DYNAMIC REVETMENTS FOR COASTAL EROSION IN OREGON

Final Report

SPR 620

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by

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16. Abstract

Gravel beaches have long been recognized as one of the most efficient forms of "natural" coastal protection, and have been suggested as a form of shore protection. "Cobble berms," "dynamic revetments" or "rubble beaches" involve the construction of a gravel beach at the shore, in front of the property to be protected. These structures are effective in defending properties because the sloping, porous cobble beach is able to disrupt and dissipate the wave energy by adjusting its morphology in response to the prevailing wave conditions. Dynamic revetments are much easier and cheaper to construct than a conventional riprap revetment or seawall. They are also aesthetically pleasing compared with "hard" engineered solutions. There remain, however, unanswered questions about their design particularly along the high-energy Oregon coast – the sizes and types of gravel to be used, their slopes and crest elevations, the volume of material to be included in the berm, and where the material may be obtained to construct such features.

This study involved an examination of the morphological and sedimentary characteristics at 13 naturally occurring gravel beach study sites along the Oregon coast. Heights of the gravel beaches ranged from 5.7 to 7.1 m (19-23 ft), while the slopes of the beaches varied from 7.7º to 14.1º. Mean grain-sizes were found to range from -4.9Ø (30 mm) to -7.0Ø (128 mm), and were classified as well sorted to moderately well sorted. However, a comparison of these parameters among stable versus eroding gravel beaches revealed no clear discernable pattern. A key difference in the stability of the gravel beaches was the volume and width of gravel contained on the beach, with beaches containing larger volumes of gravel (> 50 $m^3.m^{-1}$ (538 $ft^3.ft^{-1}$)) and larger widths (> 20 m (66 ft)) being the most stable. Based on this analysis, a crest elevation of ~7.0 m (23 ft), mean grain-size of no less than -6.0Ø (64 mm), and a beach slope of 11º was recommended in future designs of dynamic revetments for the Oregon coast.

While numerous quarry sites were identified that could supply crushed rock for the building of a dynamic revetment, rounded gravels were more difficult to locate and tended to be located farthest from the coast, increasing the costs that would be incurred to transport the material.

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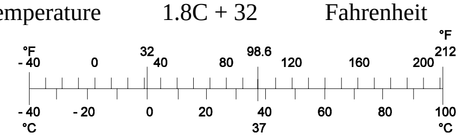
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
In	Inches	25.4	Millimeters	Mm
Ft	Feet	0.305	Meters	M
Yd	Yards	0.914	Meters	M
Mi	Miles	1.61	Kilometers	Km
		AREA		
In^2	square inches	645.2	Millimeters squared	mm^2
ft^2	square feet	0.093	Meters squared	m^2
Yd^2	square yards	0.836	Meters squared	m^2
Ac	Acres	0.405	Hectares	Ha
Mi^2	square miles	2.59	Kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
Gal	Gallons	3.785	Liters	L
ft^3	cubic feet	0.028	Meters cubed	m^3
Yd^3	cubic yards	0.765	Meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
Oz	Ounces	28.35	Grams	G
Lb	Pounds	0.454	Kilograms	Kg
T	short tons (2000 lb)	0.907	Megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8C + 32	Fahrenheit	°F



***** SI is the symbol for the International System of Measurement (4-7-94 jbp)

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We are also grateful to the members of the Technical Advisory Panel for their comments on the draft report.

DISCLAIMER

An example of cross-shore sorting of sediments at Cove Beach, Oregon

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EXECUTIVE SUMMARY

Researchers have long recognized 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. As a result they have been suggested as a form of shore protection. Such structures are variously termed “dynamic revetments,” “cobble berms” or “rubble beaches.” The approach essentially involves the construction of a gravel beach at the shore, in front of the property to be protected. The dynamic structure is effective in defending properties because the sloping, porous cobble beach is able to disrupt and dissipate the wave energy by adjusting its morphology in response to the prevailing wave conditions.

Dynamic revetments are also significantly easier to construct than a conventional riprap revetment or seawall. This is strongly aided by the fact that the particle sizes used in the construction are smaller and generally less expensive than the large armor stones, while placement of the gravels does not require any special 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. Thus 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 a number of events that resulted in the cobble berm and artificial dune being over-topped. Damage to the structure has been minimal, suggesting that these types of structures may be a viable alternative to “hard” engineering solutions in the Pacific Northwest. However, there remain a number of uncertainties concerning the physical design of dynamic revetments, especially on a high-energy beach whereby the cobble berm is fronted by a dissipative sand beach, and in terms of acquiring suitable quantities of gravel for construction and any follow-up maintenance that may be required to periodically “top-up” such structures.

This study had two key objectives:

- Undertake an assessment of 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 could be made with respect to the design of a dynamic revetment.

- 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 sediments 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, characterized by well-vegetated backshores. Most of the stable gravel beach sites can be found on the northern Oregon coast, while sites exhibiting evidence of backshore erosion tended to be concentrated on the central to 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 was no clear discernable 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 – 23 ft), while the recommended 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 for 5% of the time, the T_{WL} exceeds an elevation of 6.0 m (20 ft), while the 7.0 m height was exceeded for only 1% 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 (20 ft). However, it is important to appreciate that such a structure would be periodically over topped, as has occurred on occasion at CLSP (*Komar, et al. 2003*; *Allan, et al. 2004*).

- Mean grain sizes were found to range from -4.9Ø (30 mm) to -7.0Ø (128 mm) on the north coast, and the sediments were generally classified as well sorted to moderately well sorted. We therefore recommend that the mean particle size should be no less than -6.0Ø (64 mm) in size.

- 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, while the average slope was found to be 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 [~28 m (~92 ft)] and correspondingly larger volumes of gravel [~77 $m^3.m^{-1}$ (~830 $ft^3.ft^{-1}$)] when compared with the central to south coast gravel beaches, which are characterized by widths and volumes that are respectively 35% to 57% 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 based on an understanding of a design berm width.

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

Perhaps a major constraint that likely limits the adoption of dynamic revetments as a viable engineering solution on the Oregon coast is the identification of suitable gravel sources that could be utilized in the construction and maintenance of such structures.

- Our review of existing gravel quarries capable of producing rounded particles appears to reinforce the perception that these types of gravels are scarce in Oregon, being much more common in Washington State. Only five gravel quarry sites could be identified on the central to northern Oregon coast capable of producing "rounded" gravels in the -6Ø (64 mm) range; 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 44). In contrast, there are potentially seven sites on the south coast that could provide suitable gravels for the construction of a dynamic revetment, with the Elk River, Broadbent and Umpqua sites being closest to the coast (Figure 45).

- Quarries capable of producing crushed gravels of a particular size are more common, a number of which are located adjacent to major towns or transportation hubs (e.g., Astoria, Tillamook, Newport, and Coos Bay). As indicated in Figures 44 and 45, a significant number of these quarries are capable of producing ~50,000 tons of crushed rock annually.

- There are no quarries capable of producing crushed rock south of Port Orford.

- Production of cobble-sized 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, 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, necessarily an indefinite figure dependent in part on what modifications of production procedures would be required.

- Truck transportation costs average about $0.75 per ton per mile for hauls of a few tens of miles. However, transportation costs are dependent on a variety of factors including travel time, distance of travel, equipment type and on 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, approximately 210 miles 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.

- 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. However, this does not include port, stevedoring, stockpiling, storage, or possible demurrage fees, nor 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.

- Analyses of the along shore 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,

- More 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 include the following:
    - Cape Lookout State Park, Tillamook County;
    - Spencer Creek Bridge, Lincoln County; and
    - Hooskanaden Creek, Curry County.

1.0 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. However, there are concerns over the likely effects of such structures, including their unnatural appearance that can mar the beauty of the coast, and the potential for such structures to cause adverse impacts to adjacent unprotected properties. This latter problem, termed "*active erosion*," encompasses a variety of potential impacts, including a) enhanced toe-scour due to the reflection of wave energy from the structure; and b) transfer of wave energy to the adjacent unprotected ends of the structures, resulting in erosion in those locations (termed "*end effect*") (*Griggs, et al. 1994*; *Kraus and McDougal 1996*). Given sufficient numbers, coastal structures may also impact the stability of beaches, since the structures essentially impound the sediment contained behind them, material that would otherwise have been available to the beach sediment budget. As a result, such structures may eventually result in further losses of the public beach, 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*).

Important for minimizing such negative impacts is the testing of "soft" engineering alternatives that attempt to replicate nature by slowing the erosion to an acceptable rate while eliminating or reducing scour and beach sediment losses. One such approach is the use of a "dynamic revetment" or "cobble berm," which is in essence the construction of a cobble beach that can be effective in dissipating the wave energy and protecting shore-front 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 and Development Center (ERDC) of the US 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 on the northern Oregon coast 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 the design of dynamic revetments did not address the setting of the Oregon coast where a sand beach fronts the cobble structure. Instead, the design of the dynamic revetment in Cape Lookout State Park was based primarily on the slopes, cobble sizes, and elevations of a natural cobble beach found in the park. There are many examples of natural cobble beaches along the Oregon coast, a number of which provide protection to properties atop sea cliffs and foredunes. Additional research of those beaches, expanding on the study presently limited to Cape Lookout State Park, would greatly facilitate the design and application of future dynamic revetments for the protection of Oregon's coastal highways.

Important also is the evaluation of availability of cobble-size material to use for construction of dynamic revetments. For example, an initial data search for stream gravel sources by DOGAMI in 2003 revealed that significant erroneous information exists, demonstrating the need for the creation of a more accurate and up-to-date database of potential sources that may provide suitable coastal erosion remediation materials. Thus, an evaluation of the distribution and morphological characteristics of cobble beaches along the Oregon coast and sources of gravel-size materials are necessary in order to provide an understanding of:

- The existing cobble beach geomorphology (i.e., cobble beach slopes, crest elevations and alongshore variability, grain size characteristics and temporal and spatial characteristics of the beach) and the processes (e.g., waves and tides that may impact the beaches) that characterize the Oregon coast; and

- The potential sources of cobbles that may be used to construct a dynamic revetment, and the associated estimated costs to transport the material to a particular site.

This study had three key objectives:

Objective 1: Undertake a field study devoted to the collection of geological and oceanographic data on naturally occurring cobble beaches along the Oregon coast. This included:

- Identification of the spatial distribution of naturally occurring cobble beaches on the Oregon coast and assessment of the stability of these beaches (i.e., evidence for erosion);
- Establishment of beach profile surveys at selected study sites to evaluate beach slopes and crest elevations;
- Measurements of cobble sizes and sorting patterns along each beach profile; and,
- Model calculations of expected wave-swash runup elevations during major storms.

