has survived several major storms, including a number of events that resulted in the revetment and artificial dune being overtopped. Research on the response of the dynamic revetment at CLSP is ongoing and includes repeated beach surveys, sediment tracing, and measurements of wave runup on the structures.

Short Beach

Short Beach is a gravel beach located just south of Cape Meares (Figure 32). The beach is a composite beach type (Figure 12, type D), characterized by a prominent gravel deposit and fronted by a wide dissipative sand beach. Although there is evidence of some backshore erosion in the past, most of the beach is stable, demonstrating the effectiveness of the protective gravel. The gravel beach at Short Beach is spatially quite small and is less than 0.8 km (0.5 mi) long. However, the beach has similar morphological characteristics to other sites along the coast (Figure 14, left). Mean grain sizes (M_zØ) at Short Beach were found to be uniform at both study sites (about −5.8Ø [55 mm]) and are finer than those sediments measured to the north at Cape Meares and at Neahkahnie, being more comparable in size with gravels found between Arch Cape and Cove Beach. The width of the gravel beach ranges from 20 to 27 m (66 to 89 ft), and the gravel volume is estimated to be about 54 m^3 per linear meter (581 $ft^3 \cdot ft^{-1}$) of shoreline.

Measured crest elevations along Short Beach were some of the highest on the coast and varied around 7.3 m (24 ft) NAVD 88, and the beach slopes were steep (about 11º). Figure 33 shows that the crest of the gravel beach appears to have been as high as 8 m (26 ft) and was likely lowered to about 7 m (23 ft) following the major 1998-1999 winter storms that were characterized by extremely high wave runup elevations along the coast. Furthermore, it is apparent that the gravel beach accreted somewhat in September 2002, prograding seaward by several meters. However, this process has now been reversed so that the beach has essentially reverted back to a state similar to that of April 1998.

Oceanside

The Oceanside gravel beach (Figures 34A and 35A) is approximately 0.5 km (0.3 mi) long and has a crest elevation that ranges from 5.5 to 6.0 m (18 to 20 ft). Mean grain sizes at Oceanside are comparable to those measured at Arch Cape and at Cove Beach and ranged from −5.3Ø to −5.8Ø (39.4 to 55.7 mm), with well-sorted sediment. Monitoring of the Oceanside profiles began in November 2002 as part of the CLSP dynamic revetment study started by Allan and Komar (2002a, 2004) and are ongoing. The gravel beach is narrow, with a width that ranges from 6 to 8 m (20 to 26 ft), whereas the beach slopes (11º to 13º) are comparable to the other gravel beaches described above. The volume of gravel contained on this beach is small and ranges from 11 to 14 m^3 per meter (118 to 151 $ft^3 \cdot ft^{-1}$) of shoreline. Despite its small gravel volume, the beach at Oceanside has been characterized by only minor morphological changes and no erosion of its backshore, which suggests that other factors contribute to the overall stability of the beach system. One strong possibility is that it may be related to the location of Oceanside, which is at the north end of the Netarts cell. For example, it is now well established that the extreme erosion along the southern 3 km (1.9 mi) of the Netarts Cell (Figure 4) is related to the occurrence of major El Niños that contributed to hotspot erosion along the south end of several of Oregon's littoral cells. While some of the eroded sand is moved offshore to form nearshore bars, a large portion of the sand is transported to the north where it accumulates offshore from Oceanside (Revell and others, 2002).

Significant dune erosion and hence the release of large volumes of sand has also occurred along the northern half of Netarts Spit. For example, Allan and others (2004) reported that about 1.1 million m^3 (1.5 million yd^3) of sand was eroded from the northern 4.5 km (2.9 mi) of the spit between 1998 and 2002. As a result, there has been a considerable injection of sand into the coastal system. Furthermore, there is an indication that significant quantities of sand are accumulating offshore from Oceanside, to the extent that the sand now affects the operation of the town's sewer outfall: the diffuser head is periodically buried. Accordingly, the accumulation of sand at Oceanside is likely helping to further dissipate winter storm waves so that little energy is contained in the waves to erode the gravel beach and backshore.

Cape Lookout State Park (Netarts Spit)

Cape Lookout State Park (CLSP) is located at the south end of Netarts Spit, a 9-km-long (5.6 mi) beach-spit complex that serves as a barrier to Netarts Bay (Figures 17 and 34B). Two thirds of the spit is sand and has undergone considerable erosion in recent years; one third is fronted by a gravel beach (Figure 35) that provides erosion protection for the sand dunes. The Netarts gravel beach extends from Cape Lookout northward for about 2.8 km (1.7 mi). The natural gravel beach is characterized by crest elevations that range from about 4 to 7.2 m (13 to 23.6 ft); the average elevation is 5.6 m (18.4 ft).

The constructed dynamic revetment at CLSP has a mean elevation of 6.9 m (22.6 ft), much of which has been built up by wave swash since 2001 when monitoring began on the structure. In particular, aggradation of the dynamic revetment has occurred along the northern half of the structure, as this portion of the berm was constructed to a lower crest elevation (initially about 5.0 m [16.4 ft] and now about 6.5 m [21.3 ft]). The width of the natural gravel beach is narrow when compared with other examples on the north coast and averages about 11 m (36 ft). In contrast, the constructed dynamic revetment has a width of 27 m (88.6 ft). Mean grain sizes at CLSP are comparable to those measured elsewhere and range from −6.2Ø (73.5 mm) on the natural gravel beach to −6.5Ø (90.5 mm) on the dynamic revetment. Beach slopes are very similar to the other study sites, with the slopes varying around 10.4º to 11.4º. Finally, the volume

Figure 35. (**A**) The Oceanside gravel beach. Note the well-vegetated bluff face; photographs from the 1920s confirm that this site has been stable for a long time. (**B**) The gravel beach at Cape Lookout State Park. The photo was taken north of the constructed dynamic revetment and artificial dune. The beach is backed by an eroding scarp, which indicates that wave swash is attacking the toe of the dune during storms.

of gravel contained in the beach ranges from 24 m^3 per linear meter (258 $ft^3 \cdot ft^{-1}$) of shoreline on the natural gravel beach to an average of 66 $m^3 \cdot m^{-1}$ (710 $ft^3 \cdot ft^{-1}$) on the dynamic revetment.

Analyses of the response of the natural cobble beaches and dynamic revetments sites have revealed that the areas respond in a similar fashion. At the north end of the dynamic revetment, the structure initially lost 5.2 $m^3 \cdot m^{-1}$ (56 $ft^3 \cdot ft^{-1}$) of cobbles between July 2001 and February 2002, with most eroded from the lower portion of the gravel face. After February 2002 the structure did not lose appreciable volume until early in winter 2002-2003, when a series of large storms between November and December 2002 resulted in the loss of an additional 6.1 $m^3 \cdot m^{-1}$ (66 $ft^3 \cdot ft^{-1}$) of gravel. Although some of the eroded material was transported up the profile face, causing the gravel beach to steepen, the largest change occurred on the lower gravel face, which continued to lose material.

This process, however, was reversed between December 2002 and late January 2003, when the north end of the dynamic revetment received a 12.9-$m^3 \cdot m^{-1}$ (139-$ft^3 \cdot ft^{-1}$) injection of gravel that caused the structure to prograde seaward by 3.5 to 5.0 m (11 to 16 ft). The dynamic revetment did not change significantly following winter 2002-2003, although the upper portion of the structure continued to accumulate gravel between March and June 2003 as material was moved up the gravel beach. With the onset of winter 2003-2004, the north end of the structure again entered an erosional phase, although some gravel accumulated on the upper portion of the gravel beach as sediment was transported up the face of the structure.

In contrast, the southern portion of the dynamic revetment underwent little change over the first two winters (Allan and others, 2003b). Recently, however, the south end of the structure received additional gravel (3.2 $m^3 \cdot m^{-1}$ [3.8 $yd^3 \cdot yd^{-1}$]) as a mass of material moved across the structure in response to a series of storms in early October 2003. This response was also observed further north, midway along the dynamic revetment. As a result, the additional volume of gravel that accumulated along the southern half of the structure is approximately 125 m^3 (163 yd^3).

The source of this material is believed to be the natural gravel beach to the south of the structure, which has been steadily losing sediment since monitoring began. Sediment tracing of tagged gravel and analyses of grain-size statistics along Netarts Spit confirm that gravel is being transported from south to north (Allan and others, 2003b). In fact, the loss of sediment south of the dynamic revetment is now beginning to pose a problem for OPRD, as erosion of the backshore deposits has increased (about -3 $m \cdot yr^{-1}$ [-10 $ft \cdot yr^{-1}$]) to the extent that the dynamic revetment structure may begin to be flanked. As a result, a key outcome of the CLSP study is the realization that some form of periodic topping up of the gravel is required to maintain the integrity of such structures in areas subject to strong littoral drift.

Lincoln County

Heceta Littoral Cell

The region between Cape Perpetua and Heceta Head is composed of a series of small pocket beach littoral cells that form the larger Heceta littoral cell. The smaller pocket beaches, many of which contain gravel beach deposits, are simply reentrants along the shore that likely do not inhibit longshore sediment transport. The morphological characteristics of these beaches are different from those gravel beaches on the northern Oregon coast. For example, most of the central coast gravel beaches are characterized by a series of offshore basaltic reefs that likely provide significant protection to the beaches by causing waves to break offshore on the reefs, thereby mitigating much of the incident wave energy. In contrast, the north coast study sites do not have this morphological feature. Furthermore, several of the central coast gravel beaches are aided by the presence of a wide sand beach that also serve to mitigate incoming waves. The central coast gravel beaches are much smaller in extent and volume than the north coast beaches, typically averaging only several hundred meters in length. The exception is the gravel beach adjacent to Muriel O. Ponsler State Scenic Viewpoint (Figure 36), which is almost 3 km (1.9 mi) long.

Cummins Creek, Bob Creek, and Muriel O. Ponsler State Scenic Viewpoint

Six representative profile lines were selected between Cummins Creek and Heceta Head (Figure 36). Figure 37 shows the morphological response of the beaches over the past several years. Gravel beach widths were found to range from several meters up to 26 m (85 ft), with an average width of about 14 m (46 ft), compared with 40 m (131 ft) on the north coast. As a result, the volume of gravel contained on the central coast beaches tends to be significantly lower, with the majority of the beaches containing less than 40 m^3 per linear meter of beach (430 $ft^3 \cdot ft^{-1}$). Despite their relatively small dimensions, the beaches had crest elevations comparable to those on the north coast and ranged from 5 to 7.2 m (16 to 24 ft). Apart from the large gravel identified at profile 2 (−6.6.ø [100 mm]), adjacent to the Muriel O. Ponsler State Scenic Viewpoint, mean grain sizes (M_zØ) were

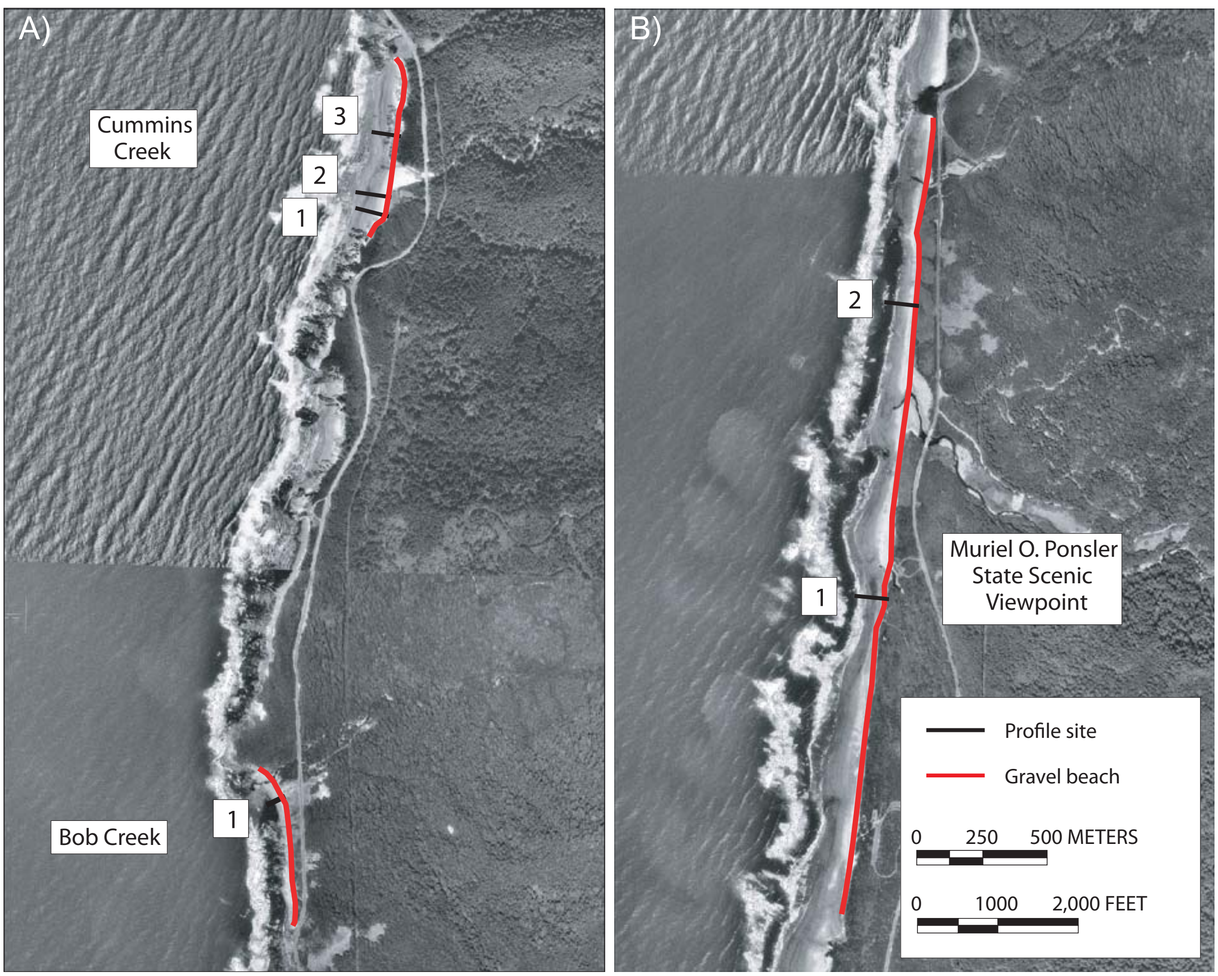


Figure 36. Aerial photographs of gravel beach study sites on the Central Oregon coast. (**A**) Beach profile sites and grain-size sampling locations for Cummins Creek and Bob Creek locations; (**B**) the gravel beach adjacent to Muriel O. Ponsler State Scenic Viewpoint.