These data will be extremely useful in 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 cobble material in sufficient quantities for use along Oregon's highways. Appropriate Oregon, Washington, and Canadian resources were examined. These data were contrasted with the feasibility and cost effectiveness of generating cobble-size material from crushed rock. An accurate spatial database of natural and man-made cobble sources was developed for coastal remediation.

Objective 3: Produce a report that synthesizes the results of this study, with emphasis on the development of improved design criteria for dynamic revetments and cost-benefit assessments of cobble sources for the construction of such structures on the Oregon coast to protect the State's highways.

2.0 BEACH PROCESSES ON THE OREGON COAST

2.1 INTRODUCTION

The Oregon coast is approximately 360 miles in length (Figure 2.1) and can be broadly characterized as consisting of long stretches of sandy beaches that are bounded by resistant headlands. These types of systems are referred to as littoral cells (*Komar 1997*), and include both a cross-shore (littoral zone, Figure 2.2) and a longshore extent. There are at least 18 major littoral cells identified on the Oregon coast (Figure 2.1), with the majority of the shoreline (72%) consisting of dune-backed sandy beaches, while the remaining 28% of shore is comprised of a mixture of bluff-backed beaches, rocky shores, and coarse grained (gravel) beaches. Because the headlands extend into deep water, wave processes are generally regarded as unable to transport beach sediment around the ends of the headlands. As a result, the headlands essentially form a natural barrier for sediment transport, preventing sand exchange between adjacent littoral cells. Thus, a littoral cell is essentially a self-contained compartment, deriving all of its sediments from within that cell.

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

1) Promoting the supply of sediments to the beach system for beach construction;
2) Transferring sediments through the system; and
3) Ultimately, the removal of sediments through the process of erosion.

The response of beaches along the Oregon coast is largely dependent on the occurrence of high magnitude events such as those that occurred during the March 2-3 1999 storm (*Allan and Komar 2002*), or in response to enhanced periods of storm activity such as the 1982-83 and 1997-98 El Niños, and 1998-99 winters. Collectively, these events resulted in some of the most significant examples of coastal retreat observed during the past three decades. For example, dune erosion averaged about 11.5 m (38 ft) to 15.6 m (49 ft) during the late 1990's along the Neskowin and Netarts littoral cells respectively, and as much as 55 m (180 ft) in some locations, damaging those properties located adjacent to the eroding shore (*Allan, et al. 2004*). Farther south, the erosion along the Garrison Lake shoreline near Port Orford was especially acute, resulting in the retreat of beaches there by some 100 to 120 m (328 – 394 ft). Much of the erosion during the 1998-99 winter was likely caused by four 100-year storms that generated significant wave heights in excess of 10 m (33 ft). Longer term adjustments may also be perceived in the beaches and may be related to a change in sea level. However, existing attempts to quantify this last process suggest that erosion due to sea level rise is likely to be quite low (*Allan, et al. 2003*).

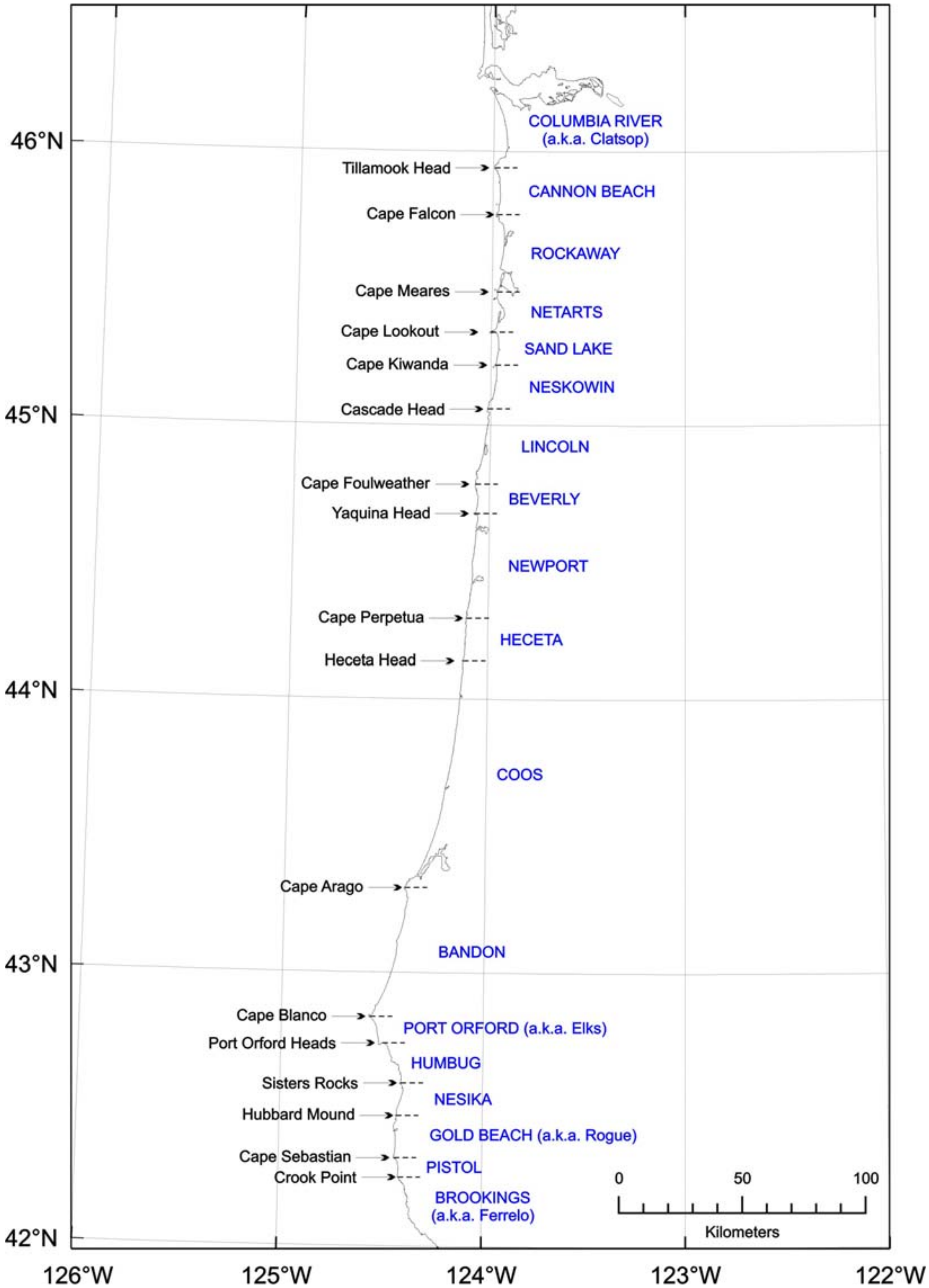

Figure 2.1: Map of the Oregon coast identifying the various littoral cells

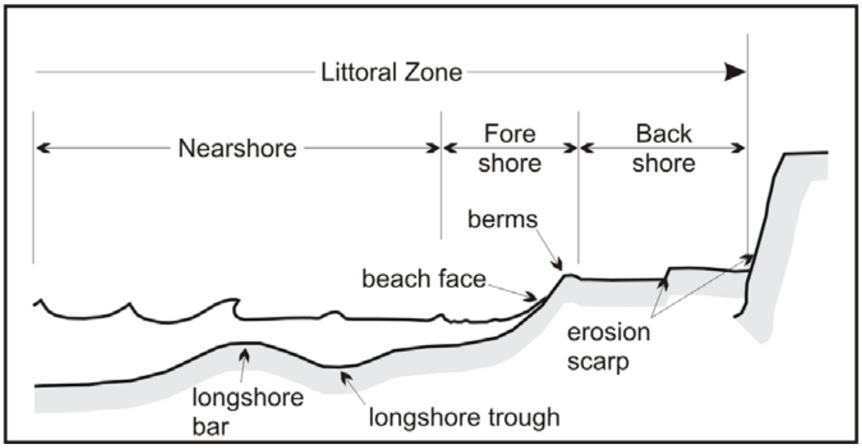

Figure 2.2: Terminology used to define aspects of the beach (*Komar 1998b*). The backshore is composed of some combination of a foredune, a foredune backed by a dune field, or a bluff. The erosion scarp typically lies on the seaward edge of the foredune or bluff.

Terminology used to describe the form of a beach is shown in Figure 2.2. As indicated, a typical beach cross-section comprises both a sub-aerial component (the beach foreshore and backshore) and an underwater component that includes the nearshore and offshore zones. Furthermore, the visible sandy foreshore comprises only a small portion of an onshore-offshore sand exchange system that extends well to seaward. Thus, the cross-shore extent of the littoral zone extends from the backshore (which may encompass a dune field, beach ridge, sea-cliffs etc.), seaward to some limiting depth where underwater bed changes tend to be minimal. The seaward limit of onshore-offshore sand exchange can be estimated empirically using formulas developed by coastal engineers based on 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 – 14 m (33 – 46 ft).

2.2 LONGSHORE SEDIMENT TRANSPORT

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

Along the Oregon coast the role of longshore currents is especially important due to a seasonal variation in the direction of wave approach between summer and winter (Figure 2.3A). During a "normal year," summer waves approach the coast from the northwest, driving sediment towards the southern ends of Oregon's littoral cells. This process is further aided by strong north to northwesterly winds that develop throughout the summer that are further capable of transporting large volumes of sand and fine gravel towards 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, which is now directed toward the north and can erode the beaches. Thus, over several normal years there is a net equilibrium balance so that the net sediment transport is close to zero (i.e., there is no net long-term build up (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, it is unlikely to be the case for gravels. This is because the energy flux required to transport gravels and cobbles is significantly greater and because the waves may only reach the cobbles during the winter. As a result, it can be expected that on the Oregon coast coarse sediments may preferentially move in one direction during the winter months, but they are unlikely to return towards the same direction from which they originally came.