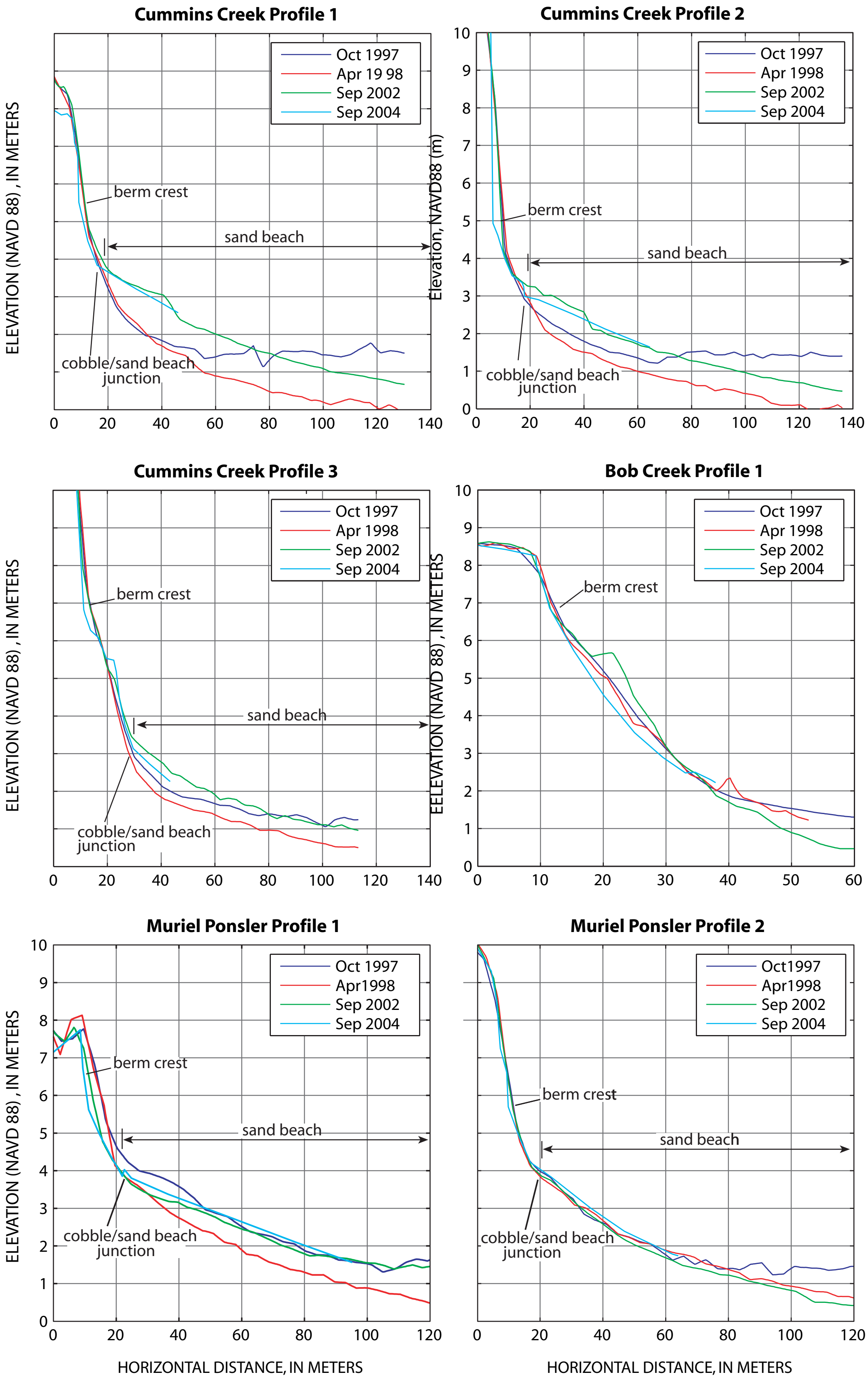


Figure 37. Beach profile surveys undertaken at Cummins Creek, Bob Creek, and adjacent to Muriel O. Ponsler State Scenic Viewpoint. The locations of the transect sites are shown in Figure 36.

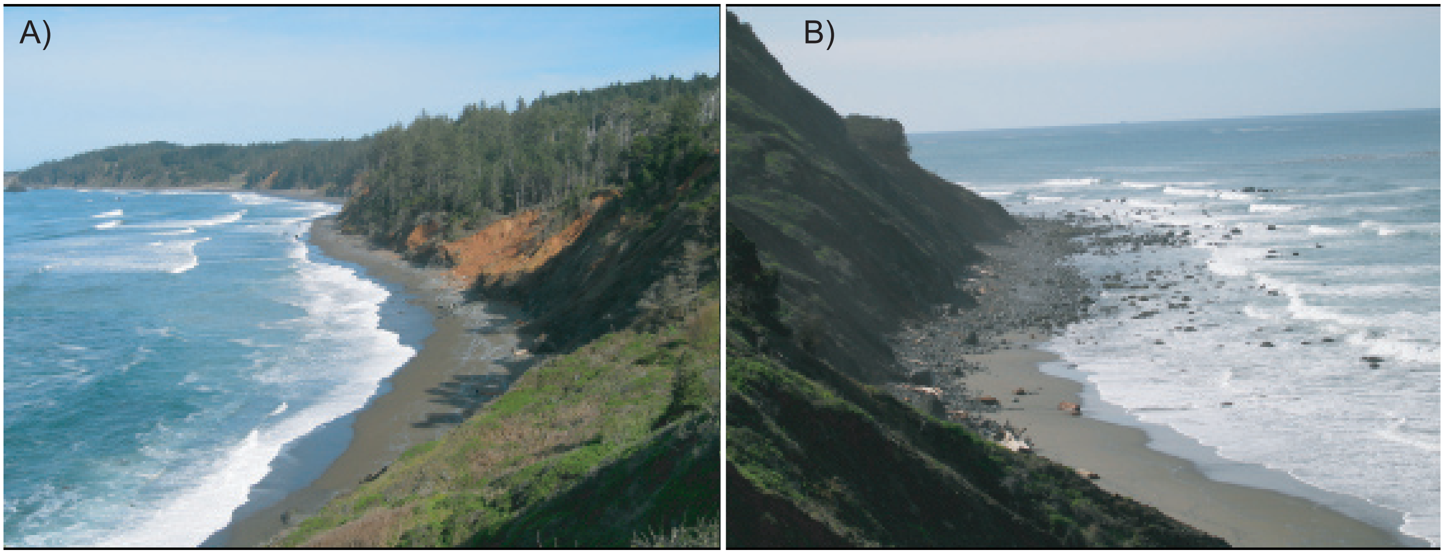


Figure 38. Mixed sand and gravel beach and a coarse sand beach. (**A**) View north of a mixed sand and gravel beach south of Port Orford that is backed by a small amount of gravels. (**B**) View south at part of the Humbug littoral cell (Figure 1) of a coarse sand beach that merges into a boulder beach near Humbug Mountain.

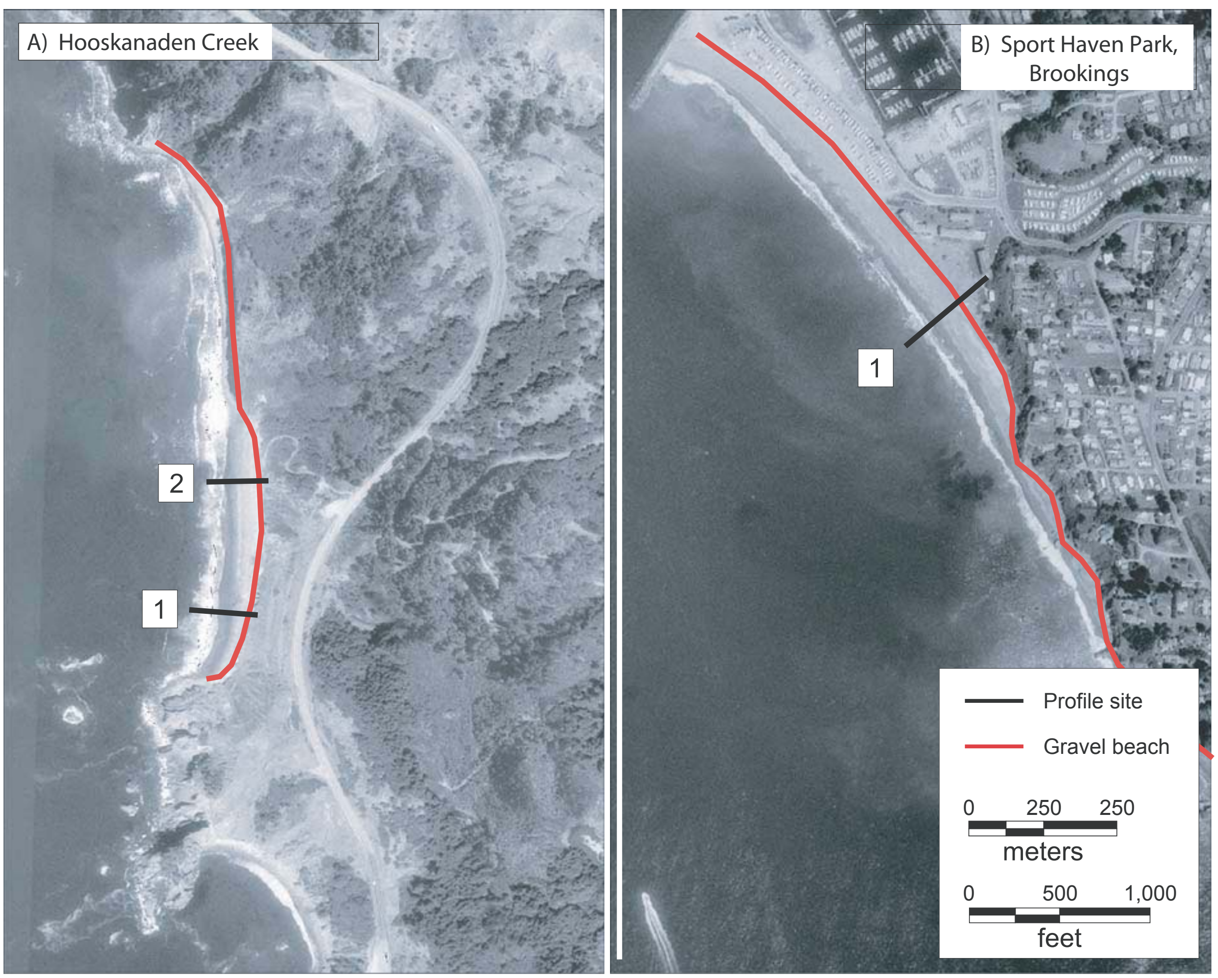


Figure 39. Aerial photographs of gravel beach study sites on the southern Oregon coast. (**A**) Locations of beach profile sites and grain-size sampling locations for Hooskanaden Creek. (**B**) The gravel beach at Sport Haven State Park, Brookings.

uniform and ranged from –5.77ø to –5.96ø (55 to 62 mm). As a result, the predominant beach slopes tended to be much the same as those on the north coast averaging 11.5º.

The largest change at each of the study sites is the seasonal variability in the sandy portion of the beach (Figure 37), which typically varies by 1 to 2 m (3 to 6 ft) vertically, whereas the gravel portion of the beach tends to undergo minor morphological change. Nevertheless, it is apparent from Figure 37 that all six sites have undergone some degree of erosion during the past several years. The erosion is greatest at Muriel Ponsler 1 and at Cummins Creek 2. Both have eroded landward by up to 5 m (16 ft) since 1997, whereas the response of the gravel beach at the other profile sites indicates only minor erosion.

Both Muriel Ponsler 1 and Cummins Creek 2 contain very small volumes of gravel. Cummins Creek 2 is also characterized by a very low crest elevation. The greater erosion rates observed at these sites may be largely a function of the low gravel volumes of the gravel beaches. In addition, neither site receives protection from an offshore reef, so each is almost entirely dependent on its sand beach to mitigate much of the incoming wave energy.

Curry County

Brookings Littoral Cell

Oregon's coastal geomorphology changes markedly south of Port Orford, with the beaches increasingly dominated by rocky shorelands and coarse sand or boulder beaches (Figure 38). Although many of the beaches contain some gravel material, invariably the volume of gravel on the beaches is negligible. As a result, true gravel beaches are much less common on the south coast compared with the central and northern Oregon coast. Because of their relative rarity on the southern Oregon coast, only two sites were identified for further investigation: Hooskanaden Creek, located about 20 km (12 mi) north of Brookings (Figure 39A), and the Brookings site in Sport Haven Park adjacent to the Chetco River (Figure 39B). Unfortunately, only one survey period is shown in the beach survey data set (Figure 40). At the time of the study we did not have a GPS system for surveying in the transect locations. Furthermore, there are no LIDAR data for 1997 and 1998 for this part of the coast. As a result, it is not possible to include LIDAR data in these plots for comparative purposes.

Hooskanaden Creek

The Hooskanaden Creek site is on a 1-km-long (0.6 mi) gravel and sand beach. A significant gravel beach exists along the northern two thirds of the shore (Figure 40, profile 2). In contrast, the southern portion has been depleted of its gravels and is now eroding (Figure 40, profile 1). The site is particularly relevant to this study as U.S. Highway 101, located adjacent to the beach, was built on fill that is now being eroded by ocean waves. At the time of our site visit in April 2004 an ODOT crew was in the process of removing about 3 to 4.5 m (10 to 15 ft) of the Hooskanaden Culvert that was, at the time, suspended over the beach,

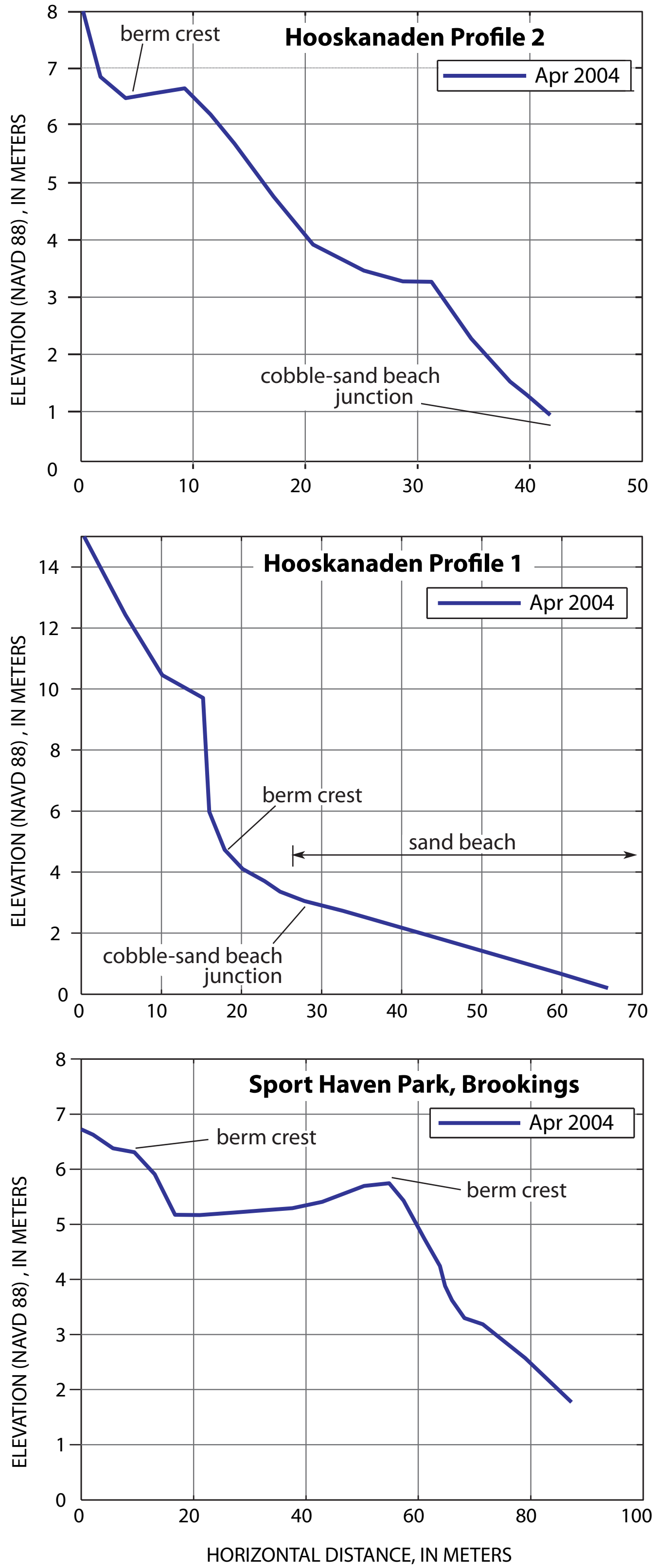


Figure 40. Beach profile surveys from Hooskanaden Creek (top and middle) and Sport Haven Park adjacent to Brookings (lower). The locations of the transect sites are shown in Figure 39.

a testimony to the amount of erosion at the site in recent years. In contrast, the north end of the beach (including profile 2) is characterized by an extensive gravel beach, while the backshore is well vegetated and shows no evidence of erosion.

The well-sorted sediment identified at Hooskanaden Creek has a mean grain size of –6.8ø (112 mm), classified as large cobbles. Despite the coarse nature of the sediment on the beach, the slope of the two profile sites averages only 8.8º and is typically less steep compared with sites in the north. The gravel beach south of the culvert is characterized by one of the lowest berm crest elevations identified, reaching only 4.7 m (15 ft), with a gravel beach width of less than 20 m (66 ft). As a result, the south end of the beach is characterized by an extremely small volume of gravel that averages about 7 m^3 per linear meter of beach (75 $ft^3 \cdot ft^{-1}$). In contrast, the northern profile site indicates a crest elevation of 6.5 m (21 ft), consistent with most of the other gravel beach sites, while the width of the gravel beach is about 40 m (131 ft). As a result, the volume of gravel on the beach in the north is significantly greater, reaching about 120 $m^3 \cdot m^{-1}$ (1291 $ft^3 \cdot ft^{-1}$). These data suggest that gravel from the south end of the beach is probably being stripped out and transported northward along the shore where it is accumulating around profile 2 and further to the north. As a result, the loss of gravel in front of the culvert at Hooskanaden Creek is probably a key factor contributing to the erosion observed at the site. This suggests that a mitigation strategy for Hooskanaden Creek could include relocating some portion of the gravel in the north and placing it in the south in front of the culvert, thereby raising the existing gravel beach crest elevation of 4.7 m (15 ft) to about 6.5 m (21 ft) and increasing the overall gravel volume accordingly.