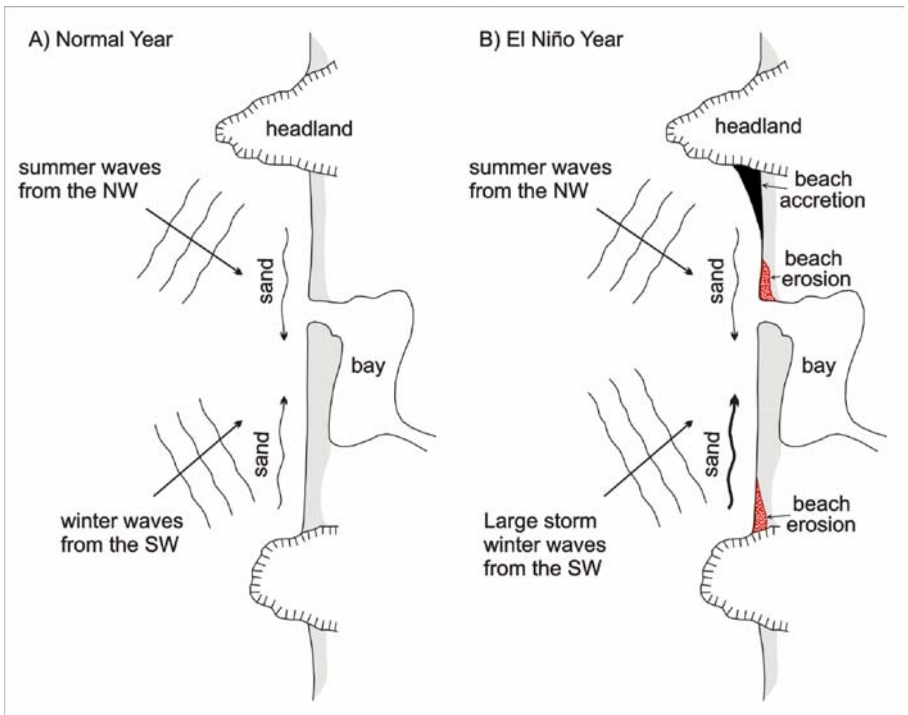

Figure 2.3: Alongshore-seasonal movement of beach sediments on the Oregon coast for A) a typical year and B) an El Niño year (*Komar 1998a*)

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

El Niños impact Oregon's beaches in a variety of ways, most notably by elevating the mean water levels, causing the measured tides to be much higher than usual. Under normal conditions, the Oregon coast experiences a seasonal variation in its monthly mean water levels. During the summer water levels tend to be lowest, a result of coastal upwelling that produces cold, dense water, which depresses water levels along the coast. With the onset of winter, the upwelling process breaks down and ocean temperatures are much warmer, and its 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, et al. 2003*). During an El Niño, however, ocean temperatures are further enhanced due to the release of a warm pool of ocean water that emanates from the tropics. The arrival of this warm pool along the Oregon coast during the winter 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.

Aside from changes to the mean water levels along the coast, during an El Niño there is also a southward displacement of the storm tracks so they mainly cross the coast of central California (*Seymour 1996*). As a result, storm waves reach the Oregon coast from a more southwesterly quadrant, creating an abnormally large northward transport of sand within its littoral cells. This creates "hotspot" erosion at the southern ends of the cells, north of the bounding headlands and also north of migrating inlets, shown conceptually in Figure 2.3B. The opposite response is found south of the headlands, where the northward displaced sand accumulates, causing the coast there to locally advance seaward (Figure 2.3B).

A detailed documentation of this northward sand displacement and hotspot erosion became possible during the 1997/98 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 Administration (NASA) to collect topographic data (position and elevation) of the beach. Additional information on LIDAR and its application can be found at the NOAA Coastal Service Center website (http://www.csc.noaa.gov/crs/tcm/index.html) and is discussed in detail by Brock, et al. (*2002*) and Stockdon, et al. (*2002*).

Analyses by Revell, et al. (*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, et al. (*2003*) undertook additional analyses of the LIDAR data in the Netarts cell, quantifying the "hotspot" erosion effect along the south end of the cell (Figure 2.4). Apparent in the figure is the concentrated zone of erosion along the southern 3 kilometers (1.9 miles) of shoreline, where negative values indicate erosion while positive values indicate accretion. The "hotspot" erosion effect is greatest along the southern 1 – 2 kilometers (0.6 – 1.2 miles) of the coast where it reaches about -20 m (-65 ft) and progressively decreases northward along the spit. Figure 2.4 also demonstrates the northward transport of sediment along the cell, as conceptualized in Figure 2.3, with the shoreline having prograded seaward by some 10 m (33 ft) along the northern extent of the spit, and by several meters north of the mouth of Netarts Bay.

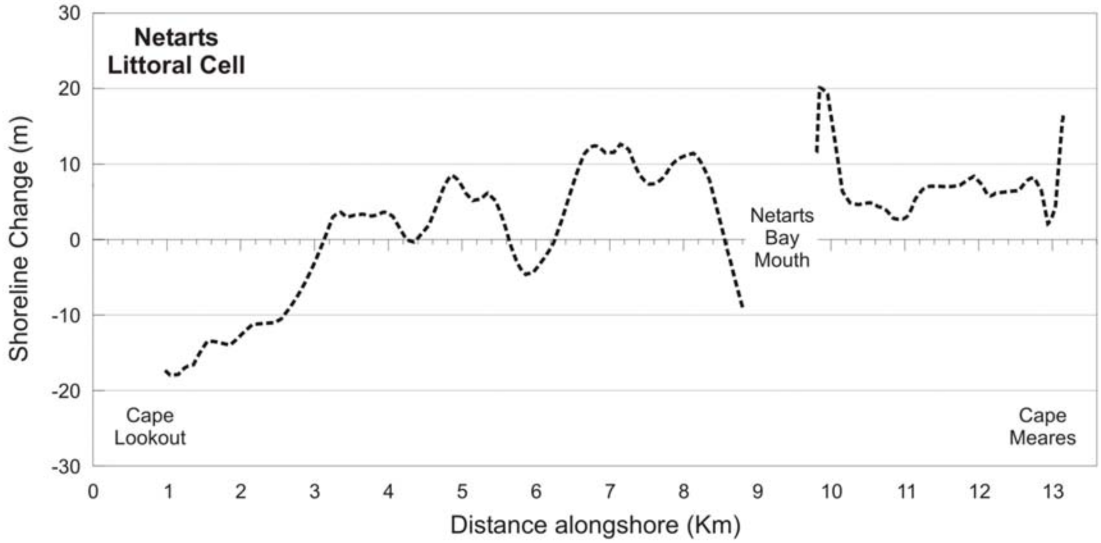

Figure 2.4: Example of the "hotspot" erosion effect identified in the Netarts littoral cell in Tillamook County (after *Allan, et al. 2003*)

2.3 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 also characterized by strong winds, the two factors that account for the development of large wave heights and long wave periods (*Tillotson and Komar 1997*). These storm systems originate near Japan or off the Kamchatka Peninsula in Russia, and typically travel in a southeasterly direction across the North Pacific towards the Gulf of Alaska, eventually crossing the coasts of Oregon and Washington or along the shores of British Columbia in Canada (*NMC 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 northwards so that only a few storms approach the PNW, and those that do tend to be weak. While storm waves during the summer months are relatively rare (i.e., locally generated wind waves predominate throughout the summer), long period swell waves may still be experienced throughout the summer. These latter waves are likely generated by storms located in the far North Pacific (e.g., near the Aleutians) or from storm systems that develop in the Southern Hemisphere during their winter (e.g., winter storms that occur offshore from the New Zealand coast).

With the onset of winter, the Pacific High is displaced to the south, 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 PNW. These storm systems develop in the form of rapidly moving intense frontal systems, or low pressure systems, and periodically as severe outbreaks, or extratropical "bombs" that develop rapidly and are characterized by a dramatic drop in atmospheric pressure (typically greater than 24 mb over a 24 hour period) (*Sanders and Gyakum 1980*). Although North Pacific storms rarely acquire wind strengths comparable to hurricanes, their influence is often more widespread, affecting stretches of coast up to 1,500 km in length and can produce extreme wave heights (significant wave heights of 10 to 14 meters) on a fairly regular basis during the winter months.

2.3.1 Wave Climate Characteristics

Wave statistics (heights and periods) and some meteorological information have been measured in the North Pacific using wave buoys and sensor arrays since the mid 1970s. These data have been collected by 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. However, there are currently no active CDIP buoys operating along the Oregon coast. In addition, the CDIP datasets tend to be characterized by short bursts of sampling (i.e., project specific) and long durations of no measurements so that the data tends to have significant gaps in the records. As a result, for the purposes of this report the CDIP dataset has not been used. 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 20 – 30 miles from the Oregon coast (Figure 2.5), with a fourth buoy having recently been installed by NOAA approximately 70 miles west of Tillamook. Table 2.1 describes the general characteristics of each of the wave buoys, and includes their World Meteorological Organization station names, locations, water depths, and type of buoy. 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*), and a slight decrease in the wave heights by the time one reaches the Columbia River buoy in the north (*Allan and Komar 2000*). Thus an assessment of the wave-swash runup elevations during major storms was based on wave statistics derived from the Newport buoy. These latter calculations were used to compare the crest elevations of the cobble beaches with the swash elevations and will be discussed in more detail in the results section.

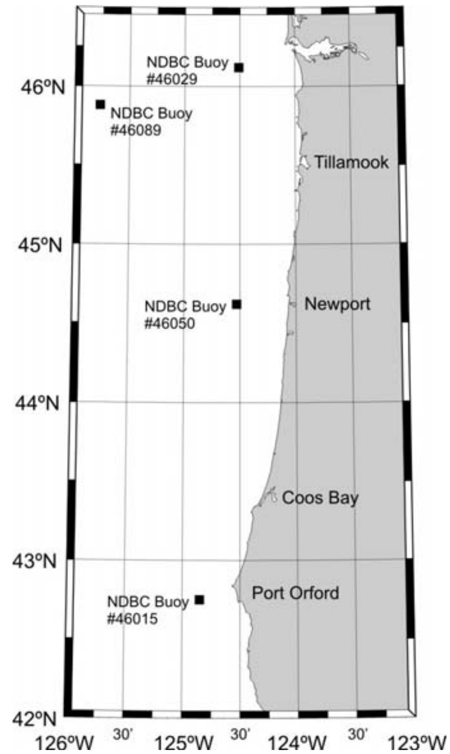

Figure 2.5: Location of NDBC wave buoys

Table 2.1: Wave buoy site characteristics

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

There is a strong seasonality to the wave climate along the Oregon Coast, with the strongest storms and largest generated waves occurring in the winter months. This has been shown, for example, by Tillotson and Komar (*1997*) and Allan and Komar (*2000a*). Figures 2.6 and 2.7 present the monthly average deep-water significant wave heights (H_S) and peak spectral wave periods (T_P) for the Newport (NDBC # 46050) buoy. The graphs clearly show a prominent cycle in the mean monthly wave heights and peak wave periods. Waves are characteristically smallest (<2.0 m (6.6 ft)) between May and September, reaching a minimum in August (Figure 2.6). The range (+/-1 standard deviation) of wave heights during July and August is generally less than 0.15 m (0.5 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 - 13.1 ft). However, during major winter storms, wave heights in excess of 7 m (23 ft) are not uncommon, with the most extreme storms producing deep-water significant wave heights on the order of 14 to 15 m (45.9 – 49.2 ft) (*Allan and Komar 2002*). A similar pattern can be seen for the peak wave periods (Figure 2.7), such that during the summer the periods are typically less than ~10 sec, reaching a minimum of 8.3 sec in July. Wave periods tend to be longest in December and January and range from 12 to 14 sec on average and may reach as much as 25 seconds during major storms.

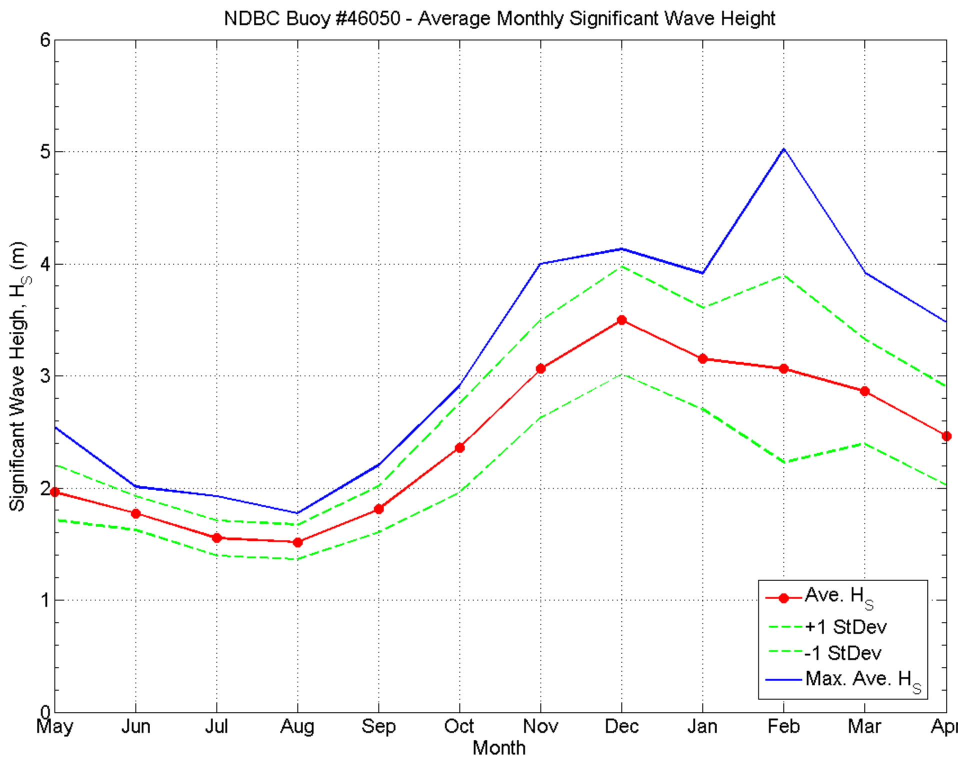

Figure 2.6: Monthly averages of the significant wave height (1987 – 2004). The graph shows the average monthly significant wave height, the monthly average maximum significant wave height, and the range (+/- 1 standard deviation) for each month.

Beginning with the 1997-98 winter, an El Niño, the Oregon coast experienced over 20 large storms when the deep-water significant wave heights exceeded 6 m (20 ft) for 9 hours or longer (*Allan and Komar 2000b*); prior to the 1997/98 winter the maximum number of storms experienced using the above criteria was 10 – 12, which occurred in the early 1980s, highlighting the unusual nature of the 1997/98 winter. These storms affected shipping and produced considerable beach and property erosion along the coasts of Oregon and Washington. Based on wave data up through 1996, Ruggiero, et al. (*1996*) had calculated the 100-year storm wave to be around 10 m (33 ft) for the Oregon coast. A storm on 19-20 November 1997 exceeded that projection. Wave conditions were far worse during the following 1998/99 La Niña winter, 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 2-4 March 1999, generating 14.1 m (46 ft) deep-water significant wave heights. Thus, the PNW received a "one-two punch" from the successive El Niño and La Niña winters, with severe cumulative erosion of the coast (*Allan and Komar 2002*). 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, et al. 2003*). This latter process, however, is much slower so that the foredunes may take several years to a few decades to rebuild.

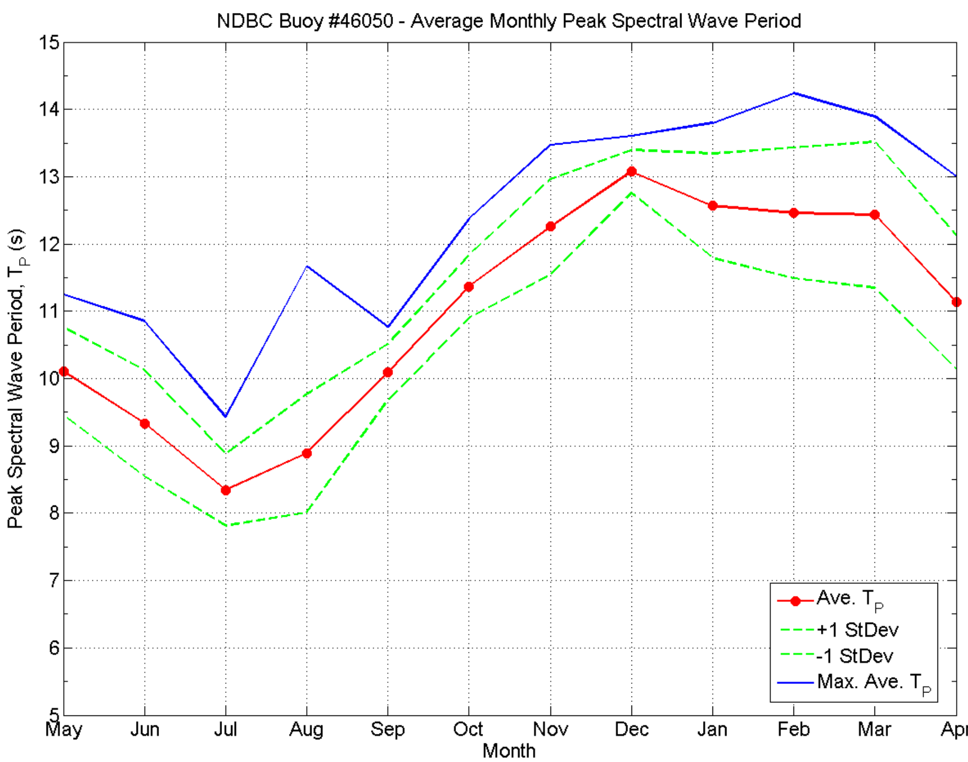

Figure 2.7: Monthly averages of the peak spectral wave period (1987 – 2004). The graph shows the average peak spectral wave period , the monthly average maximum peak spectral wave period , and the range (+/- 1 standard deviation) for each month.

Unfortunately, our confidence in the wave direction information is less certain, as there is much less data on wave direction offshore from Oregon, mainly because these data have only recently begun to be compiled, and because of a dearth in instrumentation sites along the U.S. West Coast. Nevertheless, as a general rule it is understood that during the winter, waves typically arrive from the west or southwest, while in the summer the predominant wave direction is from the northwest, and is largely determined by the local wind regime (*Komar 1997*).

2.4 TIDES

Measurements of tides on the Oregon coast are available from gauges located at four locations: the Columbia River (Astoria), Yaquina Bay (Newport), Charleston (Coos Bay) and Port Orford. The long-term record from Crescent City, California, is also useful in analyses of tides on the southern Oregon coast. 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 2.8). 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 2.8 shows the daily tidal elevations derived from the Newport tide gauge (#9435380). Tides at Newport have a mean range[1] of 1.9 m (6.27 ft) and a diurnal range[2] of 2.54 m (8.34 ft). The highest tide measured at Newport reached 3.73 m (12.25 ft) and was recorded in November 1969.

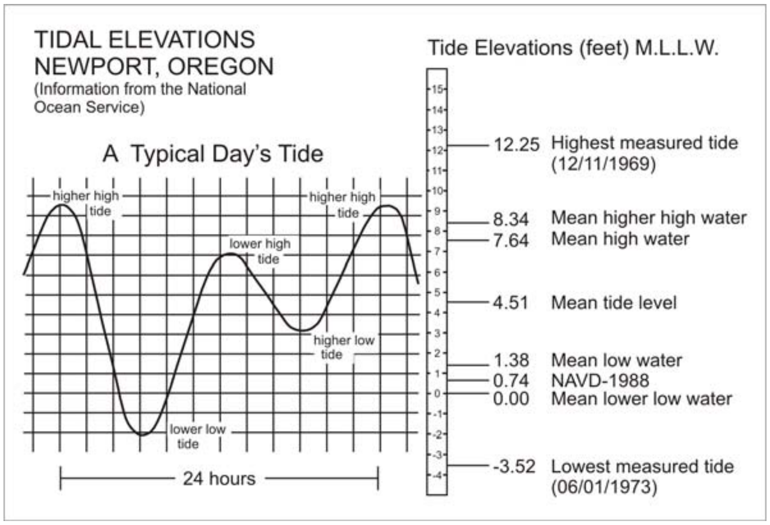

Figure 2.8: Daily tidal elevations measured in Newport on the central Oregon coast. Data from the National Ocean Service (http://www.co-ops.nos.noaa.gov/).

The actual level of the measured tide can be considerably higher than the predicted level provided in standard Tide Tables. It is a function of a variety of atmospheric and oceanographic forces, which ultimately combine to raise the mean elevation of the sea. These latter processes also vary over a wide range of timescales and may have quite different effects on the coastal environment. For example, strong onshore winds coupled with the extreme low atmospheric

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

pressures associated with a major storm can cause the water surface to be raised along the shore as a storm surge. However, during the summer months these processes can be essentially ignored due to the absence of major storm systems. The El Niño climate phenomena may also super-elevate 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 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 2.9), derived from the Newport tide gauge, but where the averaging process has removed the water-level variations of the tides, yielding a mean water level for the entire month. Based on 36 years of data, the results in Figure 2.9 show that on average, monthly-mean water levels during the winter are 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 occurred particularly during the unusually strong 1982-83 and 1997-98 El Niños; as seen in Figure 2.9, water levels during those climate events 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 would be elevated by that amount, low tides as well as high tides, enabling wave swash processes to reach much higher elevations on the beach.