Sport Haven State Park, Brookings

The final site of interest is the Brookings site located in Sport Haven Park on the south side of the Chetco River mouth. This beach is considered to be stable due to the presence of a wide gravel beach deposit at Sport Haven Park (Figure 40), characterized by at least two gravel ridges with elevations that ranged from 5.7 m (18.7 ft) to 6.3 m (20.7 ft) and a well-vegetated backshore. Much of the growth of this beach can probably be attributed to the construction of jetties at the mouth of the Chetco River, which has enabled gravel to accumulate on the south side of the jetty, causing the beach to prograde seaward. The beach is characterized by the smallest sediment size of all the study sites. The mean grain size (M_zø) is −4.9ø (30 mm), classified as coarse pebbles. Accordingly, the beach slopes at Sport Haven Park tend to be slightly lower (about 8.8º) when compared with those at other gravel study sites. Beach crest elevations reached 5.7 m (18.7 ft), only slightly lower than at other sites on the Oregon coast, while the width of the gravel beach was the second largest, reaching 70 m (230 ft). As a result, the volume of gravel contained in the beach was the second highest identified on the coast, reaching 189 $m^3 \cdot m^{-1}$ (2034 $ft^3 \cdot ft^{-1}$).

Discussion of Gravel Beach Morphologies and Dynamic Revetment Design Characteristics

On the basis of our site surveys, we recognize several variables that characterize the morphology of Oregon's gravel beaches. These variables include gravel beach crest elevation, gravel beach slope, sand beach slope (if present), gravel beach width, gravel volume, and mean grain size. Site data are shown in Table 2 for comparative purposes. Table 2 also includes summary data expressed as averages of all available data and as averages based on discernible regional differences. With respect to the latter, we have divided the coast into two regions, north coast gravel beaches and central to south coast gravel beaches, to better identify any along-coast variability.

Table 2 displays, in the shaded rows with italic text, the 10 sites that exhibited evidence of recent backshore erosion. This erosion suggests that gravel beaches at those locations are generally ineffective at mitigating incoming wave energy. With the exception of the beaches at Netarts and Cove Beach, the majority of the sites subject to erosion are located on the central to southern Oregon coast. As discussed previously, backshore erosion was apparent in the field as either a prominent erosion scarp or as an over steepened bluff face that lacked any vegetation. In almost all cases, field observations were supported by analyses of LIDAR data, which demonstrated evidence of shore retreat. Intuitively, one might expect to see some differences in the morphological characteristics of beaches that are eroding and beaches that are stable. However, as shown by the data in Table 2, this is not always the case. For example, although the profile lines for five of the beaches subject to erosion exhibit crest elevations less than 6.0 m (19.7 ft), the other five do not; the dramatically eroding Cove Beach site actually has a beach crest of 7.0 m (23 ft). Similarly, there is no clear pattern in beach slopes and grain sizes identified along the coast. On the other hand, seven of the sites are characterized by narrow beach widths (< 20 m [66 ft] wide) and therefore have low sediment volumes. In this regard, the width and volume of the gravel beach may be an important consideration when designing a dynamic revetment for the Oregon coast and will be discussed in more detail later in this section.

As indicated in Table 2, the mean crest elevation identified for Oregon's gravel beaches is about 6.4 m (21 ft). The standard deviation is ±0.7 m (2.3 ft), giving crest elevations that range from 5.7 to 7.1 m (19 to 23 ft). There is some suggestion that north coast gravel beaches are on average higher than central and south coast sites (an average of 6.6 m [22 ft] versus 5.9 m [19 ft], respectively). However, there are exceptions to this pattern; a number of south coast sites are characterized by elevations more comparable to north coast gravel beaches. Accordingly, it is probably prudent to adopt a crest elevation of around 7 m (23 ft) as a minimum when considering how high to construct a dynamic revetment on the Oregon coast.

Along each gravel beach there are also significant alongshore variations in the heights of the gravel beaches (Figure 41), as demonstrated at Seaside, Arch Cape, Cove Beach, and Neah-

Table 2. Oregon gravel beach morphology summary.

Profile (*N* = 27)	Gravel Beach Crest Elevation (m)	Gravel Beach Slope (degrees)	Sand Beach Slope (degrees)	Gravel Beach Width (m)	Gravel Volume ($m^3 \cdot m^1$)	Mean Grain Size Ø	Mean Grain Size mm
Seaside 1	6.6	14.0	–	54	150	-5.68	51.3
Seaside 2	6.6	8.9	0.5	47	124	-6.02	51.3
Seaside 3	5.8	8.6	0.8	132	427	-6.11	51.3
Arch Cape 1	6.5	11.9	2.2	25	46	-5.96	51.3
Arch Cape 2	6.7	9.3	2.8	23	5	-5.44	43.4
Cove Beach 1	*7.0*	*12.6*	*1.0*	*33*	*104*	*-5.74*	*53.5*
Cove Beach 2	*7.1*	*23.8*	*0.5*	*45*	*160*	*-6.19*	*73.0*
Neahkahnie 1	7.1	9.0	1.5	12	51	-6.44	86.8
Neahkahnie 2	6.2	7.5	2.2	27	40	-6.26	76.6
Neahkahnie 3	7.3	9.0	–	50	177	-7.00	128.0
Cape Meares 1	6.8	8.6	1.1	30	81	-6.44	86.8
Cape Meares 2	5.8	6.9	1.8	52	102	-6.65	100.4
Short Beach 1	7.4	10.5	2.0	27	67	-5.81	56.1
Short Beach 2	7.2	11.4	1.4	20	41	-5.77	54.6
Oceanside 1	6.0	13.0	2.5	8	14	-5.33	40.2
Oceanside 2	5.5	11.3	2.3	6	11	–	–
Netarts Spit (a)	*5.6*	*11.4*	*1.6*	*11*	*24*	*-6.16*	*71.5*
Netarts Spit (b)	6.9	10.4	2.6	27	66	-6.46	88.0
Cummins Creek 1	*5.5*	*13.8*	*2.4*	*7*	*8*	*-5.96*	*62 3*
Cummins Creek 2	*4.9*	*9.4*	*1.7*	*12*	*12*	*-5.93*	*61.0*
Cummins Creek 3	*6.8*	*11.3*	*3.7*	*18*	*42*	*–*	*–*
Bob Creek	*6.9*	*10.0*	*–*	*26*	*52*	*-5.91*	*60.1*
Murial Ponsler 1	*6.7*	*12.8*	*1.8*	*13*	*14*	*-5.67*	*50.9*
Murial Ponsler 2	*5.7*	*11.8*	*3.0*	*14*	*7*	*-6.65*	*100.4*
Hooskanaden 1	*4.7*	*8.8*	*4.3*	*17*	*7*	*–*	*–*
Hooskanaden 2	6.5	8.3	–	38	119	-6.81	112.2
Sport Haven Park (Brookings)	5.7	8.8	5.1	70	89	-4.90	29.9
Mean (North Coast)	**6.6**	**11**	**1.7**	**35 (28*)**	**97 (77*)**	**-6.09**	**68.1**
Mean (Central to South Coast)	**5.9**	**10.9**	**3.1**	**24 (18*)**	**50 (33*)**	**-6.0**	**64.0**
Mean (all)	**6.4**	**10.9**	**2.1**	**31.3 (25*)**	**81.0 (63*)**	**-6.05**	**66.3**
Standard Deviation	**±0.7**	**±3.2**	**±1.1**	**±26.1**	**±88.4**	**± -0.5**	

Notes:
Netarts Spit (a) was derived from LIDAR beach profile data and represents an average.
Netarts Spit (b) was derived from beach surveys and grain-size measurements undertaken by Allan and others (2003b), Komar and others (2003), and Allan and Komar (2004).
Shaded rows with italic text denote sites subject to backshore erosion.
Asterisks indicate averages that exclude Seaside 3 and Sport Haven Park in the calculation.
To convert gravel volumes in column 6 to imperial units, multiply the values by 10.76 to yield cubic feet per foot of shoreline.

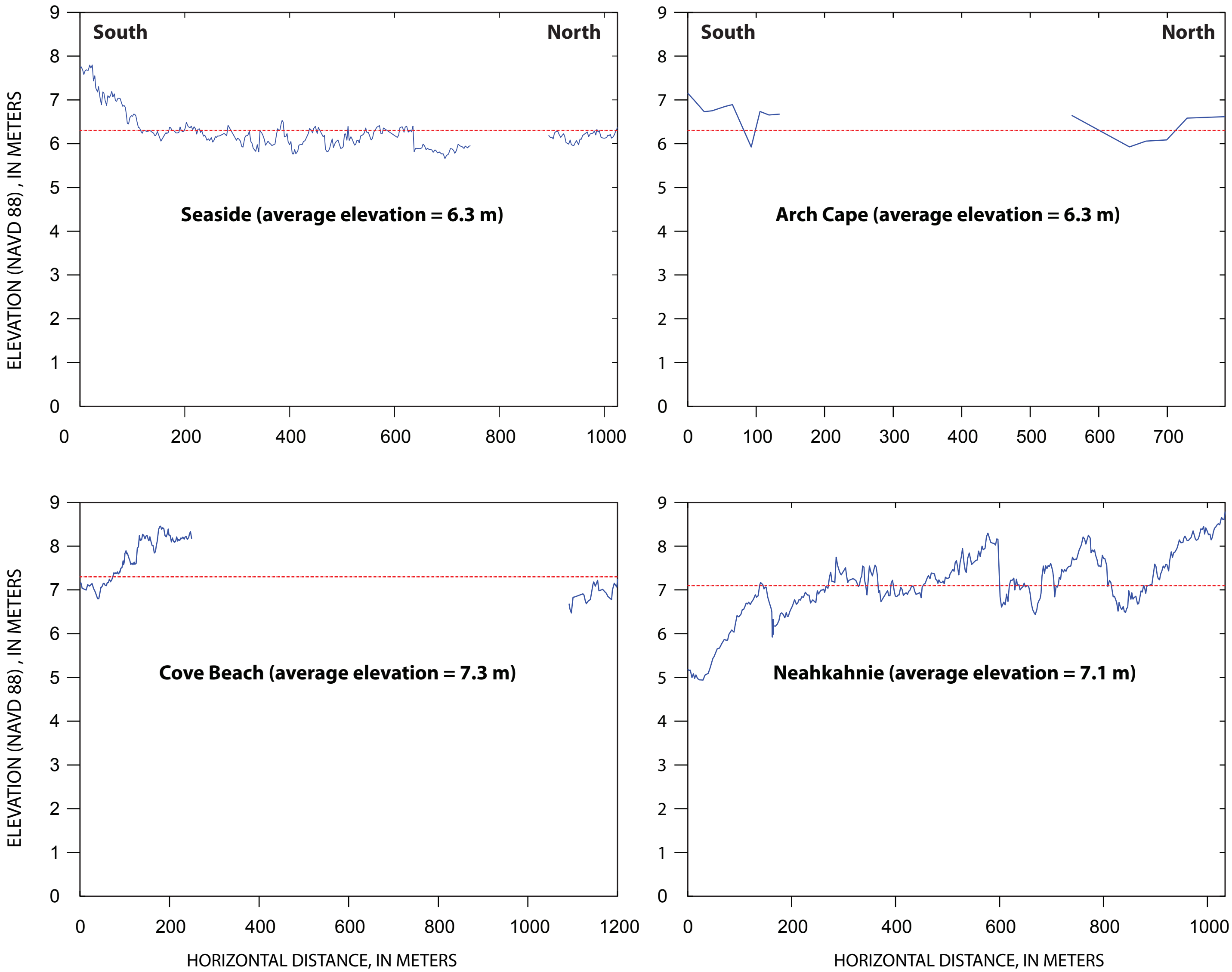


Figure 41. Alongshore variability in crest elevation of gravel beaches at Seaside, Arch Cape, Cove Beach, and Neahkahnie study sites on the northern Oregon coast. Data were derived using real-time kinematic differential global positioning system (RTK-DGPS) surveys.

kahnie. These plots were derived by mapping the crest of the gravel beach using a Trimble 5700/5800 GPS surveying system. Also included in Figure 41 is the average elevation of the beach crest. The most significant variations can be seen along the Seaside and Neahkahnie gravel beaches. At Seaside, the crest elevation decreases from about 8 m (26 ft), 300 m (1000 ft) west of profile 1 (Figure 22), to about 6.3 m (21 ft) adjacent to profile 2 (Figure 41). Over much of the beach crest, the elevation is extremely uniform, varying slightly about the average height of 6.3 m. In contrast, the crest of the gravel beach at Neahkahnie varies widely (Figure 41), from a low of 5.0 m (16 ft) south of profile 2 (Figure 29) to a high of 8.8 m (29 ft) about 600 m (2000 ft) northwest of profile 3. These results reveal that the highest crest elevations are located out on the headlands—areas that are subject to the most intense wave action as there is no fronting sand beach to dissipate incoming wave energy. Accordingly, the wave swash is able to reach much higher elevations in these areas, pushing the gravel up the beach face. At each of these sites the mean crest elevation is consistent with those presented in Table 2.

A comparative plot of the change in gravel beach crest elevations based on the 1997, 1998, and 2002 LIDAR data reflect information extracted from transects spaced 100 m (328 ft) apart in a geographical information system (Figure 42). The sites presented in Figure 41 are again the focus here, with the exception that Cove Beach and Arch Cape are now combined into a single plot. The purpose of these plots is to better understand the temporal and spatial response of the gravel beaches with respect to how much the beach may aggrade or erode. With the exception of Cove Beach and Arch Cape, the response of the gravel beach is generally minor. The beach crest varies in elevation

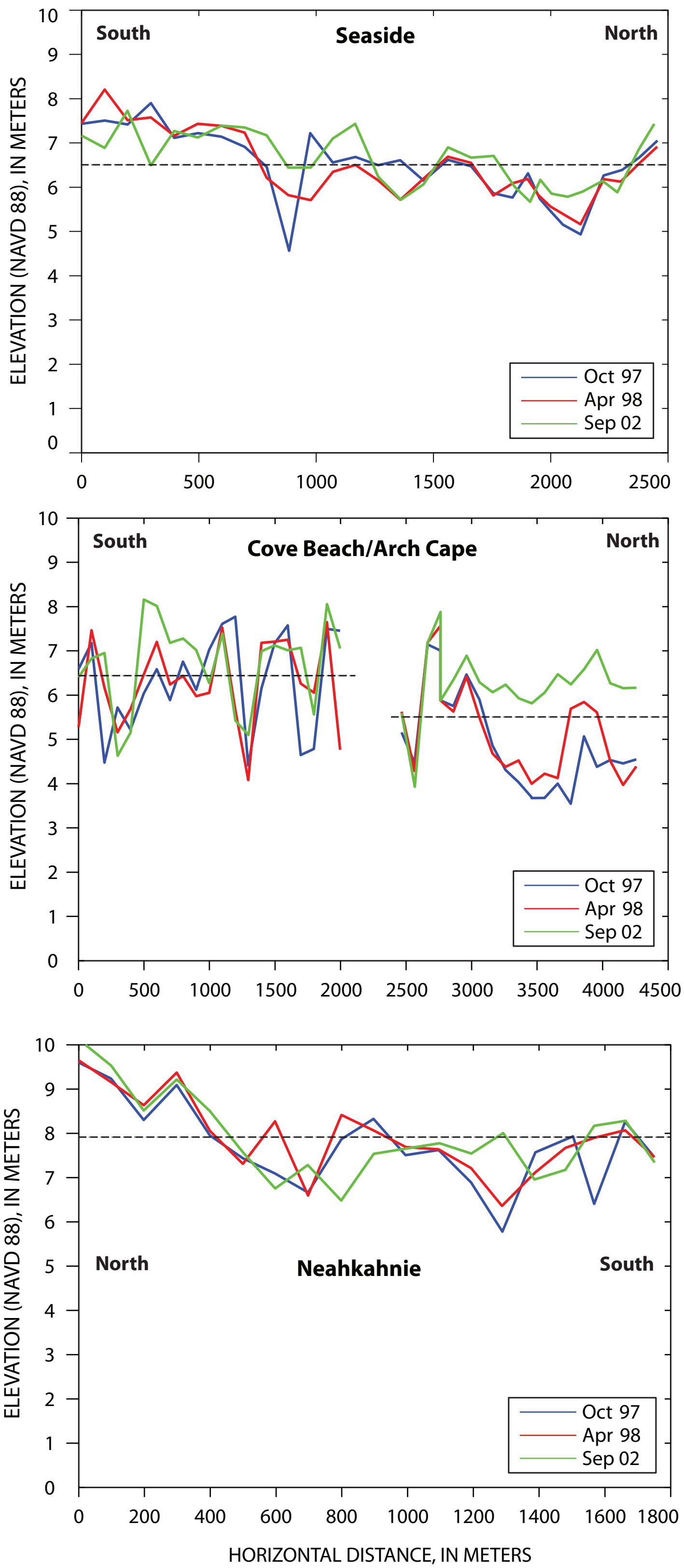


Figure 42. Temporal and spatial variability of the elevation of the berm crest along the four selected north coast gravel beach study sites of Figure 41. Data are derived from LIDAR.

by about 0.5 to 1.0 m (1.6 to 3.3 ft) around a mean elevation of 6.5 to 7.9 m (21 to 26 ft). It is possible that at Seaside and Neahkahnie these minor morphological changes are due to the coarse nature of the sediment and the generally larger size of the gravel beaches compared with Cove Beach and Arch Cape. Figure 42 also highlights the alongshore decrease in the crest of the beach, consistent with our measurements presented in Figure 41. However, the results for Neahkahnie indicate that further out on the headland the elevation of the gravel beach reaches almost 10 m (Figure 42).

Of interest is the response of the gravel beaches at Cove Beach and Arch Cape. The gravel beach at Arch Cape (Figure 42) has undergone significant aggradation since 1997, having been raised by 1.5 m (4.9 ft) from an average height of 4.8 m (16 ft) in 1997 to 6.3 m (21 ft) in 2002. It is unclear where this gravel came from, as there is no evidence for a loss of gravel elsewhere along the beach. Apart from landslides, one likely possibility is that the sediment may have been located further offshore on the lower beach face, where it was buried beneath the sand. With the arrival of large winter storm waves during the 1998-1999 winter the sand beach would have been lowered, exposing the gravel. As gravel tends to remain on the beach face due to its larger size, it is likely that the sediment was carried onshore and up on to the gravel face due to the high swash velocities associated with the extreme 1998-1999 winter waves.

The above analysis suggests that a 7.0-m (23 ft) design crest elevation is probably the minimum construction height for a dynamic revetment on the Oregon coast. Of interest is how this estimate, which is based on the predominant morphology of the gravel beaches, relates to physical processes, particularly total water levels (wave runup plus tides) achieved during extreme storms. One might expect a correlation between the height of total water levels (T_{WL}) and the crest elevation of the gravel beaches. This is because the maximum height of the gravel beach is a function of available sediment, the velocity of the swash uprush, and how high the swash reaches on the gravel beach.

As indicated in the Methods section, wave runup can be calculated empirically (equation 2) using a model developed for the Oregon coast by Ruggiero and others (2001). The model requires information on deep-water wave heights, peak spectral wave periods, and beach slope. The addition of the wave runup plus tidal component provides a measure of the total water level (T_{WL}).

Wave statistics have been derived from the Newport buoy for the period 1988–2004. Tide data covering the same period were obtained from the Newport tide gauge located in Yaquina Bay. Because gravel beaches on the Oregon coast are of the composite type, that is, composed of a gently sloping sand beach backed by a steep gravel slope, determining an appropriate slope to use is not straightforward. The approach adopted here is to use a composite, or average, beach slope that is based on both portions of the beach. For the purposes of this study we have used a 10.9° gravel slope and a 1.7° sand beach slope, which equates to a composite slope of 6.3°. The hourly total water levels (T_{WL}) were subsequently calculated using a script developed in MATLAB.

From these data we have derived a maximum total water level for each winter month, as this is the period when the beaches are most susceptible to change. An extreme value analysis was subsequently undertaken using the Coastal Engineering Design and Analysis System (CEDAS) software developed by U.S. Army Corps of Engineers. The best-fit distribution curve is presented in Figure 43 and represents a Weibull fit with $k = 2.00$.

Calculated total water levels are estimated to range from 8.1 m (27 ft) for an annual event to about 12.5 m (41 ft) for a 100-yr storm (Figure 43). Due to the small amount of data available, estimates greater than 50 years are unlikely to be meaningful. Given these values, it is apparent that there is no clear relationship between calculated extreme total water levels and the preferred height of the gravel beaches presented in Table 2, although some of the heights shown in Figures 41 and 42 are close to the annual extreme event. Removing the effects of the extreme events that occurred during the 1998-1999 winter from the extreme value analysis produced 100-yr water levels that were about 11.5 m (37.7 ft), which is still unreasonably high, although the annual T_{WL} dropped to about 7.8 m (25.6 ft), much closer to the preferred heights of the gravel beaches.

Although the extreme value analysis tends to overpredict T_{WL}, this process is probably also enhanced by the Ruggiero and others (2001) wave runup model, which was originally derived for Oregon's dissipative sand beaches, not gravel beaches. As a result, the wave runup model is likely overestimating the true T_{WL} for Oregon's gravel beaches. In addition, it is important to bear in mind that the Ruggiero and others wave runup model is based on a 2 percent runup exceedance and thus reflects the higher-elevation end of the wave swash spectrum. Nevertheless, our monitoring efforts at CLSP have identified storms that resulted in total water levels that exceeded the berm crest and artificial dune constructed in the park, to at least 7-m (23 ft) and even 8-m (26 ft) elevations (Komar and others, 2003; Allan and others, 2003b). However, these events are probably not as common as suggested by Figure 43. An ongoing part of our work at CLSP is measurement of wave runup, which may be used to develop a suitable empirical runup model for coarse beaches on the Oregon coast.

Figure 44 presents a histogram plot of hourly total water levels, binned at 0.1 m (0.3 ft) intervals, and a cumulative frequency plot of calculated total water levels. Calculated total water level (T_{WL}) reaches a maximum elevation of 10.6 m (35 ft), while the median T_{WL} calculated for the gravel beaches is 3.9 m (13 ft). According to Figure 44, the total water levels exceed an elevation of 4.8 m (16 ft) 25 percent of the time, 5.6 m (18 ft) 10 percent of the time, 6.0 m (20 ft) 5 percent of the time, and 7.0 m (23 ft) only 1 percent of the time. Accordingly, these results suggest that it is probably reasonable to construct a dynamic revetment to an elevation of 7.0 m (20 ft). It is important, however, to understand that such a structure would be periodically overtopped. One approach for minimizing potential impacts on the backshore associated with such events is to create a berm with a broad crest;

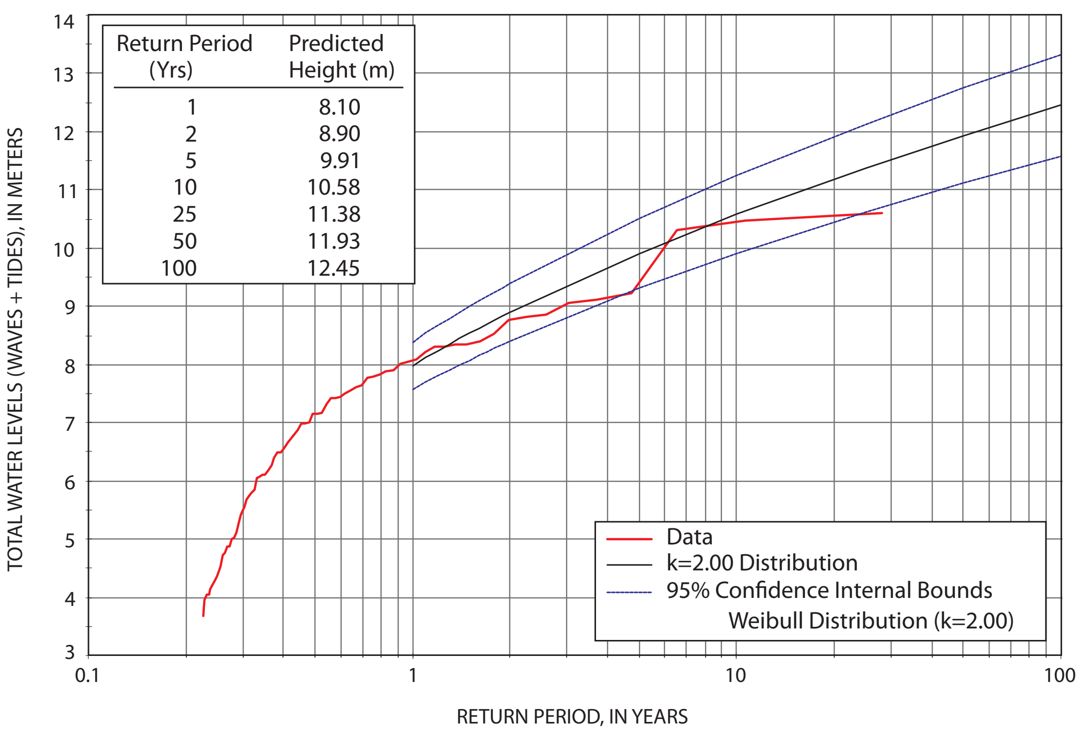


Figure 43. An extreme value analysis of total water levels (combined wave runup and tidal elevations) performed for gravel beaches on the Oregon coast ($N = 76$).

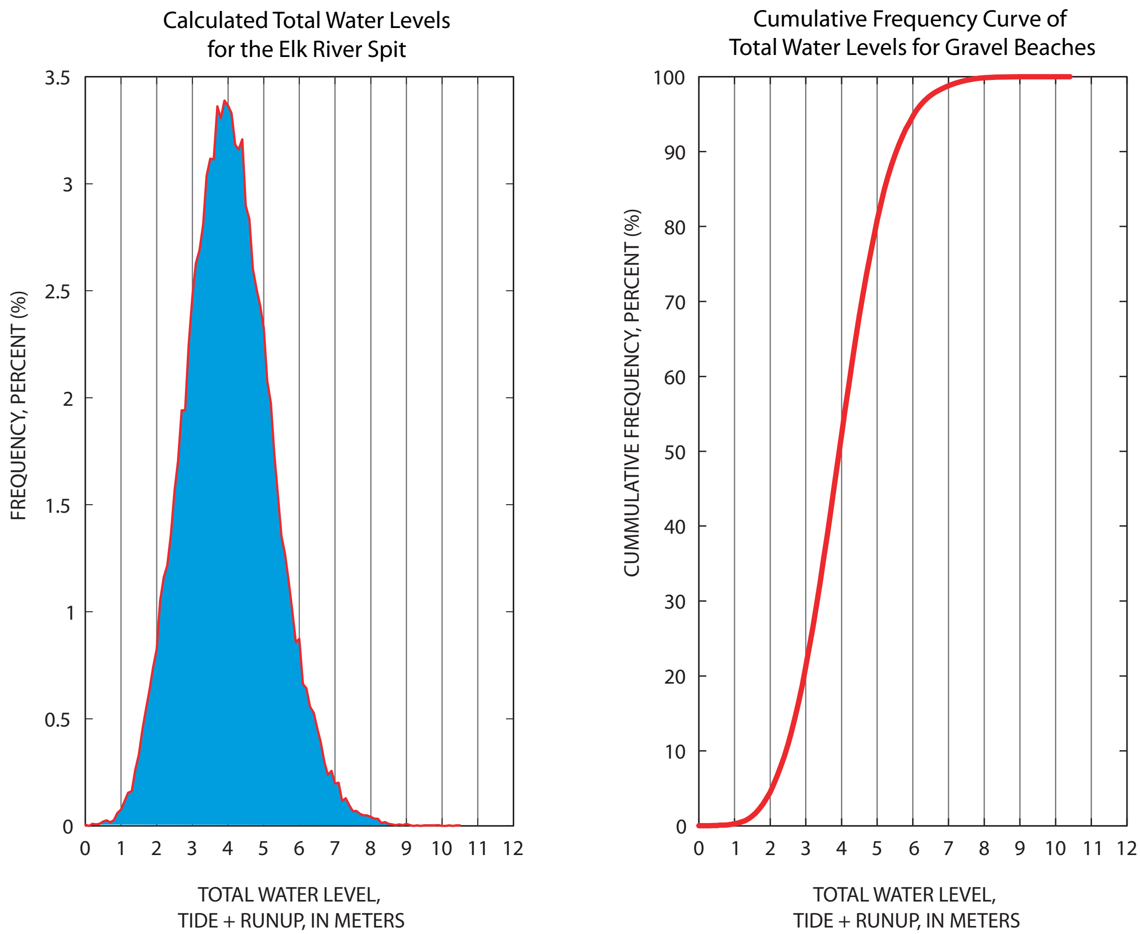


Figure 44. Calculated winter total water levels for gravel beaches based on an average beach slope ($S = 0.110$) expressed as a frequency distribution and a cumulative frequency curve ($N = 55{,}504$). Note: Data span the period from January 1988 to December 2004.

alternatively, an artificial dune such as was constructed at CLSP could be used.

In addition to identifying a preferred design-crest elevation for dynamic revetments, it is also necessary to assess beach slopes and gravel grain sizes. As indicated in Table 2, there is little variation in the slopes of the gravel beaches and grain sizes along the Oregon coast. The mean slope averages 10.9º (a 1-on-5.2 slope), and the average mean grain size is approximately –6.05Ø (66.3 mm), which is classified as small cobble. This is expected, as beach slope and mean grain size are closely related (Komar, 1998). A summary plot of grain-size distribution curves for each study site is presented in Figure 45. These data are plotted on a log probability graph that has the advantage of allowing the user to visually examine the distribution of the grain-size populations that characterize a particular study site. With this approach one can quickly identify study sites that may be influenced by a mixing of different sediment populations such as sand, gravel, and boulders. Sites with sediment that is normally distributed plot as a straight line in Figure 45, whereas sites subject to a mixing of sediment populations are characterized by inflections on the lines. Included in Figure 45 are average mean grain sizes identified for each shoreline segment.

The majority of the study sites sampled are characterized by straight lines (Figure 45), which indicate uniform sediment populations dominated by gravel in the 16- to 256-mm range. This greatly simplifies the design of a dynamic revetment for the Oregon coast. There are of course a few exceptions such as Cape Meares, where the grain-size population is a mixture of predominantly coarse gravel and a tail of boulder-size clasts. At the other end of the spectrum, the Brookings site is dominated by a mixture of gravel, with a long tail of granules and coarse sand that are likely related to both the fluvial origins of the sediment and the different lithologies that characterize this part of the Oregon coast. Although subtle differences in grain-size distributions

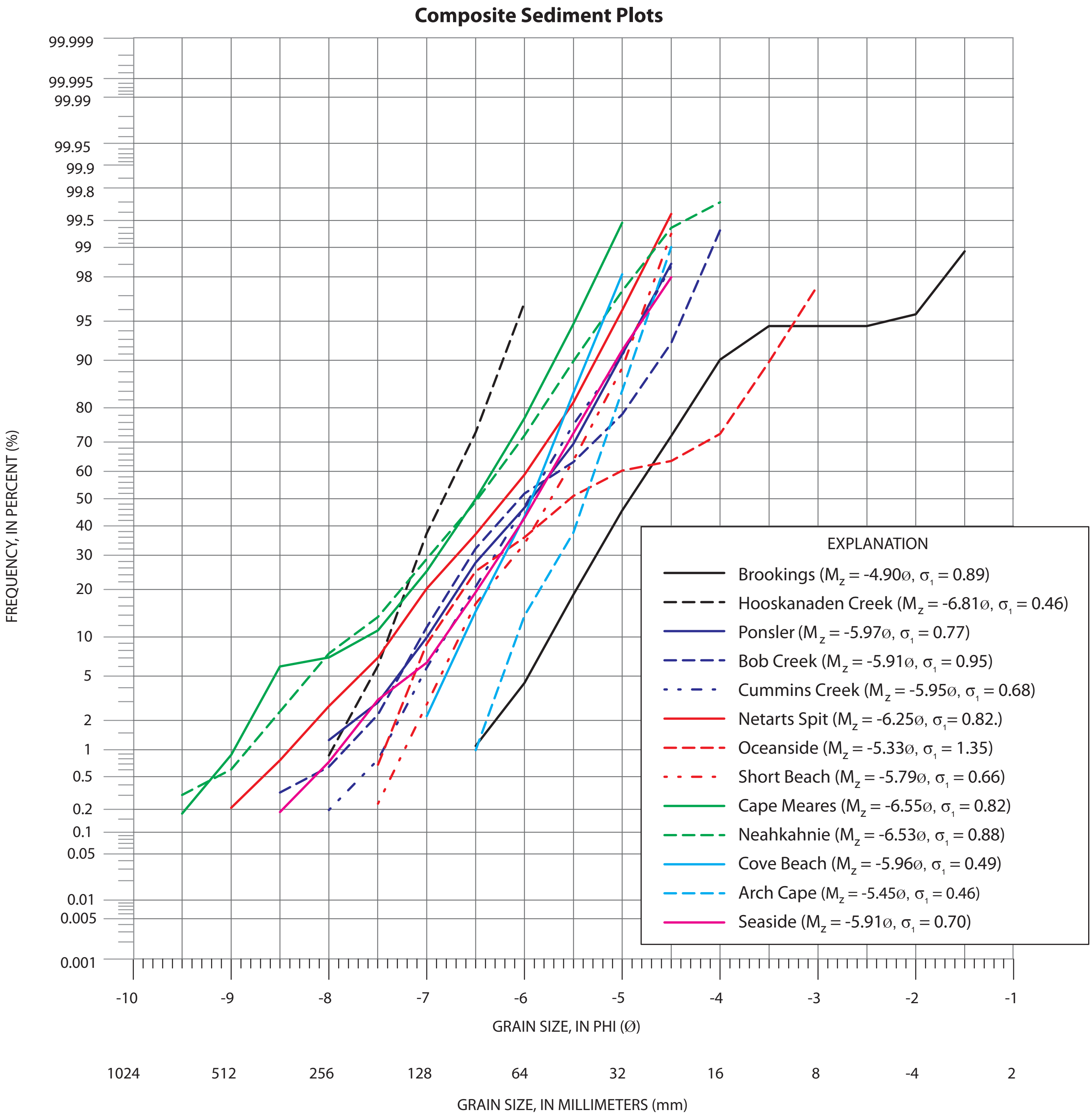


Figure 45. Grain-size distribution curves derived for various gravel beach sites along the Oregon coast.