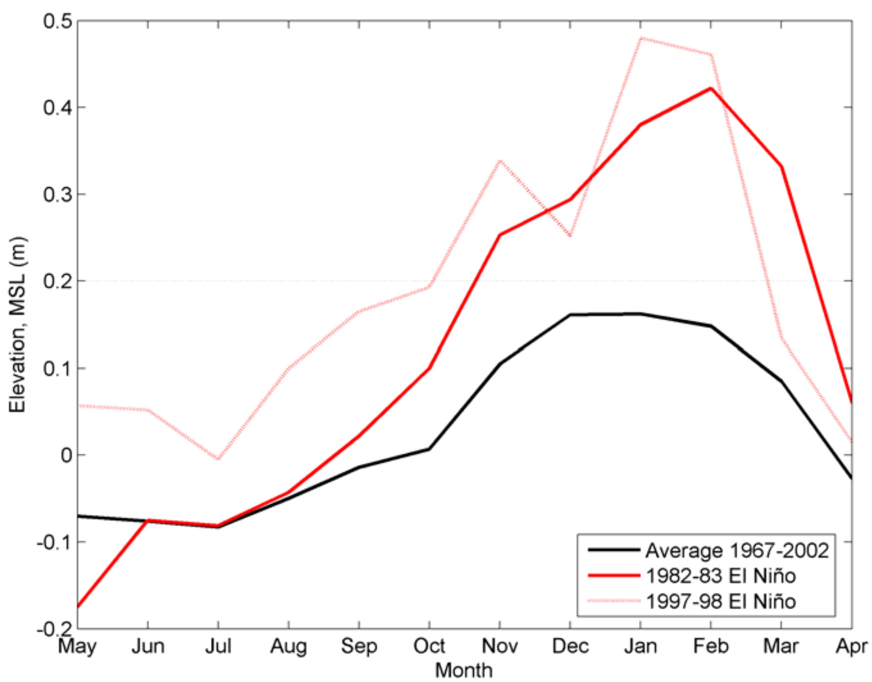

Figure 2.9: Mean monthly tides determined from the Port Orford tide gauge, Oregon expressed as a long-term average and as monthly averages for the 1982-82 and 1997-98 El Niños.

3.0 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.

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 and the range of metamorphic rocks — schist and gneiss. Other rock sources supply coarse-grained material to the beach, ranging from pebbles to cobbles, and even boulders. However, in contrast to pure sand beaches the level of research directed at understanding the morphology and response of coarse beaches to coastal processes is comparatively lower.

Jennings and Shulmeister (*2002*) identified three predominant beach categories, while Horn and Walton (*in review*) and Komar (*2005*) have noted two additional beach categories, with each category being dependent on their mixtures of grain sizes. These include:

a) **Pure coarse-grained beaches**
Those composed of particle sizes ranging from pebbles to cobbles and boulders, with minimal sand;
b) **Mixed sand-and-gravel beaches**
Those consisting of high proportions of both coarse particles and sand, with there being an intimate mixing of the two size fractions in the beach deposit;
c) **Composite beaches – mixed sand and gravel**
Those beaches having a higher proportion of sand, which has been 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. As a result, these beaches are characterized by a distinct boundary at the junction of the two predominant sediment groups;
d) **Composite beaches – pure gravel**
Those beaches having a higher proportion of sand, which has been sorted by the waves and nearshore currents, so the beach consists of an upper foreshore or backshore ridge composed of gravel and cobbles, fronted by a lower foreshore of sand, generally with a distinct boundary between them;
e) **Pure sand beaches**
Beaches consisting almost entirely of sand, and if coarse particles are present the quantity is insignificant so it does not appreciably affect the morphology and dynamics of the beach.

The Oregon coast exhibits examples of each of the above beach types, although it is the pure sand beaches (**e**) that make up the predominant shoreline morphology followed by a smaller component of mixed sand and gravel beaches (**b** and **c**) (Figure 3.1). However, of greatest interest for the purposes of this study are the composite beaches that exhibit a gravel berm or beach ridge composed of pure gravel fronted by a sand beach (**d**) (Figure 3.2). Along the U.S. West Coast, including Oregon, these latter beaches are characterized by a steep sloping [average slopes ~ 9.8º (1-on-5.8) but may reach as much as 23º (1-on-2.3)] gravel berm or ridge that is fronted by a wide gently sloping sand beach [average slope ~2.3º (1-on-25)], which provides the first line of defense to the backshore by dissipating the incident incoming wave energy. On these beaches, the sandy beachface is exposed at all tidal stages during the summer, only becoming submerged in the winter when storms occur and much of that sand has moved to offshore bars, allowing the waves to reach the gravel ridge at mid- to high-tides (*Allan and Komar 2002; Everts, et al. 2002; Allan and Komar 2004*).

Figure 3.1: Example of a mixed sand and gravel beach that includes a backshore consisting of a gravels, which transitions to a wide, gently sloping dissipative sand beach that is primarily exposed at low tide

Figure 3.2: Composite beaches on the northern Oregon coast in Tillamook County. The beach includes a backshore consisting of a steep faced gravel berm, which transitions to a wide, gently sloping dissipative sand beach that is exposed at all tidal levels (e.g., Short beach) or at low tide (e.g., Cove Beach).

Coarse-grain beaches are found in many parts of the world. They have been variously termed pebble, shingle, gravel or cobble beaches (*Marshall 1927; Bluck 1967; McLean 1970; Carr 1974; Carter and Orford 1984; Nicholls and Webber 1988; Jennings and Shulmeister 2002*). Typically, the sediments contained on coarse beaches are partly rounded and have been sorted by marine processes, while the grain sizes fall within the range of 4 mm (-2Ø)[3] to 256 mm (-8ø) as measured along their intermediate (B) axis (*Carr 1974; Sherman 1991*). However, as the proportion of sand volume increases on coarse beaches (typically ranging from 15% to 68% by volume), they are then termed mixed sand and gravel (*Mason and Coates 2001*). For the purposes of this study, the term gravel beach will be used to describe those beaches containing sediments between 4 mm and 256 mm.

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, et al. 2002*). As a result they have been suggested as a form of shore protection or breakwater (*van Hijum 1974*). For example, Carter and Orford (*1984*) noted that gravel-dominated barrier beaches remain relatively stable in the face of sustained wave attack, in part due to the inability of the particles within a gravel mass to become entrained except under high-energy events. In fact, Carter and Orford have observed gravel beaches in southeast Ireland that built-up during storms, a finding that is consistent with observations by Allan, et al. (*2003*) at Cape Lookout State Park on the northern Oregon coast. Furthermore, analyses of LIDAR data presented by Allan, et al. (*2004*) reveal that dunes fronted by composite gravel beaches (type **d**) in the Netarts cell experienced erosion rates that were typically 20 – 40% of the rates experienced by adjacent pure sand beaches, highlighting the level of protection offered by a gravel beach compared with a sand beach.

Researchers in southern California have also noted that gravel beaches there tend to gain material and increase their crest elevations during severe storms, while the neighboring sand beaches eroded significantly so that the sand berms present on those beaches disappeared (*Lorang, et al. 1999; Everts, et al. 2002*). Horn and Walton (*in review*) noted that coarse beaches are likely to become increasingly important in practical terms on the coast of the United Kingdom as many of these beach types constitute an important defense against erosion and flooding. They further observed that these beaches form barriers in front of low-lying marshes, toe protection along eroding cliffs, and help to 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 US.

3.1 BEACH MORPHODYNAMICS

The range of beach categories described above exhibits contrasting morphologies with different degrees of stability when assaulted by storms. This can be illustrated by placing the categories in

[3] Ø = -log2 D, where D = grain size in millimeters

the morphodynamics classification developed by Wright and Short (*1983*); a modified version of their morphodynamic model is shown in Figure 3.3. The "morpho" portion of the classification refers to the geometry of the beach, both in its two-dimensional profile and in the three-dimensional topography of bars and troughs, while the "dynamics" part refers to how that morphology changes in response to the varying wave conditions.

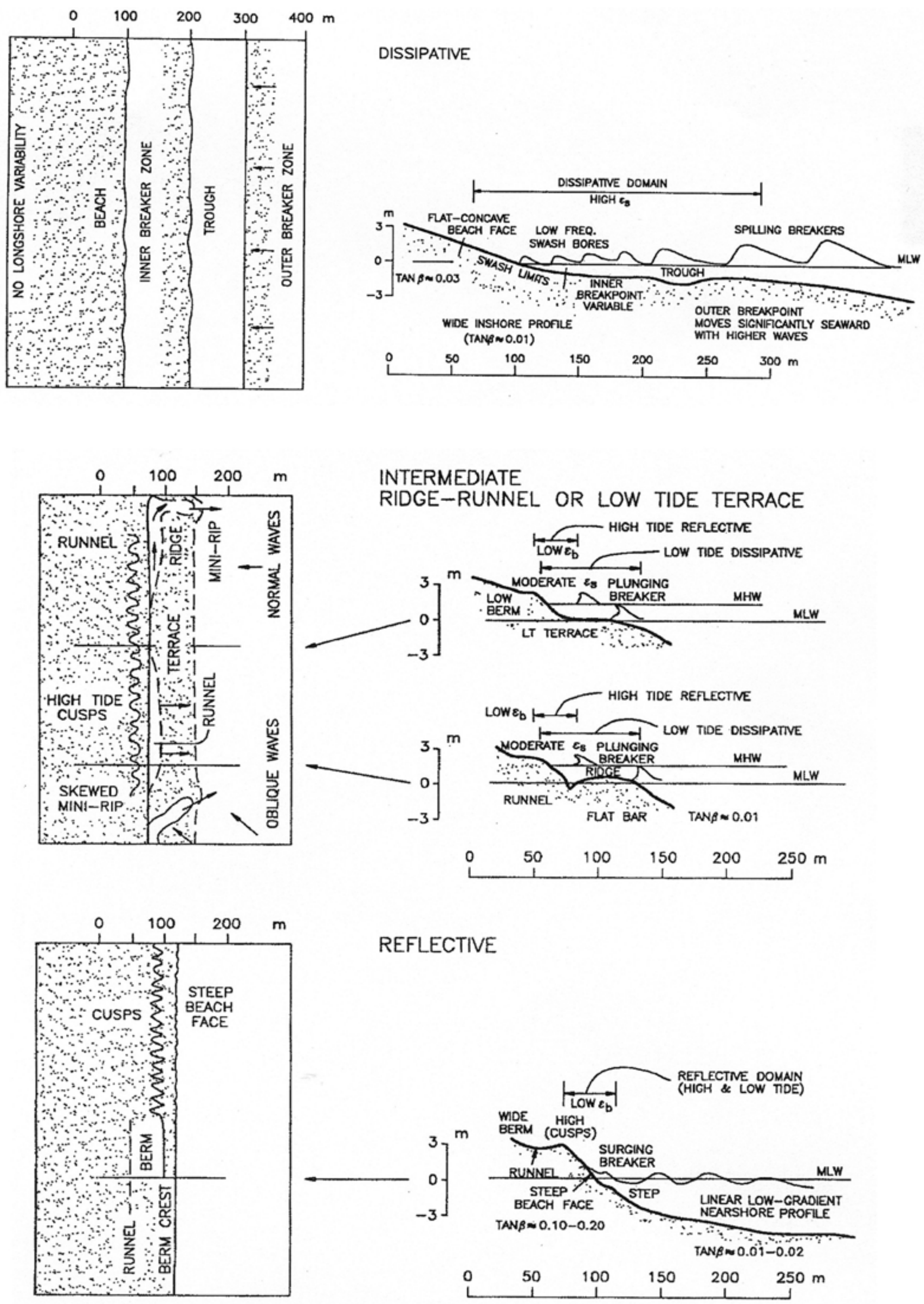

Figure 3.3: The morphodynamics classification of sand beaches (after *Wright and Short 1983*)