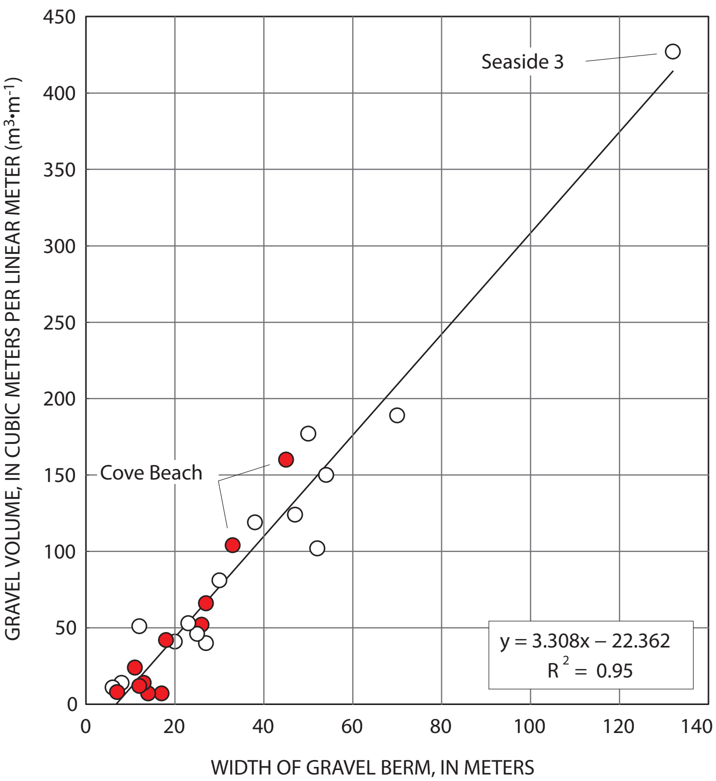


Figure 46. A stepwise linear correlation between gravel volume and gravel beach width derived for the Oregon coast. Red circles are sites currently experiencing erosion.

can be identified, the differences are unlikely to complicate the choice of preferred grain size. Accordingly, we recommend a mean grain size of no less than –6.0ø (64 mm).

The slopes of the gravel beaches appear to be uniform, but Table 2 indicates that the same cannot be said for the slopes of the sand beaches that front the gravel beaches. The sand beach slopes at the north coast study sites average about 1.7º, whereas the sand beach slopes at the central to south coast study sites are steeper, averaging about 3.1º. The difference in the sand beach slopes is probably related to an increase in the proportion of coarse sand on the central to south coast study sites so that these beaches are more akin to mixed sand and gravel beach categories described previously (Figure 12, types B and C). However, these characteristics are unlikely to influence the overall design of a dynamic revetment, other than the recognition that a dynamic revetment constructed landward of a sand beach is likely to be more stable because the sand beach provides additional dissipation of wave energy, thereby providing some protection for the dynamic revetment.

Finally, dynamic revetment design requires examination of the predominant widths and volumes of the gravel beaches. Table 2 indicates that the mean gravel beach width is 31 m (102 ft), while the gravel volume is about 81 $m^3 \cdot m^{-1}$ (about 871 $ft^3 \cdot ft^{-1}$) of shoreline. These data are likely skewed, however, by the extremely wide gravel beaches at Seaside on the north coast and Sport Haven Park on the south coast. As a result, separate estimates of the average widths and gravel volumes are also included in Table 2. These estimates indicate a mean width and volume of 25 m (82 ft) and 63 $m^3 \cdot m^{-1}$ (678 $ft^3 \cdot ft^{-1}$), respectively. Furthermore, there is also a regional difference in the widths and volumes of the gravel beaches (Table 2); the central and south coast study sites are characterized by values that are, respectively, 35 percent and 57 percent lower than the north coast gravel beaches.

Also of interest is the direct relationship between the width of the gravel beaches and the volume of beach gravel. Figure 46 presents a stepwise linear regression that has been fitted to these data, with the width of the gravel beach being the independent variable. Both parameters are highly correlated ($R^2 = 0.95$). This is useful as it provides an empirical method of estimating the volume of gravel needed to construct a dynamic revetment based on various gravel beach widths, irrespective of the height of the gravel beaches, previously thought to be uniform along the coast. The red circles in Figure 46 identify sites that have been experiencing erosion. With the exception of Cove Beach, the general pattern suggests that sites subject to lower gravel volumes, less than 50 $m^3 \cdot m^{-1}$ (538 $ft^3 \cdot ft^{-1}$), and gravel beach widths less than 20 m wide tend to be eroding (for example, the central coast beaches) while sites characterized by higher values are generally more stable. The Cove Beach site is an exception, as this site has no sand beach in front of the gravel face. Accordingly, at Cove Beach the first line of defense is the gravel beach. As can be seen in Figure 14, the beach is subject to waves at all tidal elevations and therefore tends to be more responsive to waves and currents.

COBBLE SOURCES AND TRANSPORTATION

Introduction

This component of the study investigates potential sources of cobble-size rock and both naturally rounded and crushed quarry rock, and it examines the logistics involved in moving the material to coastal project sites. Data have been extracted from departmental databases, site visits, and by personal and telephone interviews with rock quarry operators, sand and gravel producers, port officials, and rail officials. Material source locations and operator contact information are tabulated in accompanying GIS databases (see Appendices A and B).

The successful use of cobble-size gravel (about −6Ø [64 mm]) as a dynamic revetment to slow beach erosion at Cape Lookout State Park offers the possibility of employing this approach to similar portions of the Oregon coast. Natural gravel beaches dissipate wave energy by adjusting their morphologies to the prevailing conditions, whereas a conventional riprap revetment or seawall remains static in the face of sustained ocean wave attack and mitigates wave energy largely by mass.

The dynamic revetment built at Cape Lookout State Park involved the relocation of about 5340 m^3 (about 7000 yd^3) of naturally subrounded to rounded basalt cobbles obtained from two locations on Netarts Spit; 3058 m^3 (4000 yd^3) were obtained north of the completed dynamic revetment, while an additional 2294 m^3 (3000 yd^3) came from the south end of the littoral cell adjacent to Cape Lookout. Although Oregon Parks and Recreation Department (OPRD) was able to derive gravel locally, the same cannot be said for other potential project sites, raising obvious questions regarding suitable gravel sources and how to transport materials to a point of interest. Suitable round-rock sources are not common along the Oregon coast, nor is extraction likely to be permitted from existing locations (mainly fluvial sources). In contrast, roughly equidimensional, broken-faced quarry rock of appropriate size may be serviceable, but no data are available comparing the relative effectiveness of this material to rounded cobbles.

Material and Production

Particles in the 64-mm range are not a standard commercial product from either round rock pits or crushed-stone quarries. This is because the sediment in this size range is generally oversized for most applications and is typically crushed to smaller size fractions. Some operators produce unscreened (“pit-run” or “quarry-run”) material, but most operators crush and screen incremental fractions below −6.65Ø (76 mm). A few operators stockpile sediments larger than −6.65Ø (76 mm) for purposes of landscaping, with the much larger clasts stored for such purposes as constructing riprap revetments. Further size separation is rarely done, so these materials may range up to large boulders (that is, intermediate axis widths that are about 0.5 to 0.8 m [1.7 to 2.5 ft]).

Round-rock particle size is a function of source-rock characteristics plus erosion and transportation processes. Cobble-size round rock can be generated in reaches of high-energy streams, at sites of sea cliff erosion, and by glaciers and glacial floods. Although such deposits occur in Oregon, few accessible sources are located near the coast. Examples of the sources include glacial flood deposits in Columbia County and alluvial deposits along the eastern margin of the Willamette Valley, where major tributaries debouch on to the valley floor.

Crushed-rock particle size depends in part on the joint spacing of the rock mass itself and in part on production techniques. If explosives are required, quarry operators use blasting patterns designed to shatter rock as near as possible to finished product sizes. This minimizes oversize material, which would require additional handling and processing. In some quarries the blasting program could be altered to produce more coarse material.

Production of cobble-size round rock or quarry rock may require an operator to modify procedures in excavating, blasting, quarrying, sizing, storage, and handling. The ability and willingness of an operator to effect these changes is a function of the source’s physical characteristics (jointing, fracturing, particle size distribution), location of the active operating face at the time of need, and economic conditions at the time of need (including transportation costs, individual source economics, and the size of an ODOT contract). Some operators expressed willingness to effect such changes for a 10,000-ton project; others did not.

Transportation and Handling

Any coastal project requiring cobbles will require truck transport to the project site either from a near-coast source or from an interim stockpile ultimately sourced from a more distant producer. The maximum load for a truck/trailer combination is 35 to 40 tons. Depending on the project location it may be necessary to consider haul route load limits when locating a materials source. For example, had the Beverly Beach project proceeded as a dynamic revetment, material from any source north of the beach could not have been transported on a fully loaded truck/trailer because of load limits on the bridge crossing Spencer Creek.

Rail transportation is possible for some projects, especially if round rock from inland sources is required. Large volumes could be moved more quickly and at lower cost than by truck, but the number of loading and unloading facilities is more limited. Railcars for aggregate transport have 70- or 100-ton capacities and are either bottom dumping or side dumping. Some railroads have their own fleet of cars; others would have to lease equipment. Some producers have dedicated sidings with appropriate loading and stockpiling facilities; others would have to make short truck hauls with additional handling to sidings near their pits. Loading directly to a main line track is not feasible, as no other traffic could be moved on the line during the operation. Unloading a side-dumping car takes only minutes if the material can be dropped and stockpiled immediately adjacent to the tracks. This approach is used by the Port of Tillamook Bay Railroad to deliver

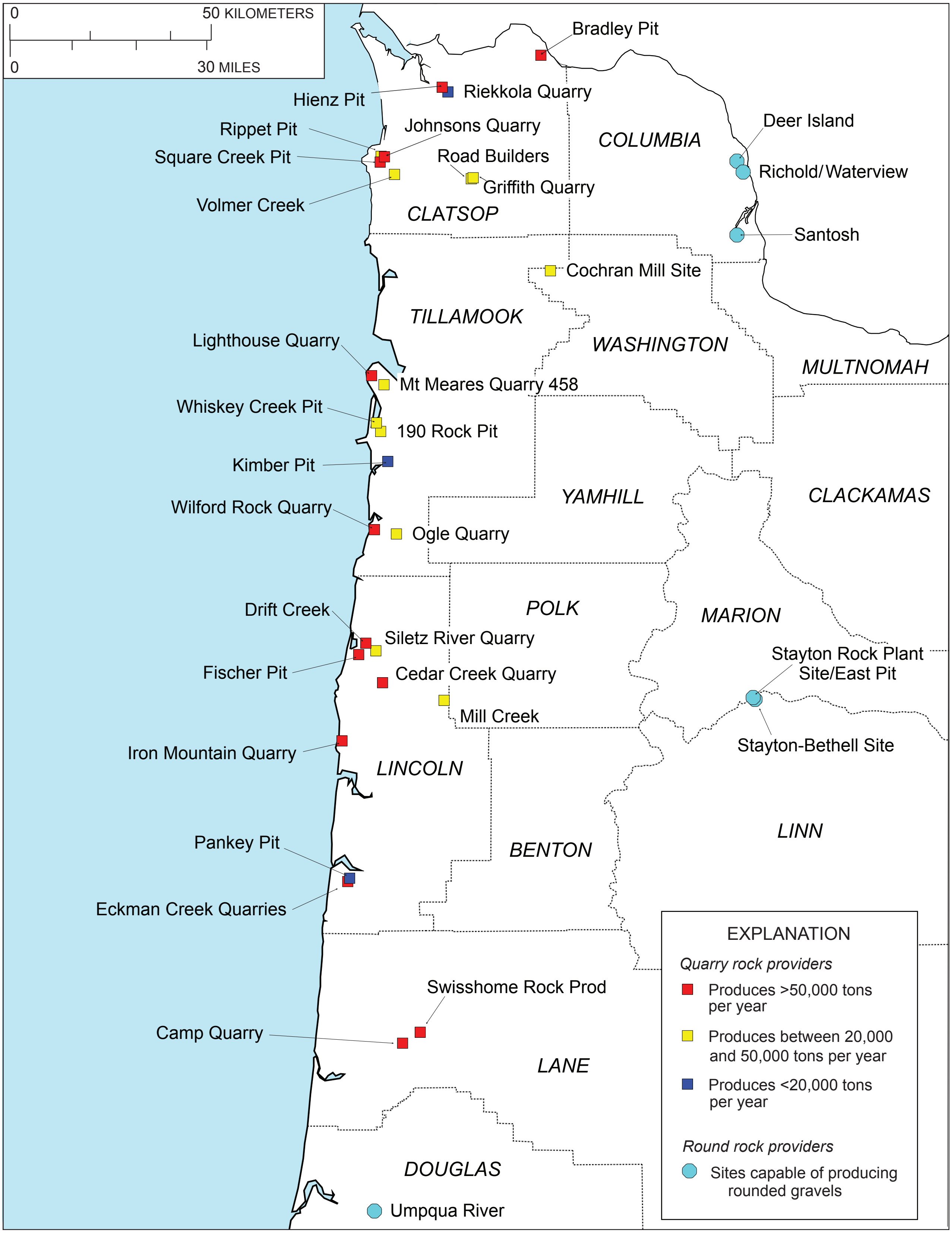


Figure 47. Location map of active rock quarry sites and quarries on the central to northern Oregon coast capable of producing rounded gravels.