It is seen in Figure 3.3 that at one end of the spectrum are dissipative beaches, at the other end reflective beaches, with four stages of intermediate categories, although only one of these is shown in Figure 3.3. The average beach slope is seen to progressively steepen from the dissipative to the reflective condition, with the profiles of the intermediate categories tending to be more irregular due to the presence of offshore bars and troughs, or rip-current embayments.

Dissipative beaches are so termed because they are characterized by having low slopes and wide surf zones. Thus, on dissipative beaches the waves tend to break well offshore from the dry beach, with the bores formed from the broken waves crossing a wide surf zone and losing most of their energy before they reach the shore and swash up the beach face. In the opposite extreme, on reflective beaches the profile slope is steep so the waves break very close to the shore (often breaking on a plunge step), and 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 the sense that because of their steep slopes, they can reflect a significant portion of the wave energy, so one can often observe waves returning seaward after having been reflected from the beach face. The Oregon coast exhibits examples of each of the beach states that fall under the Wright and Short (*1983*) morphodynamic model, although it is the dissipative beach that is the most common beach type. As noted previously, reflective beaches are also found along the Oregon coast (Figures 2.9 and 3.1), though they are not as common as the dissipative sand beach.

The position of a specific beach within this morphodynamics classification depends on both 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 a steep face 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*). This is an interesting natural response of the sand beaches to storms, as their becoming dissipative at the height of the storm helps to reduce the energy of the waves at the shore, thereby limiting the extent of the 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 3.3, 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.

Of particular significance, beaches that are at the extremes, either dissipative or reflective, tend to show the least variability in their three-dimensional morphologies or in a simple set of beach profiles; it is the intermediate beaches that are most dynamic in their responses to storms, and therefore tend to be the most hazardous in terms of the potential erosion of shore-front properties (*Wright and Short 1983*). For example, on the Oregon coast we have found by repeated beach-profile surveys that the finer-grained Dissipative beaches change in elevations by about 1 - 2 m (3 – 6 ft) between the summer and winter (*Aguilar-Tunon and Komar 1978; Shih and Komar 1994; Allan, et al. 2003*), 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 - 3 m (3.3 – 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 gravel and cobbles tend to always remain reflective due to their persistent steep seaward slopes. As shown by 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 in effect provides a dissipative sand beach backed by a reflective coarse-grained ridge (e.g., Figure 3.2), the two most stable end members in the morphodynamics classification of Wright and Short (*1983*). As will be discussed below, because of this relative stability of pure coarse-grained beaches, some mixed beaches, and particularly composite beaches that have both dissipative and reflective elements, it has been recognized that constructing a comparatively small ridge of cobbles at the back of a sand beach can provide the same degree of protection to shore-front properties as does a large volume of sand added in a beach nourishment project. In some cases this can even substitute for a hard structure such as a riprap revetment or seawall.

3.2 THE DYNAMIC REVETMENT CONCEPT

A strategy for shore protection of relatively recent origin is the use of what has been variously termed "cobble berms", "dynamic revetments" or "rubble beaches". The approach involves the construction of a gravel (shingle) or cobble beach at the shore, in front of the property to be protected. In this respect, a constructed cobble berm represents a transitional strategy between a conventional riprap revetment of large stones and a beach nourishment project. The name "dynamic revetment" reflects this transition in that by consisting of gravel and cobbles, the material is expected to be moved by waves and nearshore currents — it is "dynamic", contrasting with a conventional "static" riprap revetment where the boulder-sized quarry stone is designed not to move under the expected forces of waves during extreme storms (*Ahrens 1990; Ward and Ahrens 1991*). Thus a dynamic revetment is designed for the wave action to rearrange the gravels 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, not failing when movement occurs.

In application, 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. Indeed, the objective is to construct the cobble berm to be as close as possible to the form of natural cobble beaches in order to be compatible with the natural environment and to insure its stability wherein it responds to ocean processes like a natural cobble beach (*Komar, et al. 2003*).

The origin of the use of a dynamic revetment for shore protection is unclear. There are early papers on artificial nourishment of gravel beaches (e.g., *Muir Wood 1970*), and aspects of their design can be similar to those for a cobble berm. The concept of a structure having a dynamic response to wave attack has also been applied to rubble-mound breakwaters, but of a much larger scale (*Bruun and Johannesson 1976; Willis, et al. 1988*).

The earliest published paper that clearly considers the design of an artificial gravel beach is that of van Hijum (*1974*), the application having been along the bank of the entrance to Rotterdam Harbor in the Netherlands, needed to dissipate wave energy rather than serving for shore protection. A similar engineering application is that of Ahrens (*1990*), who undertook research into the use of a constructed cobble berm to protect a bulkhead located in shallow water. As noted above, the use of dynamic revetments for shore protection has been particularly advanced by the observation that natural cobble beaches often protect the backshore from erosion (*Nicholls and Webber 1988; Powell 1988; Everts, et al. 2002*). Such occurrences are common along the Oregon coast, where natural cobble beaches served as the basis for the design of a dynamic revetment to protect a State park (*Allan and Komar 2002; Allan, et al. 2003; Komar, et al. 2003*).

Whatever the origin of the concept, the basic strategy has evolved into one of building a gravel or cobble beach for shore protection (Figure 3.4). 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*), including the following:

- Stone size is smaller and is 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 material may be dumped in place rather than the stones being individually placed, making the construction process much simpler.

- Movement does not constitute failure. In fact movement is desirable in that the cobble 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 so that it conforms with the setting of the coast, being indistinguishable from natural cobble beaches. This may make its construction more acceptable by management authorities, even on coasts that do not permit the use of conventional "hard" structures.

Although dynamic revetments require more material to construct than a riprap revetment, its construction is generally less expensive than “hard” engineering structures. However, it cannot be expected that a cobble berm will provide the same level of shore protection as a conventional riprap revetment or seawall. Since the gravel and cobbles can be moved by the waves, the placed material may be transported alongshore or offshore by extreme storm waves (*Allan, et al. 2003*), so that maintenance requirements can be expected to be more frequent than in the use of "static" structures. The cobble berm itself may also become a hazard to shore-front properties if the cobbles become projectiles during a storm, flung by the waves against houses. Because of this potential, the use of cobble berms is safest if backed by a bluff or substantial sand dune, or if developments are sufficiently set back beyond the reach of wave-flung cobbles. Another problem that may limit their acceptance as a form of soft engineering is identification of suitable gravel sources at acceptable costs (i.e., supply and transportation costs). This study will address availability and cost from the Oregon perspective.

Figure 3.4: Comparison of a dynamic revetment constructed at Cape Lookout State Park (left) versus a conventional riprap revetment constructed at Neskowin (right)

3.3 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 into the design of cobble berms was undertaken at the Delft Hydraulics Laboratory in the Netherlands (*van Hijum 1974; van der Meer and Pilarczyk 1986; van der Meer 1987; van der Meer and Stam 1992; van der Meer, et al. 1996*). Most of their laboratory work was conducted with relatively deep water at the toe of the structure, the results being 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*) extended the Dutch research through additional laboratory investigations, 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 the "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 thereby provide guidance on the quantity of stone needed to provide adequate protection from wave attack. A shortcoming of the experimental studies undertaken by engineers is that they have not included the composite beach condition (category **d**, Figure 3.2), where a sand beach fronts the cobble berm, which is the more common setting for their use in protecting shore-front properties.

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

Threshold equations have been developed for boulder entrainment by waves on beaches (e.g., *Lorang 2000*), but there is only limited 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*), finding a variety of patterns but generally having an onshore, up-slope decrease in grain size that reflects the decreasing competence of the wave swash. In addition to the size sorting there can be distinctive patterns of sorting based on the shapes of the individual particles, the extent of their departure from being spherical, the shape governing the gravel's ability to be swept up the beach by the wave surge versus its tendency to roll back down the beach under the backwash. Sorting can also occur along the length of the beach (*Carr 1969, 1974*), caused by different rates of transport by the waves or longshore variations in wave-energy levels as can occur within a pocket beach.

Research has also been undertaken in the laboratory and field to measure the processes responsible for the morphologic responses of gravel and cobble beaches. Due to the difficulty of process measurements on natural cobble beaches, the majority of this research has been conducted in the controlled conditions offered by laboratory wave basins. For example, Deguchi et al. (*1996*) provide wave-flume measurements of wave-height variations and swash runup elevations, while Powell (*1988*) and Bradbury and Powell (*1992*) have examined the dynamic responses of shingle beaches to random waves, with measurements of swash runup and wave reflection. Although this laboratory work generally utilizes scaled-down grain sizes of material of lower density (e.g., coal particles), when the resulting empirical relationships are compared with the limited data from the field, the agreement is encouraging. While measurements of such processes are difficult on natural coarse-grained beaches, studies like that of Kirk (*1975*) have focused on the swash runup on mixed sand and gravel beaches, while studies utilizing aluminum pebbles as tracers have measured the longshore transport and sorting of shingle by waves on English beaches (*Nicholls and Webber 1987; Nicholls and Wright 1991*).