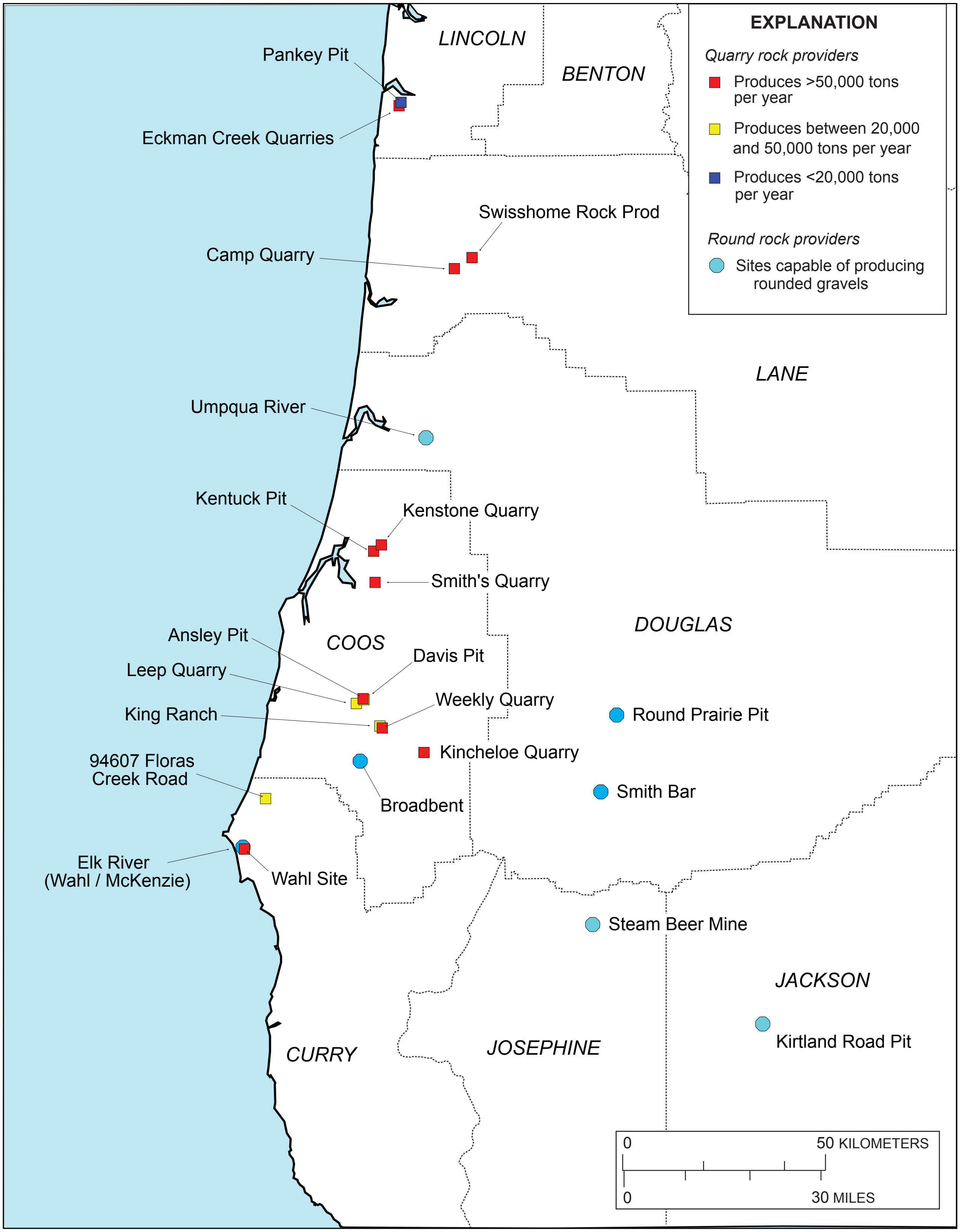


Figure 48. Location map of active rock quarry sites and quarries on the central to southern Oregon coast capable of producing rounded gravels.

riprap to some coastal communities. Bottom dumping is a longer process using conveyors placed under the cars to move material to stockpiles or waiting trucks. Due to time requirements this would need to be done only from a siding.

Barge transportation could be used to move rock from sources on the Columbia River or ports elsewhere in the Pacific Northwest. Glacier Northwest currently operates ocean-going barges of 8,000- to 10,000-ton capacity to transport aggregate to Portland from sources along the Columbia as well from pits on Puget Sound near Tacoma, Washington. Dedicated vessels also carry aggregate along the coast from British Columbia to southern California and gypsum from Mexico northward to wallboard plants, including one at Rainier, in Columbia County, Oregon. The ships and most of the barges have a conveyor system for rapid self-unloading and require appropriate port facilities. Use of port facilities would incur docking, demurrage, and stockpile storage fees as well as union wages for all longshoremen.

Some operators expressed concern about effectively using their conveyor equipment with cobble-size round rock. Systems designed to move smaller particles with a relatively high angle of repose may not be able to contain larger round cobbles that could roll off conveyor belts, especially at steep conveyor angles.

Cobble Sources

Most potential coastal project sites are within 48 km (30 mi) of a rock quarry that could produce cobble-size stone (Figures 47 and 48), assuming that crushed stone would be satisfactory. Nearly 40 quarries listed in the accompanying database (Appendix B) either are currently active or have produced for at least two of the last five years. Presently inactive sites are included because operation can be sporadic, even for some large-volume quarries, if they are dependent on local but large episodic projects, such as highway construction. As an indication of which quarries could absorb a custom order for 10,000 tons of material each is ranked in one of three levels of production for the periods during which the quarry has actually been active. It seems probable that an operation capable of producing over 50,000 tons annually would be more likely able to supply custom material than would one producing only 10,000 tons annually.

Round rock cobble sources present their own concerns. Potential production is totally dependent on the amount of cobble-size material present in the deposit at selected quarries. Few deposits are cobble rich, and rounded cobbles cannot be produced by machine processes on a large scale. If a coastal project requires round cobbles, sources further afield may have to be considered.

Only three near-coast sites appear to have potential for sufficient volume of round cobbles (Figure 48). All are owned by LTM, Inc. of Medford, and none are in full production. The Elk River site, about 6.5 km (4 mi) north of Port Orford, and the Broadbent site, about 8 km (5 mi) south of Myrtle Point, were not yet permitted or in production in spring 2004, and a permit application for a dredging operation on the lower Umpqua River was rejected. Inland cobble-producing sources are located near the Interstate Highway 5 corridor in Jackson, Josephine, Douglas, and Linn Counties (Figures 47 and 48). All have varying access to rail. Operations near the Columbia River in Columbia County (Figure 47) have both rail and barge access, and one company can also source cobbles by barge from its pits near Tacoma. Although there are other probable sources along the north Pacific coast, no attempt was made to identify additional sites, companies, or carriers in Washington, British Columbia, or Alaska.

Aesthetics may also be of concern to some. Cobble and pebble beaches in Oregon are composed primarily of locally derived dark colored rocks, typically basaltic material. Cobbles from Cascade and Coast Range drainages are also predominately dark. Columbia River glacial flood deposits and alluvial and glacial deposits found further north, however, can contain lighter colored stone including granite.

Costs

Few operators are willing to commit to material or transportation costs without a specific project description. Nevertheless, conversations with several producers and transportation companies yielded generalized estimates from which the following cost approximations can be made.

Material cost currently runs be about $10 per ton at the pit or quarry, necessarily an indefinite figure dependent in part on what modifications of production procedures would be required. Transportation costs are additional. For example, truck transportation averages about $0.75 per ton per mile (1.6 km) for hauls of a few tens of miles (Tony Synder, Oregon Department of Transportation, written communication, 2005). This cost is dependent on a variety of factors including travel time, distance of travel, equipment type, and road surface and thus will vary accordingly. For example, travel costs may increase to as much as $1.60 per ton per mile (1.6 km) on unpaved (gravel) roads.

A hypothetical rail haul of 10,000 tons of round rock from a Roseburg source to a siding in Coos Bay or North Bend, about 337 km (210 mi) by rail, would cost about $8 per ton. This figure assumes three trips of 30 cars and includes car leasing for a month. It does not include stockpiling or storage fees, local handling and truck transport to the project site, or possible demurrage charges. Trucking cost from Roseburg to Coos Bay, 136 highway kilometers (85 miles), would be about $22 per ton.

A hypothetical barge haul of 10,000 tons of round rock from Scappoose (or Tacoma) to the Port of Newport would cost about $6 per ton. This does not include port, stevedoring, stockpiling, storage, possible demurrage fees, or local handling and truck transport to the project site. Truck transport from Scappoose to Newport, 250 highway km (150 mi), would be about $38 per ton.

Transportation costs may be negotiable depending on project size. These many variables cannot be further quantified unless source and project site are defined.

Databases

A quarry rock database and a round rock database (see Appendix B) were compiled from DOGAMI's Mineral Land Regulation and Reclamation (MLRR) database, from the Mineral Information Layer for Oregon (MILO) database, and from site visits and personal and telephone conversations with members of the aggregate industry. The databases contain site names, company contact information, and site locations by section, township, and range, and locations by latitude and longitude.

The quarry rock database includes quarries meeting the following criteria:

1. Production of at least 50,000 tons of quarry rock over the last five years.
2. Production of at least 20,000 tons in one year of the last five years.
3. Location west of the approximate crest of the Coast Range.

Each quarry site is categorized by annual production, which is obtained by dividing total production by the number of years of production. The categories are a) less than 20,000 tons per year, b) 20,000 to 50,000 tons per year, and c) more than 50,000 tons per year. Larger-volume operators would more likely be able to produce 10,000 tons of a specialty product, cobble-size material without major impact on their normal operation.

The round rock database includes gravel pits from which naturally rounded, cobble-size material can be produced. Round rock is not common in the coastal area, so sources east of the Coast Range and west of the Cascades were included. Some sites have direct loading to rail or barge, some could probably obtain intermittent rail access, and others require truck haulage to a railhead or to the project itself.

CONCLUSIONS

Erosion of beaches along the Oregon coast has increased the demand for aesthetically acceptable "soft" forms of coastal engineering. Researchers recognize that gravel beaches are one of the most efficient forms of coastal protection, exhibiting a remarkable degree of stability in the face of sustained wave attack. Because of this, such structures, variously termed cobble berms, dynamic revetments, or rubble beaches, have been recommended as a form of shore protection. This method essentially involves the construction of a gravel or cobble beach at the shore, in front of the property to be protected.

The purpose of this research was to address uncertainties concerning both the physical design of such structures and the acquisition of suitable quantities of gravel to construct and maintain a dynamic revetment. The study had two key objectives. The first objective was to undertake an assessment of the geomorphology of gravel beaches along the Oregon coast, with emphasis on identifying predominant crest elevations, gravel beach widths, beach slopes, gravel volumes, and mean grain sizes, from which appropriate recommendations could be made with respect to the design of a dynamic revetment. The second objective was to identify potential sediment sources that could be used to construct such structures elsewhere on the Oregon coast and to evaluate the methods and costs of transporting the sediment to those locations.

The study's principal findings on the geomorphology include the following:

- 27 profile lines at 13 gravel beach study sites along the Oregon coast revealed that the majority of the gravel beaches were stable and characterized by well-vegetated backshores. Most of the stable gravel beach sites are found on the northern Oregon coast, whereas sites exhibiting evidence of backshore erosion tend to be concentrated on the central and southern Oregon coast.
- An examination of the morphological characteristics of stable versus eroding gravel beaches revealed that in most cases the key difference was the width of the gravel beach and its associated sediment volume. In contrast, there is no clearly discernible pattern in gravel beach crest elevation and slope and grain size among stable versus eroding beaches.
- Gravel beach crest heights ranged from 5.7 to 7.1 m (19 to 23 ft); we recommend a constructed berm crest height of no less than 7.0 m (23 ft).
- Gravel beach height is regarded as a function of maximum wave runup during storms. Therefore analyses were undertaken to compare beach heights measured on the Oregon coast with calculated total water levels (T_{WL} [wave runup plus tidal elevation]) using a model developed for dissipative sand beaches by Ruggiero and others (2001) and incorporating a composite beach slope of 6.3º. An extreme value analysis was subsequently performed on the monthly maximum T_{WL} values. This analysis revealed extreme T_{WL} values that ranged from 8.1 m (27 ft) for an annual event to about 12.5 m (41 ft) for a 100-year storm. Although the annual extreme T_{WL} was found to be close to a few gravel beach crest heights, the model probably overpredicts T_{WL} on gravel beaches. Accordingly, further efforts should be directed at developing a suitable empirical model to predict wave runup on coarse beaches, which would better represent Oregon's typical situation of a wide, dissipative, gently sloping sand beach backed by a steeply sloping gravel beach.

- Although the extreme value analysis on T_{WL} did not yield any meaningful correlation with gravel beach heights, a cumulative frequency plot of hourly T_{WL} revealed that T_{WL} exceeds an elevation of 6.0 m (22 ft) 5 percent of the time, but T_{WL} exceeds the 7.0-m height only 1 percent of the time. Accordingly, it is probably reasonable to construct a dynamic revetment to an elevation of 7.0 m (23 ft). However, it is important to appreciate that such a structure would be overtopped periodically, as has occurred on occasion at CLSP (Komar and others, 2003; Allan and others, 2004). One approach for minimizing potential impacts on the backshore associated with such events is to create a dynamic revetment with a broad crest; an alternative is an artificial dune such as was constructed at CLSP.
- Mean grain sizes were found to range from −4.9Ø (30 mm) on the southern Oregon coast to −7.0Ø (128 mm) on the north coast. In general, the predominant grain sizes were found to be extremely uniform in size, with the sediment generally classified as well sorted to moderately well sorted. On the basis of this study, we recommend using small cobbles with a mean grain size of −6.0Ø (64 mm).
- The preferred lithology for the gravel is basalt due to its relative abundance throughout Oregon and because basalt is more likely to undergo slower rates of abrasion.
- The slopes of the gravel beaches were found to range from 7.7º to 14.1º; the average slope was found to be 10.9º. Accordingly, we recommend that the minimum slope should be no less then 11º.
- Analyses of the widths of the gravel beaches and their volumes revealed that north coast gravel beaches tended to exhibit wider beaches (about 28 m [92 ft]) and correspondingly larger volumes of gravel (about 77 $m^3 \cdot m^{-1}$ [830 $ft^3 \cdot ft^{-1}$]) compared with central to south coast gravel beaches, which were characterized by widths and volumes that were, respectively, 35 percent and 57 percent lower. Furthermore, because these two variables were highly correlated, a simple empirical model was developed to estimate appropriate gravel volumes based on an understanding of a design berm width.

In addition to the above findings, we recommend that consideration of the potential impact of longshore drift be included in any project design on the Oregon coast. The important role of longshore currents in transporting large quantities of sediment out of a project area has been addressed by several studies (for example, Cape Lookout State Park; Vancouver, British Columbia; and Flathead Lake, Montana). Accordingly, we recommend that the project design include a procedure for periodic maintenance, which may include returning some portion of the sediment that was transported out of the project area or periodically introducing additional new sediment as gravel volume decreases. Alternatively, one could evaluate an engineering solution such as a low weir-type groyne constructed across the dynamic revetment, which could reduce the rate of alongshore gravel transport (at least until the gravel begins to overtop the groyne).

A major constraint that could limit the adoption of dynamic revetments as a viable engineering solution for the Oregon coast is the availability of suitable gravel sources. In an effort to address this issue, we assessed the spatial distribution and operational capabilities of quarry sites along the Oregon coast and west of the Willamette Valley. These data are summarized in graphical form in Figures 47 and 48 and are provided as a searchable GIS database (see Appendix B).

Our main findings on the availability of and transportation issues associated with gravel source rock include the following:

- The apparent paucity of existing gravel quarries in Oregon capable of producing rounded particles was confirmed by this study. Identified resources are much more common in Washington State. Only five gravel quarry sites on the central to northern Oregon coast could be identified as capable of producing "rounded" gravel in the −6Ø (64 mm) range. These are the Deer Island, Richold/Waterview, and Santosh sites located in Columbia County adjacent to the Columbia River and the two Stayton sites in Linn County (Figure 47). In contrast, seven sites on the south coast could provide suitable sediment for the construction of a dynamic revetment; of these, the Elk River, Broadbent, and Umpqua River sites closest to the coast (Figure 48).
- Quarries capable of producing crushed gravel of a particular size are relatively more common. A number of these sites are located adjacent to major towns or transportation hubs (for example, Astoria, Tillamook, Newport, and Coos Bay). As indicated in Figures 47 and 48, many of these quarries are capable of producing about 50,000 tons of crushed rock annually. However, production of cobble-size round rock or quarry rock may require an operator to modify procedures in excavating, blasting, quarrying, sizing, storage, and handling. The ability and willingness of an operator to effect these changes is a function of the source's physical characteristics (jointing, fracturing, and particle size distribution), location of the active operating face at the time of need, and economic conditions at the time of need (including transportation costs, individual source economics, and the size of an ODOT contract).
- No quarries south of Port Orford are capable of producing crushed rock. Accordingly, the construction of a dynamic revetment at Hooskanaden Creek, for example, would require using existing beach sediment (an abundance of gravel has accumulated north of profile 2) or importing material from an alternative source.
- Material and transportation costs proved to be the most difficult items to estimate, as few quarry and transportation operators were willing to provide any cost estimate without a specific project description.

- Material costs were estimated to be about $10 per ton at the pit or quarry, necessarily an indefinite figure dependent in part on what modifications of production procedures would be required.
- Truck transportation cost was estimated to be about $0.75 per ton per mile for hauls of a few tens of miles. Actual cost is dependent on a variety of factors including travel time, distance, equipment type, and road surface. For example, travel costs may increase to as much as $1.60 per ton per mile on unpaved (gravel) roads.
- A hypothetical rail haul of 10,000 tons of round rock from a Roseburg source to a siding in Coos Bay or North Bend, about 210 miles by rail, was estimated to cost about $8 per ton. This figure assumes three trips of 30 cars and includes car leasing for a month. It does not include stockpiling or storage fees, local handling and truck transport to the project site, or possible demurrage charges.
- A hypothetical barge haul of 10,000 tons of round rock from Scappoose (or Tacoma) to the Port of Newport was estimated to cost about $6 per ton. However, this does not include port, stevedoring, stockpiling, storage, possible demurrage fees, or local handling and truck transport to the project site.

In summary, transportation costs may be negotiable depending on project size. However, because of the many variables involved in assessing quarry operator and transportation issues, it is not possible to provide a clearer understanding of these issues without defining a source and project site.

RECOMMENDATIONS

Unresolved questions in need of further long-term study include:

- Investigation of the rate at which crushed rock rounds to the appropriate diameter under varying wave conditions;
- Analyses of alongshore transport of gravels and crushed rock as a function of wave conditions, currents, and the geomorphology of the coastline;
- Development of quantitative numerical models of erosion and deposition of gravel beaches based on empirical observations;
- Development of suitable wave runup equations for gravel beaches; and,
- Additional detailed economic analyses based on small-scale pilot projects designed to test viability at sites with large differences in gravel movement, geomorphology, wave conditions, and availability of artificial sources. Three sites we consider to be the most appropriate for this type of analysis are:
  - Cape Lookout State Park, Tillamook County,
  - Spencer Creek Bridge, Lincoln County, and
  - Hooskanaden Creek, Curry County.

The latter two sites are especially pertinent to the Oregon Department of Transportation (ODOT) and U.S. Federal Highway Administration, as these sites are located adjacent to U.S. Highway 101. Both sites are currently experiencing backshore erosion, which is beginning to affect the safe operation of Highway 101. Furthermore, these sites are characterized by small gravel beaches that could be expanded in an attempt to reduce the future erosion of the beach.

REFERENCES

Aguilar-Tunon, N. A., and Komar, P. D., 1978, The annual cycle of profile changes of two Oregon beaches: Ore Bin, v. 40, no. 2, p. 25–39.

Ahrens, J. P., 1990, Dynamic revetments, *in* Proceedings of the 22nd coastal engineering international conference, July 2–6, 1990, Delft, The Netherlands: American Society of Civil Engineers, p. 1837–1850.

Allan, J. C., 2004, An evaluation of the risks from storm erosion and overwash of the Elk River Spit, Oregon, associated with restoring Western Snowy Plover breeding habitat: Open-File Report O-04-17: Portland, Oregon Department of Geology and Mineral Industries, 44 p.

Allan, J. C., and Komar, P. D., 2000a, Are ocean wave heights increasing in the eastern North Pacific?: Eos, Transactions of the American Geophysical Union, v. 81, no. 47, p. 561, 566–567.

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

Allan, J. C., and Komar, P. D., 2002a, A dynamic revetment and artificial dune for shore protection at Cape Lookout State Park, Oregon *in* McKee Smith, J. ed., Coastal engineering 2002, Proceedings of the 28th international conference on coastal engineering, July 7–12, 2002, Cardiff, Wales: American Society of Civil Engineers, p. 2044–2056.

Allan, J. C., and Komar, P. D., 2002b, Extreme storms on the Pacific Northwest Coast during the 1997-98 El Niño and 1998-99 La Niña: Journal of Coastal Research, v. 18, no. 1, p. 175–193.

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

Allan, J. C., and Priest, G. R., 2001, Evaluation of coastal erosion hazard zones along dune and bluff backed shorelines in Tillamook County, Oregon: Cascade Head to Cape Falcon: Open-File Report O-01-03: Portland, Oregon Department of Geology and Mineral Industries, 126 p.

Allan, J. C., Komar, P. D., and Hart, R., 2003a, A dynamic revetment and reinforced dune as “natural” forms of shore protection in an Oregon state park, *in* Melby, J. A., ed., Proceedings of the coastal structures 2003 conference, Aug. 26–30, 2003, Portland, Oreg.: American Society of Civil Engineers, p. 1048–1060.

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

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

Bluck, B. J., 1967, Sedimentation of beach gravels: Examples from South Wales: Journal of Sedimentary Petrology, v. 37, no. 1, p. 128–156.

Bradbury, A. P., and Powell, K. A., 1992, The short term response of shingle spits to storm wave action: Coastal Engineering, v. 16, p. 2695–2707.

Brock, J. C., Wright, C. W., Sallenger, A. H., Krabill, W. B., and Swift, R. N., 2002, Basis and methods of NASA airborne topographic mapper lidar surveys for coastal studies: Journal of Coastal Research, v. 18, no. 1, p. 1–16.

Bruun, P., and Johannesson, P., 1976, Parameters affecting stability of rubble mounds: Journal of the Waterways, Harbors and Coastal Engineering Division, ASCE, v. 102, no. 2, p. 141–164.

Carr, A. P., 1969, Size grading along a pebble beach: Chesil Beach, England: Journal of Sedimentary Petrology, 39, 297–311.

Carr, A. P., 1971, Experiments on longshore transport and sorting of pebbles: Chesil Beach, England: Journal of Sedimentary Petrology, v. 41, p. 1084–1104.

Carr, A. P., 1974, Differential movement of coarse sediment particles, *in* Proceedings of the 14th coastal engineering conference: American Society of Civil Engineers, p. 851–870.

Carter, R. W. G., and Orford, J. D., 1984, Coarse clastic barrier beaches: A discussion of the distinctive dynamic and morphosedimentary characteristics: Marine Geology, v. 60, p. 377–389.

Deguchi, I., Ono, M., and Sawaragi, T., 1996, Wave on pebble beach and deformation of pebble beach, *in* Proceedings of the 25th conference on coastal engineering, Sept. 2–6, 1996, Orlando, Fla.: American Society of Civil Engineers, p. 3349–3362.

Downie, K. A., and Saaltink, H., 1983, An artificial cobble beach for erosion control, *in* Weggel, J.R., ed., Coastal structures ’83, A speciality conference on the design, construction, maintenance and performance of coastal structures, March 9–11, 1983, Arlington, Va.: American Society of Civil Engineers, p. 846–859.

Everts, C. H., Eldon, C. D., and Moore, J., 2002, Performance of cobble berms in Southern California: Shore & Beach, v. 70, no. 4, p. 5–14.

Folk, R. L., 1965, Petrology of sedimentary rocks: Austin, Tex., Hemphills Publishing Co., 159 p.

Folk, R. L., and Ward, W. C., 1957, Brazos River Bar: a study in the significance of grain size parameters: Journal of Sedimentary Petrology, v. 27, no. 1, p. 3–26.

Johnson, C. N., 1987, Rubble beaches versus revetments: Proceedings of coastal sediments '87, May 12–14, 1987, New Orleans, La.: American Society of Civil Engineers, p. 1217–1231.

Griggs, G. B., Tait, J. F., and Corona, W., 1994, The interaction of seawalls and beaches: Seven years of monitoring, Monterey Bay, California: Shore & Beach, v. 62, no. 3, p. 21–28.

Hattori, M., and Suzuki, T., 1978, Field experiment on beach gravel movement, *in* Proceedings of the 16th international conference on coastal engineering, Sept. 1978, Hamburg, Germany: American Society of Civil Engineers.

Horn, D. P., and Walton, S. M., in review, Spatial and temporal variations of sediment size on a mixed sand and gravel beach: Sedimentary Geology.

Holman, R. A. 1986, Extreme value statistics for wave run-up on a natural beach: Coastal Engineering, v. 9, p. 527–544.

Intergovernmental Panel on Climate Change (IPCC), 1995, Climate Change 1995, The science of climate change: Summary for policymakers approved by Working Group I of the IPCC and accepted by the IPCC and technical summary of the Working Group I report, 56 p.

Jennings, R., and Shulmeister, J., 2002, A field based classification scheme for gravel beaches: Marine Geology, v. 186, p. 211–228.

Kirk, R. M., 1975, Aspects of surf runup processes on mixed sand and gravel beaches: Geografiska Annaler, v. 57(A), p. 117–133.

Kirk, R. M., 1992a, Artificial beach growth for breakwater protection at the Port of Timaru, east coast, South Island, New Zealand: Coastal Engineering, v. 17, p. 227–251.

Kirk, R. M., 1992b, Experimental beach reconstruction-renourishment on mixed sand and gravel beaches, Washdyke Lagoon, South Canterbury, New Zealand: Coastal Engineering, v. 17, p. 253–277.

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

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

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

Komar, P. D., 2005, Hawke's Bay, New Zealand: Environmental change, shoreline erosion and management issues: Unpublished report to the Hawe's Bay Regional Council.

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

Komar, P. D., Allan, J. C., and Winz, R., 2003, Cobble beaches—The "design with nature" approach for shore protection, *in* Coastal Sediments '03, Proceedings of the 5th international symposium on coastal engineering and science of coastal sediment processes, May 18–23, 2003, Clearwater Beach, Fla.: American Society of Civil Engineers.

Kraus, N. C., and McDougal, W. G., 1996, The effects of seawalls on the beach: Part I, An updated literature review: Journal of Coastal Research, v. 12, no. 3, p. 691–701.

Lippmann, T. C., and Holman, R. A., 1990, The spatial and temporal variability of sand bar morphology: Journal of Geophysical Research, v. 95(C7), p. 11,575–11,590.

Lorang, M. S., 1991, An artificial perched-gravel beach as a shore protection structure, *in* Kraus, N. C., Gingerich, K. J., and Kriebel, D. L., eds., Coastal Sediments '91, Proceedings of a specialty conference on quantitative approaches to coastal sediment processes, June 25–27, 1991, Seattle, Wash.: American Society of Civil Engineers, vol. II, p. 1916–1925.

Lorang, M. S., 2000, Predicting threshold entrainment mass for a boulder beach: Journal of Coastal Research, v. 16, no. 2, p. 432–445.

Lorang, M. S., Namikas, S. L., McDermott, J. P., and Sherman, D. J., 1999, El Niño storms and the morphodynamic response of two cobble beaches, *in* Kraus, C. N., and McDougal, G. W., eds., Coastal sediments '99, Proceedings of the 4th international symposium on coastal engineering and science of coastal sediment processes, June 21–23, 1999, Hauppauge, Long Island, N.Y.: American Society of Civil Engineers, p. 922–937.

Marshall, P., 1927, The wearing of beach gravels: New Zealand Institution Transactions, v. 58, p. 507–532.

Mason, T., and Coates, T. T., 2001, Sediment transport processes on mixed beaches: A review for shoreline management: Journal of Coastal Research, v. 17, no. 3, p. 645–657.

McLean, R. F., 1970, Variations in grain size and sorting on two Kaikoura beaches: New Zealand Journal of Marine and Freshwater Research, v. 4, p. 141–164.

Muir Wood, A. M., 1970, Characteristics of shingle beaches: The solution to some practical problems, *in* Proceedings of the 12th international conference on coastal engineering, Sept. 1970, Washington, D.C.: American Society of Civil Engineers, p. 1059–1075.

National Marine Consultants, 1961, Wave statistics for twelve most severe storms affecting three selected stations of the coast of Washington and Oregon during the period 1950–1960: Prepared for U.S. Army Engineers District, Seattle, Washington and Portland, Oregon, National Marine Consultants, Santa Barbara, Calif., 17 p.

Nicholls, R., and Webber, N., 1988, Characteristics of shingle beaches with reference to Christchurch Bay, S. England, *in* Proceedings of the international 21st coastal engineering conference, June 20–25, Costa del Sol-Malaga, Spain: American Society of Civil Engineers, p. 1922–1936.

Nicholls, R.J., and Wright, P., 1991, Longshore transport of pebbles: experimental estimates of *K*, *in* Kraus, N. C., Gingerich, K. J., Kriebel, D. L., eds., Coastal Sediments '91—Proceedings of a specialty conference on quantitative approaches to coastal sediment processes, June 25–27, 1991, Seattle, Washington: American Society of Civil Engineers, p. 920–933.

Noble Consultants, 2000, Recommended protection for Surfers Point, Ventura County, California: unpublished report prepared for the City of Ventura.

Orford, J. D., 1975, Discrimination of particle zonation on a pebble beach: Sedimentology, v. 22, p. 441–463.

Powell, K. A., 1988, The dynamic response of shingle beaches to random waves, *in* Proceedings of the international 21st conference on coastal engineering, June 20–25, 1988, Costa del Sol-Malaga, Spain: American Society of Civil Engineers, p. 1763–1773.

Revell, D., Komar, P. D., and Sallenger, A. H., 2002, An application of LIDAR to analyses of El Niño erosion in the Netarts littoral cell, Oregon: Journal of Coastal Research, v. 18, no. 4, p. 792–801.

Ruggiero, P., Komar, P. D., McDougal, W. G., and Beach, R. A., 1996, Extreme water levels, wave runup and coastal erosion, *in* Proceedings of the 25th conference on coastal engineering, Sept. 2–6, 1996, Orlando, Fla.: American Society of Civil Engineers, p. 2793–2805.

Ruggiero, P., Komar, P. D., McDougal, W. G., Marra, J. J., and Beach, R. A., 2001, Wave runup, extreme water levels and the erosion of properties backing beaches: Journal of Coastal Research, v. 17, no. 2, p. 407–419.

Sallenger, A. H., 2000, Storm impact scale for barrier islands: Journal of Coastal Research, v. 16, no. 3, p. 880–895.

Sallenger, A. H., Krabill, W. B., Brock, J. C., Swift, R., Jansen, M., Manizade, S., Richmond, B., Hampton, M., and Eslinger, D., 1999, Airborne laser study quantifies El Niño-induced coastal change: Eos, Transactions of the American Geophysical Union, v. 80, no. 8, p. 89, 92–93.

Sanders, F., and Gyakum, J. R., 1980, Synoptic-dynamic climatology of the “bomb”: Monthly Weather Review, v. 108, p. 1589–1606.

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, Bulletin 74: Portland, Oregon Department of Geology and Mineral Industries, 164 p.

Seymour, R. J., 1996, Wave climate variability in Southern California: Journal of Waterway, Port, Coastal, and Ocean Engineering, v. 122, p. 182–186.

Sherman, D. J., 1991, Gravel beaches: National Geographic Research & Exploration, v. 7, no. 4, p. 442–452.

Shih, S.-M., and Komar, P. D., 1994, Sediments, beach morphology and sea-cliff erosion within an Oregon coast littoral cell: Journal of Coastal Research, v. 10, no. 1, p. 144–157.

Stockdon, H. F., Sallenger, A. H., List, J. H., and Holman, R. A., 2002, Estimation of shoreline position and change using airborne topographic lidar data: Journal of Coastal Research, v. 18, no. 3, p. 502–513.

Tillotson, K., and Komar, P. D., 1997, The wave climate of the Pacific Northwest (Oregon and Washington): A comparison of data sources: Journal of Coastal Research, v. 13, no. 2, p. 440–452.

Trenberth, K. E., 1999, The extreme weather events of 1997 and 1998: Consequences, v. 5, no. 1, p. 3–15.

van der Meer, J. W., 1987, Stability of breakwater armor layers —design formulae: Coastal Engineering, v. 11, p. 219–239.

van der Meer, J. W., and Pilarczyk, K. W., 1986, Dynamic stability of rock slopes and gravel beaches, *in* Proceedings of the 20th international conference on coastal engineering, Nov. 9–14, 1996, Taipei: American Society of Civil Engineers, p. 1713–1726.

van der Meer, J. W., and Stam, C.-J. M., 1992, Wave runup on smooth and rock slopes of coastal structures: Journal of Waterway, Port, Coastal and Ocean Engineering, v. 118, p. 534–550.

van der Meer, J. W., Tutuarima, W. H., and Burger, G., 1996, Influence of rock shape and grading stability of low-crested structures, *in* Proceedings of the 25th international conference on coastal engineering, Sept. 2–6, 1996, Orlando, Fla.: American Society of Civil Engineers, p. 1957–1970.

van Hijum, E., 1974, Equilibrium profiles of coarse material under wave attack, *in* Proceedings of the 14th conference on coastal engineering: American Society of Civil Engineers, 939–957.