A particularly relevant field study of natural cobble beaches is that of Everts, et al. (*2002*) in Southern California, in that it was undertaken with the purpose of providing improved design criteria for constructed dynamic revetments on that coast. At the study sites natural cobble accumulations are found at the back of an otherwise sandy beach that dissipates much of the energy of the waves. Repeated profiles established that the cobble deposits accrete in the winter and lose volume in the summer, opposite to the fronting sand beach and what is normally found in beaches. The explanation involved the movement and dispersal of cobbles into the sand portion of the beach during the summer, and their return to the cobble accumulation by winter waves. At times of storms, the cobble beaches steepened, again opposite to the general response of sand beaches that generally decrease in average slope as sand is moved offshore. This response has also been observed by Lorang, et al. 1999) in natural cobble beaches and by Allan, et al. (*2003*) on a constructed cobble berm on the Oregon coast, a response that is important to their stability.

3.4 EXISTING DYNAMIC REVETMENT APPLICATIONS

Until recently most of the construction of dynamic revetments for shore protection have been limited to relatively low wave-energy environments. Downie and Saaltink (*1983*) describe a dynamic revetment installation on the shore of Vancouver, Canada, within the fetch-restricted Strait of Georgia. The site is a pocket beach adjacent to the campus of the University of British Columbia, and is backed by a 200 ft high cliff that has been eroding at a rate of approximately 1.3 ft/year. The causes of the erosion ranged from 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 the engineers, who wanted to protect the University's engineering building from the threat of bluff erosion, and users of the beach. 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 along shore migration of the cobbles once the structure was built. The sills consisted of a central core of boulders that were then covered with cobbles and were designed to blend in with the morphology of the adjacent beaches. The design crest of the structure was established at 6.4 m. However, no information was provided on how the berm crest elevation was derived. Sediment material sources were located locally, within about 20 miles of the structure, while the cost of the structure was estimated to be around $500,000. The Vancouver dynamic revetment has performed relatively well with the cobbles having tended to move up the beachface to form a steep profile (~18º or 1 on 3). However, Downie and Saaltink noted that the sills did not perform as effectively in part due to their lower elevations, so that significant quantities of material were being transported over the sills and along the beach.

Johnson (*1987*) documents several examples in the Great Lakes of North America where dynamic revetments proved to be cost effective solutions for shore protection. Initially their creation was inadvertent, where 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 revetment-like deposit at the back of the beach. Based on those serendipitous examples demonstrating their potential for shore protection, dynamic revetments have been intentionally constructed at Great Lakes sites.

Lorang (*1991*) reported on the construction of a perched gravel beach used for shore protection in Flathead Lake, Montana. The completed structure is approximately 60 m in length and consisted of a base formed of boulders and cobbles, which was then backfilled with cobbles to form a sloping cobble beachface. Particle sizes ranged widely due to the glacial origins of the lake, with the median grain sizes ranging from 5 to 25 mm (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 gravels due to oblique wave approach that caused the sediments to be transported to the north.

An interesting 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 1992*). The breakwater of the port had suffered degradation due to direct attack by high-energy waves, so a protective beach was established along the length of the breakwater by constructing a short groyne at its end, which partially blocked the longshore gravel transport that previously had bypassed the breakwater. The accumulated gravel beach has been so successful in dissipating the wave energy, that large rocks of the breakwater have been "mined" for use in structures elsewhere.

Only recently have large-scale dynamic revetments been constructed on the ocean shores of the US for erosion control. A 300-meter long cobble berm, backed by an artificial dune containing sand-filled geotextile bags, was constructed in 1999 at Cape Lookout State Park, Oregon, following several years of extreme erosion (*Allan and Komar 2002; Allan, et al. 2003; Komar, et al. 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, not wanting a large-scale "hard" structure separating the park from its main attraction, the beach. An extensive monitoring program is currently underway, including periodic measurements of beach cross-sections, measurements of cobble movement and the progressive development of particle sorting patterns, and video data collection of swash runup on the berm. Another US West Coast installation of a cobble berm is a test section located at Surfers Point, Ventura, California, designed and constructed 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 in part influenced by this stretch of shore being an important surfing site.

4.0 METHODS – MORPHOLOGY SURVEYS AND WAVE RUNUP CALCULATIONS

A variety of techniques have been used to provide documentation of the coastal geomorphology of cobble beaches on the Oregon coast. These include:

- Creation of a beach profile monitoring network at selected cobble beaches identified along the full length of the Oregon coast;
- 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;
- Analysis of the response of the cobble berms and their temporal and spatial responses based on 1997, 1998 and 2002 LIDAR beach topography data;
- Measurements of the grain sizes and sorting characteristics at each of the study sites; and,
- Analysis of the potential for wave runup and over-topping of the cobble beaches.

4.1 BEACH PROFILE SURVEYS

In April 2003 a reconnaissance trip was undertaken along the northern Oregon coast to determine appropriate locations for the purposes of establishing a series of beach profile monitoring sites. Based on this initial trip it was determined that monitoring of suitable gravel beaches could be undertaken at several locations: Short Beach, Cape Meares, Neahkahnie, Cape Cove, Arch Cape, and Seaside (Figure 4.1). 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 4.1). Finally, 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 constructed in the park in 2000 (*Allan, et al. 2003; Allan and Komar 2004*). These latter datasets have been also utilized here.

The cobble beach monitoring network consists of a total of 27 profile lines (cross-sections) with multiple lines at most of the cobble beach locations, which provide a measurement of the beach morphology. Beach surveys therefore provide a snapshot of the shape of the beach for that individual survey (e.g., height of the dune crest, beach slope, presence or absence of any erosion scarps, volume of sand, information on swash runup limits etc.). Subsequent re-surveys 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. These initial 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 (i.e., a survey monument having a known location and elevation, serving as a reference point for subsequent re-surveys) installed in stable locations adjacent to the beach. The benchmarks consist of either 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. However, during the latter half of 2004, a cooperative venture was initiated 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 precisely locate the coordinates and elevations of each of the benchmarks with the exception of those sites established on the south coast and a benchmark that was respectively lost at Seaside and at Arch Cape.

4.2 LIGHT DETECTION AND RANGING (LIDAR) DATA

Additional information on the spatial and temporal variability of gravel beaches was undertaken from an analysis of 1997, 1998 and 2002 LIDAR topographic beach data measured by the U.S. Geological Survey (USGS) and NASA. LIDAR is a remote sensing approach consisting of x, y, and z values of land topography that are derived using a laser ranging system mounted on board 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. More detailed information on how the beach topography measurements are derived and processed are covered by Brock, et al. (*2002*). The LIDAR data have a vertical accuracy of approximately 0.1 m, while the horizontal accuracy of these measurements is about 1.4 m. 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 within MAPINFO's Geographical Information System (GIS) software. Having generated a grid dataset, cross-sections of the beach morphology were constructed at 100 m intervals along selected gravel beach shores (e.g., Cape Meares, Neahkahnie, Cove Beach, Arch Cape, and Seaside. The transects were then used to extract various beach and dune morphological features (e.g., berm crest elevations and beach slopes) for the 1997, 1998 and 2002 LIDAR flights.

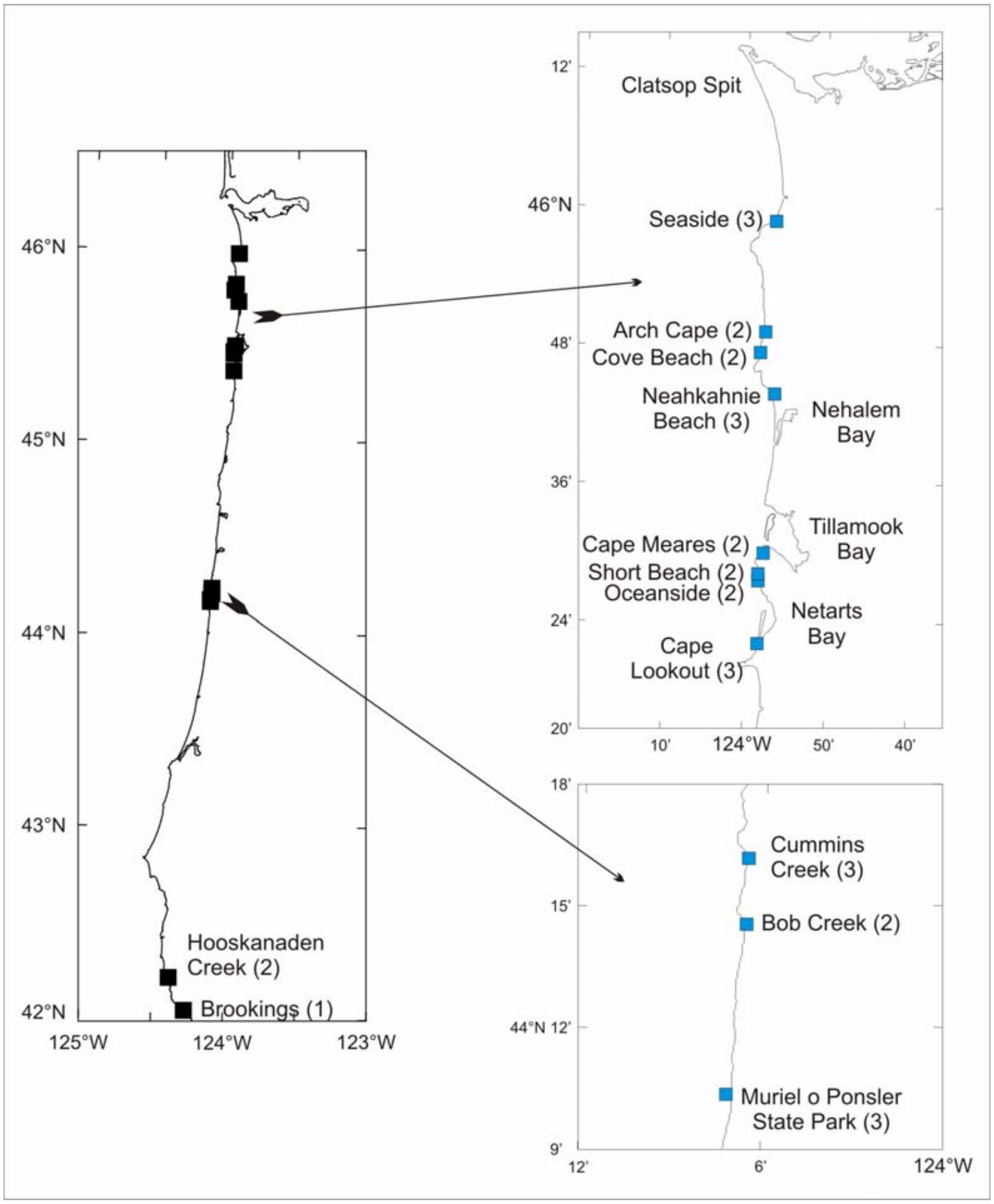

Figure 4.1: Location map of cobble beach study sites. Values in parentheses indicate the number of profile lines surveyed within each cobble beach location.