Ward, D. L., and Ahrens, J. P., 1991, Laboratory study of a dynamic berm revetment: Vicksburg, Miss., Coastal Engineering Research Center, Waterways Experiment Station, U.S. Army Corps of Engineers.

Williams, A. T., and Caldwell, N. E., 1988, Particle size and shape in pebble-beach sedimentation: Marine Geology, v. 82, p. 199–215.

Willis, D. H., Baird, W. F., and Magoon, O. T., 1988, Berm breakwaters: New York, American Society of Civil Engineers, 284 p.

Wright, L. D., and Short, A. D., 1983, Morphodynamics of beaches and surf zones in Australia, *in* Komar, P. D., ed., Handbook of coastal processes and erosion: Boca Raton, Fla., CRC Press, p. 5–64.

APPENDIX A

Tables A1 and A2 list Oregon quarries capable of producing gravels suitable for constructing dynamic revetments.

Table A1 lists, in county order from north to south, Oregon quarries meeting the following criteria: a) production of at least 50,000 tons of quarry rock over the last five years; b) production of at least 20,000 to 50,000 tons in one year of the last five years; and c) production of less than 20,000 tons per year. All sites listed are west of the approximate crest of the Coast Range. (Also see Figures 47 and 48 for quarry locations and Appendix B for the location of GIS files from which this table was produced.)

Table A1. Oregon Quarry Rock Sites West of the Coast Range

Site Name	Production Level	Owner	County	Address	City	Zip	Phone	Section	Township	Range	Latitude	Longitude
Hienz Pit	>50,000 tons/yr	M. Nygaard Logging Company	Clatsop	PO Box 100	Warrenton	97146	503 861-3305	12	7N	9W	46.1003	-123.7460
Bradley Pit	>50,000 tons/yr	Teevin Bros. Land & Timber Co., LLC	Clatsop	42894 Old Highway 30	Astoria	97103	503 458-6671	20	8N	6W	46.1684	-123.4460
Square Creek Pit	>50,000 tons/yr	Bayview Transit Mix, Inc.	Clatsop	PO Box 619	Seaside	97138	503 738-5466	4, 9	5N	10W	45.9392	-123.9340
Johnsons Quarry	>50,000 tons/yr	Howard E. Johnson & Sons Construction Co.	Clatsop	85029 Hwy 101	Seaside	97138	503 738-7328	4	5N	10W	45.9508	-123.9220
—	20,000 to 50,000 tons/yr	Road Builders Inc.; David & Lisa McClean	Clatsop	37222 Linda Lane	Seaside	97138	503 738-5458	22	5N	8W	45.9036	-123.6580
Volmer Creek	20,000 to 50,000 tons/yr	Osburn Brothers Rock	Clatsop	PO Box 2069	Gearhart	97138	503 738-7709	14	5N	10W	45.9128	-123.8910
Griffith Quarry	20,000 to 50,000 tons/yr	Bayview Transit Mix, Inc.	Clatsop	PO Box 619	Seaside	97138	503 738-5466	22	5N	8W	45.9055	-123.6520
Rippet Pit	20,000 to 50,000 tons/yr	Howard E. Johnson & Sons Construction Co.	Clatsop	85029 Hwy 101	Seaside	97138	503 738-7328	4	5N	10W	45.9511	-123.9320
Riekkola Quarry	<20,000 tons/yr	Riekkola Quarry; Jon Riekkola	Clatsop	91640 Youngs River Road	Astoria	97103	503 440-0257	18	7N	8W	46.0897	-123.7280
Lighthouse Quarry	>50,000 tons/yr	Shiloh Forest Enterprises, Inc.	Tillamook	1500 Netarts Highway West	Tillamook	97141	503 842-8438	18	1S	10W	45.4792	-123.9610
190 Rock Pit	20,000 to 50,000 tons/yr	Fallon Logging Company, Inc.	Tillamook	PO Box 637	Tillamook	97141	541 994-5976	32	2S	10W	45.3592	-123.9330
Whiskey Creek Pit	20,000 to 50,000 tons/yr	S-C Paving Company	Tillamook	PO Box 535	Tillamook	97141	503 842-7541	20	2S	10W	45.3778	-123.9460
Ogle Quarry	20,000 to 50,000 tons/yr	Nesko Rock, Inc.	Tillamook	723 Evans Street	McMinnville	97128	503 472-8571	15	5S	10W	45.1392	-123.8860
Mt Meares Quarry 458	20,000 to 50,000 tons/yr	Shiloh Forest Enterprises, Inc.	Tillamook	1500 Netarts Highway West	Tillamook	97141	503 842-8438	28, 29	1S	10W	45.4597	-123.9230
Kimber Pit	<20,000 tons/yr	Kimber, Eugene	Tillamook	25000 Sandlake Rd.	Cloverdale	97112	503 965-6670	21	3S	10W	45.2947	-123.9110

(continued on next page)

Table A1. Oregon Quarry Rock Sites West of the Coast Range (continued)

Site Name	Production Level	Owner	County	Address	City	Zip	Phone	Section	Township	Range	Latitude	Longitude
Wilford Rock Quarry	>50,000 tons/yr	D.K. Quarries, Inc.	Tillamook	PO Box 10	Otis	97368	541 994-8584	7	5S	10W	45.1477	-123.952
Cochran Mill Site	20,000 to 50,000 tons/yr	Port of Tillamook Bay	Washington	4000 Blimp Blvd.	Tillamook	97141	503 842-2413	34	3N	6W	45.7047	-123.4170
Drift Creek	>50,000 tons/yr	Devils Lake Rock Company	Lincoln	2300 SE Highway 101	Lincoln City	97367	541 994-3641	1	8S	11W	44.9042	-123.9780
Iron Mountain Quarry	>50,000 tons/yr	ODOT	Lincoln	3700 SW Philomath Blvd.	Corvallis	97333	541 757-4211	20	10S	11W	44.6936	-124.0510
Eckman Creek Quarries	>50,000 tons/yr	Eckman Creek Quarries	Lincoln	PO Box 540	Waldport	97394	—	33	13S	11W	44.3910	-124.0330
Cedar-Creek Quarry	>50,000 tons/yr	Wienert, Bob	Lincoln	PO Box 730	Newport	97365	541 265-9441	4	9S	10W	44.8190	-123.9270
Fischer Pit	>50,000 tons/yr	Cedar Creek Quarries, Inc.	Lincoln	PO Box 730	Newport	97365	541 265-9441	14	8S	11W	44.8790	-124.0000
Mill Creek	20,000 to 50,000 tons/yr	Plum Creek Timberlands, L.P.; Andrew Dobmeier	Lincoln	PO Box 216	Toledo	97391	541 336-3819	24	9S	9W	44.7806	-123.7400
Siletz River Quarry	20,000 to 50,000 tons/yr	Kauffman, Morris E.	Lincoln	PO Box 124	Lincoln City	97367	541 994-2422	7	8S	10W	44.8872	-123.9480
Pankey Pit	<20,000 tons/yr	Cedar Creek Quarries, Inc.	Lincoln	PO Box 730	Newport	97365	541 265-9441	33	13S	11W	44.3980	-124.0280
Alsea Rock Quarry*	20,000 to 50,000 tons/yr	Alsea Quarries	Benton	PO Box 265	Alsea	97324	541 487-4783	18	14S	7W	44.3567	-123.5750
Camp Quarry	>50,000 tons/yr	Mapleton Rock Products, Inc.	Lane	PO Box 63	Mapleton	97453	541 268-0300	34, 35	17S	10W	44.0430	-123.8660
Wolf Creek*	>50,000 tons/yr	Roseburg Forest Products Company	Lane	PO Box 1088	Roseburg	97470	541 784-4504	8	19S	6W	43.9267	-123.4340
Swiss-home Rock Prod	>50,000 tons/yr	Lloyd S. Hockema, Inc.	Lane	PO Box 1085	Florence	97439	541 997-7328	30	17S	9W	44.0672	-123.8130
Nonpariel Quarry*	>50,000 tons/yr	Nicholls, Kenneth	Douglas	753 Choice Lane	Sutherlin	97479-9764	541 459-9247	10	25S	4W	43.4050	-123.1620
Parker Creek*	>50,000 tons/yr	Garrett Construction Co.	Douglas	PO Box 302	Drain	97435	541 836-2166	8	22S	6W	43.6681	-123.4340

(continued on next page)

Table A1. Oregon Quarry Rock Sites West of the Coast Range (continued)

Site Name	Production Level	Owner	County	Address	City	Zip	Phone	Section	Township	Range	Latitude	Longitude
Green Valley Quarry*	>50,000 tons/yr	J. Davidson & Sons Construction Co., Inc	Douglas	PO Box 1018	Oakridge	97463	541 782-4122	22	24S	6W	43.4708	-123.4110
Bear Creek Quarry*	>50,000 tons/yr	W.W.D. Corporation	Douglas	PO Box 276	Drain	97435 -0276	541 836-2166	24	22S	6W	43.6439	-123.3510
Weaver Site*	>50,000 tons/yr	B & B Roads, Inc.	Douglas	1086 Dairy Loop Road	Roseburg	97470 -9180	541 679-6754	23	28S	8W	43.1256	-123.6040
Payne Quarry*	20,000 to 50,000 tons/yr	Payne, Darrell G.	Douglas	5210 Eagle Valley Road	Yoncalla	97499	541 849-2179	28, 29	22S	5W	43.6294	-123.3130
Yoncalla Mt. Quarry*	20,000 to 50,000 tons/yr	Roseburg Forest Products Company	Douglas	PO Box 1088	Roseburg	97470	541 784-4504	19	22S	5W	43.6460	-123.3480
Smith's Quarry	>50,000 tons/yr	Lee Webster Excavating, Inc.	Coos	PO Box 938	Coos Bay	97420	541 267-5860	27	25S	12W	43.3731	-124.1060
Kentuck Pit	>50,000 tons/yr	Main Rock Products, Inc.	Coos	96521 Kentuck Way Lane	North Bend	97459	541 756-2623	34	24S	12W	43.4394	-124.1100
Kincheloe Quarry	>50,000 tons/yr	Kincheloe & Sons, Inc.	Coos	PO Box 296	Myrtle Point	97458	541 572-5249	36	29S	11W	43.0100	-123.9580
Ansley Pit	>50,000 tons/yr	Main Rock Products, Inc.	Coos	96521 Kentuck Way Lane	North Bend	97459	541 756-2623	21	28S	12W	43.1245	-124.1420
Weekly Quarry	>50,000 tons/yr	Coos County Highway Department	Coos	250 North Baxter	Coquille	97423	541 396-3121	14	29S	12W	43.0622	-124.0840
Kenstone Quarry	>50,000 tons/yr	Coos Bay Timber Operators	Coos	PO Box G	North Bend	97459	541 756-6254	26	24S	12W	43.4536	-124.0870
Leep Quarry	20,000 to 50,000 tons/yr	Roseburg Resources Company	Coos	PO Box 1088	Roseburg	97470	541 679-3311	30	28S	12W	43.1150	-124.1630
Davis Pit	20,000 to 50,000 tons/yr	Davis, Gary	Coos	54962 Brady Road	Myrtle Point	97458	541 572-2597	21	28S	12W	43.1230	-124.1390
King Ranch	20,000 to 50,000 tons/yr	King, Dal	Coos	54041 Weekly Creek Road	Myrtle Point	97458	541 572-2640	11	29S	12W	43.0666	-124.0910
Wahl Site	>50,000 tons/yr	LTM, Inc.	Curry	PO Box 1145	Medford	97501	541 770-2960	17	32S	15W	42.8036	-124.5010
94607 Floras Creek Road	20,000 to 50,000 tons/yr	Stonecypher Ranch, Inc.	Curry	PO Box 328	Sixes	97476	541 348-2432	2	31S	15W	42.9120	-124.4370

*Site not shown in Figure 47/Figure 48.

Table A2 lists, by county from north to south, Oregon gravel pits from which naturally rounded, cobble-sized material can be produced. (Also see Figures 47 and 48 for quarry locations and Appendix B for the location of GIS files from which this table was produced.) Round rock is not common in the coastal area, so sources east of the Coast Range and west of the Cascades are included. Some sites have direct loading to rail or barge, some could probably obtain intermittent rail access, and others require truck haulage to a railhead or to the project itself.

Table A2. Oregon Round Rock Quarry Sites West of the Coast Range

Site Name	Owner	County	Address	City	Zip	Phone	Section	Township	Range	Latitude	Longitude	Comment
Deer Island	Morse Brothers, Inc.	Columbia	32260 Highway 34	Tangent	97389	541 928-6491	6	5N	1W	45.94099	-122.84987	rail access
Santosh	Glacier Northwest	Columbia	1050 N River Street	Portland	97227	503 335-2600	31	4N	1W	45.78210	-122.85044	rail access
Richold / Waterview	Morse Brothers, Inc.	Columbia	32260 Highway 34	Tangent	97389	541 928-6491	17	5N	1W	45.91723	-122.83151	rail access
Stayton Rock Plant Site/East Pit	Morse Brothers, Inc.	Linn	32260 Highway 34	Tangent	97389	541 928-6491	14, 15	9S	1W	44.78720	-122.80000	
Stayton - Bethell Site	Morse Brothers, Inc.	Linn	32260 Highway 34	Tangent	97389	541 928-6491	15	9S	1W	44.78300	-122.79440	
Round Prairie Pit	Beaver State Sand and Gravel, Inc.	Douglas	PO Box 1427	Roseburg	97470	541 679-6744	35	28S	6W	43.09030	-123.37640	deposit nearly ex-hausted
Smith Bar	Tri-City Ready Mix, Inc.	Douglas	PO Box 1344	Roseburg	97470	541 874-3141	33, 34	30S	6W	42.92580	-123.42360	
Umpqua River	LTM	Douglas	PO Box 1145	Medford	97501	541 770-2960	1	22S	11W	43.68217	-123.95256	
Broadbent	LTM	Coos	PO Box 1145	Medford	97501	541 770-2960	4, 5, 7, 8	30S	12W	42.99129	-124.15124	
Elk River (Wahl / McKenzie)	LTM	Curry	PO Box 1145	Medford	97501	541 770-2960	17	32S	15W	42.80748	-124.50519	
Steam Beer Mine	Steam Beer Mining Ltd	Josephine	4449 Lower Grave Creek Road	Sunny Valley	97497	541 479-7884	6	34S	6W	42.64240	-123.44850	intermit-tent stockpile, rail access possible
Kirtland Road Pit	Rogue Ag-gre-gates, Inc.	Jackson	PO Box 4430	Medford	97501	541 664-4155	15, 16, 21, 2	36S	2W	42.43000	-122.93530	rail access

APPENDIX B

The following database files, available on CD, can be used in a geographical information system (GIS) to display locations of quarries west of the Willamette Valley capable of producing gravels suitable for constructing a dynamic revetment. The data were compiled from the DOGAMI's Mineral Land Regulation and Reclamation (MLRR) database, from the Mineral Information Layer for Oregon (MILO) database, and from site visits and personal and telephone conversations with members of the aggregate industry.

Quarry_Rock lists quarries meeting the following criteria:

- Production of at least 50,000 tons of quarry rock over the last five years
- Production of at least 20,000 tons in one year of the last five years
- Location west of the approximate crest of the Coast Range

Round_Rock lists gravel pits from which naturally rounded, cobble-sized material can be produced. Round rock is not common in the coastal area, so sources east of the Coast Range and west of the Cascades were included. Some sites have direct loading to rail or barge, some could probably obtain intermittent rail access, and others would require truck haulage to a railhead or to the project itself.

These files have been plotted in the Oregon Lambert, 1997, feet projection system. The complete set of files includes:

Quarry_Rock – Quarry rock database
Round_Rock – Round rock database
STATE_OUTLINE – Map outline of the state of Oregon
COUNTYA – Text file listing Oregon county names
COUNTYL – Oregon county polygons
STATE_PARKS – Oregon state park locations
RIVERS – GIS database of Oregon rivers
RAILWAY2004 – Railway lines
HWYS_interst – Oregon Interstate highways
HWYS_major – Major Oregon highways
HWYS – Other Oregon highways