4.3 GRAIN SIZE ANALYSES

Assessments of the mean grain sizes and sorting characteristics of Oregon's gravel beaches is important, since such analyses are necessary to provide guidance on identifying an appropriate gravel size to use when constructing a dynamic revetment. Grain size analyses were undertaken at each of the 27 profile sites. Given the coarse nature of the particles concerned, existing techniques of grain size measurement (e.g., sieving) can not be used. However, a variant to this approach is the use of a “gravelometer” to measure the size of the particles (Figure 4.2). The gravelometer is a 5 mm 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 sediments ranging in size from -1Ø to –7.5Ø (2 to 180 mm).

Figure 4.2: Example of a “gravelometer” being used at Neahkahnie to determine grain size statistics on the beach

In measuring the particle sizes, a 20 ft long tape measure was laid out across the gravel face, parallel with the ocean. Sediments were then sampled at each one-foot section along the tape. Once the end of the tape was reached, the tape was moved 2 feet down the gravel face where the sampling process was repeated. This approach continued until a minimum of 100 samples had been measured. At most sites we attempted to measure the upper, middle and lower sections of the gravel face. However, if the sediments were of a relatively uniform size or the gravel beach face was narrow in width, sediment sampling was confined to the mid-section of the gravel slope. To operate the gravelometer the user simply passes the B-axis of a particle through the various holes until the appropriate size is found. The number of particles retained in each size category are 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 sediments is the mean value (M_z Ø). Mean grain size essentially 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:

$$M_z\phi = \frac{(\phi16 + \phi50 + \phi84)}{3} \qquad \textbf{(5-1)}$$

where Ø16, Ø50 and Ø84 represent the cumulative percentiles 16%, 50% and 84% measured from the log probability plot.

Folk (*1965*) has suggested that mean grain size is a function of two variables. First, it is dependent on the range of sediments that are available. Second, it is a function of the amount of energy that is exerted on the sediments and is therefore further dependent on the current velocity and the degree of turbulence. Other parameters have also been calculated including the grain size sorting (akin to the standard deviation) and the median (D_{50}) grain size.

4.4 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% event or some other recurrence event (e.g., an annual average wave runup). Nevertheless, it is well established that the beach crest (Figure 4.3) is generally a function of some combination of wave conditions and water levels, and by the size, sorting, and grading characteristics of the beach. As the total water levels (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 that applied to the erosion of beaches and dunes on the Oregon coast (*Shih and Komar 1994; Komar, et al. 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 as 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 gravels. Under low to moderate storm conditions, sediments carried up the gravel face are deposited often as a gravel ridge (Figure 4.3, upper), which may continue to aggrade vertically for some time depending on sediment supply rates and the wave climate. However, under extreme storm conditions, most notably when high wave energy levels are attained and are combined with extreme water levels, the gravel beaches become susceptible to very high swash excursions resulting in frequent overtopping of the crest of the beach face (i.e., $T_{WL} > E_{J\ HIGH}$, Figure 4.3, lower).

It is under these latter conditions that erosion occurs along both dunes and bluffs, since 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 (i.e., 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(s).

In a sense the conceptual model portrayed in Figure 4.3 is akin to the storm impact scale developed by Sallenger (*2000*), which couples the forcing processes associated with a major storm and 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 based on 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). Based on the ratios of these variables, Sallenger (*2000*) identified four regimes, which were respectively termed swash, collision, overwash and inundation. 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 (i.e., 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} (i.e., the berm crest) producing overwash (lower diagram in Figure 4.3). Along the U.S. East Coast, overwash of the barrier islands has often resulted in the landward migration of the barrier. While such effects could occur at a few sites on the Oregon coast, in the majority of cases it won't, since most of Oregon's gravel beaches are backed by either a dune or sea cliff, limiting its landward movement.

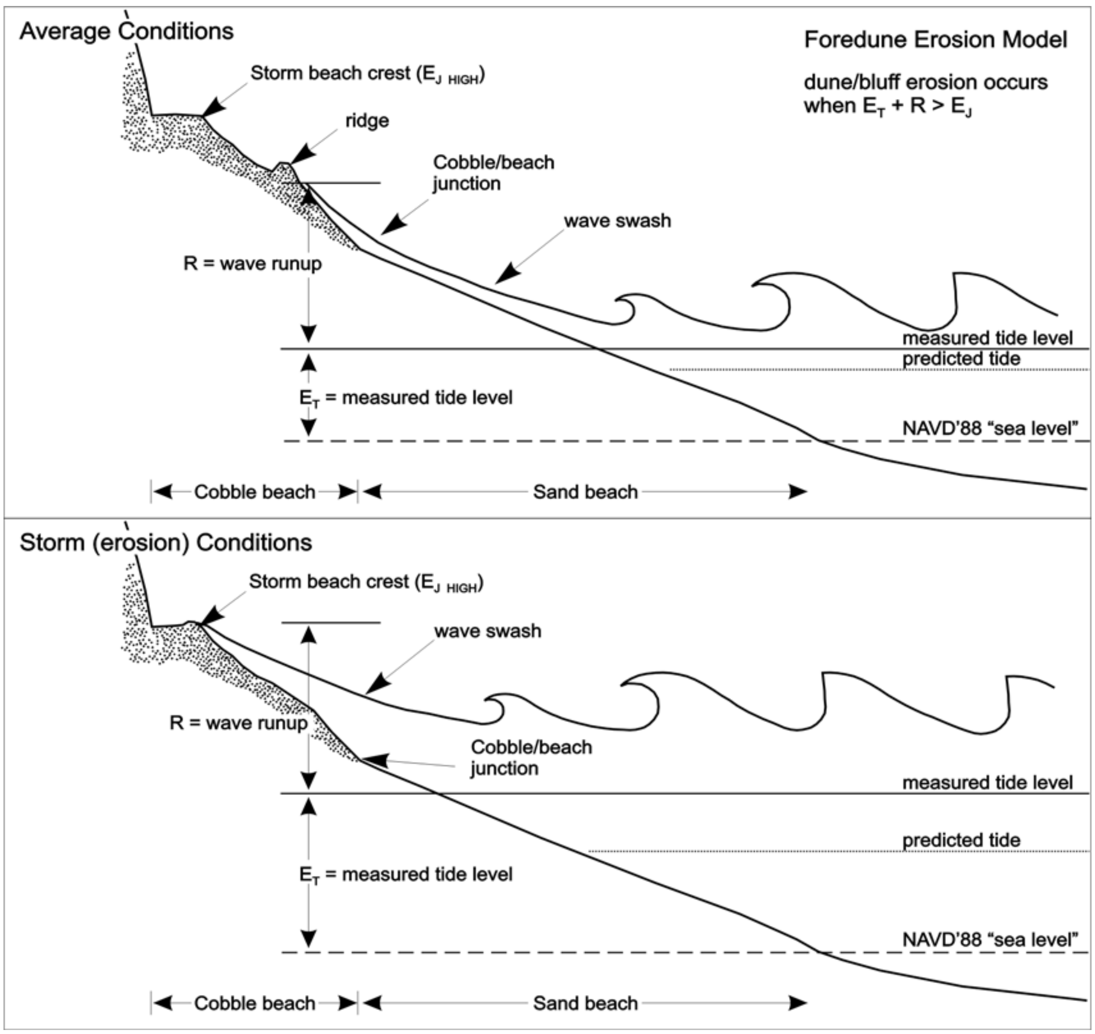

Figure 4.3: (Upper) A typical composite gravel/sand beach exposed to wave runup (R) and tidal (E_T) conditions, which may result in erosion of the cobble foredune toe (E_J) and/or berm development. (Lower) During large storms and elevated water levels, wave runup is able to reach much higher elevations 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, et al. 1999*).

Measurements of wave runup along the Oregon Coast under a range of wave conditions and beach slopes (*Ruggiero, et al. 1996; Ruggiero, et al. 2001*) have yielded the relationship:

$$R_{2\%} = 0.27\left(S\, H_{SO}\, L_O\right)^{1/2} \qquad \textbf{(5-2)}$$

for estimating the 2% exceedence runup (R) elevation, where S is the beach slope (tan ß), H_{SO} is the deep-water significant wave height, L_O is the deep-water wave length given by $L_O = (g/2\pi)T^2$ where T is the wave period, and g is acceleration due to gravity (9.81 m/s^2).

Therefore, estimates of the wave runup elevations depend on an availability of data for the 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 was 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 (e.g., 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 just 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 & Analysis System (CEDAS) software developed by the U.S. Army Corps of Engineers.

5.0 RESULTS

The development of cobble beaches on the Oregon coast is the product of a balance between the supply of suitable quantities of coarse material to the beach face and the coastal processes (primarily waves and currents), that 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 (e.g., 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 sediments to the gravel beaches is likely from mass movement (Figure 5.1), either as debris flows, landslides or rockfalls. Once the sediments are introduced into the littoral zone, they are rapidly reworked by waves and currents, and redistributed across the beaches.

Figure 5.1: A landslide that occurred early in 2003 on the north side of Cape Lookout and adjacent to Cape Lookout State Park. Such events periodically introduce significant quantities of coarse material to the coastal zone where it is then redistributed along the shore to form cobble berms.

Most of the cobble and boulder material introduced to the coastal zone in Oregon are from crystalline volcanic or metamorphic rocks. Tertiary basalt is the main source on the northern and central Oregon coast, the Columbia River basalt being the most common unit (*Schlicker, et al. 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 basaltic gravels may be mixed with Tertiary sandstones, such as around Cove Beach and along the Arch Cape shore. Once introduced, the gravels may form extensive beaches that span several thousand meters along the shore (e.g., at Netarts Spit, Figure 5.2a), or as smaller accumulations within shoreline reentrants (e.g., near Bob Creek on the central Oregon coast, Figure 5.2b) or as a thin veneer on the landward edge of shore platforms (e.g., Bob Creek, Figure 5.2c). Invariably though, the best examples of gravel beaches can 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", which has effectively helped to slow the erosion of the backshore.

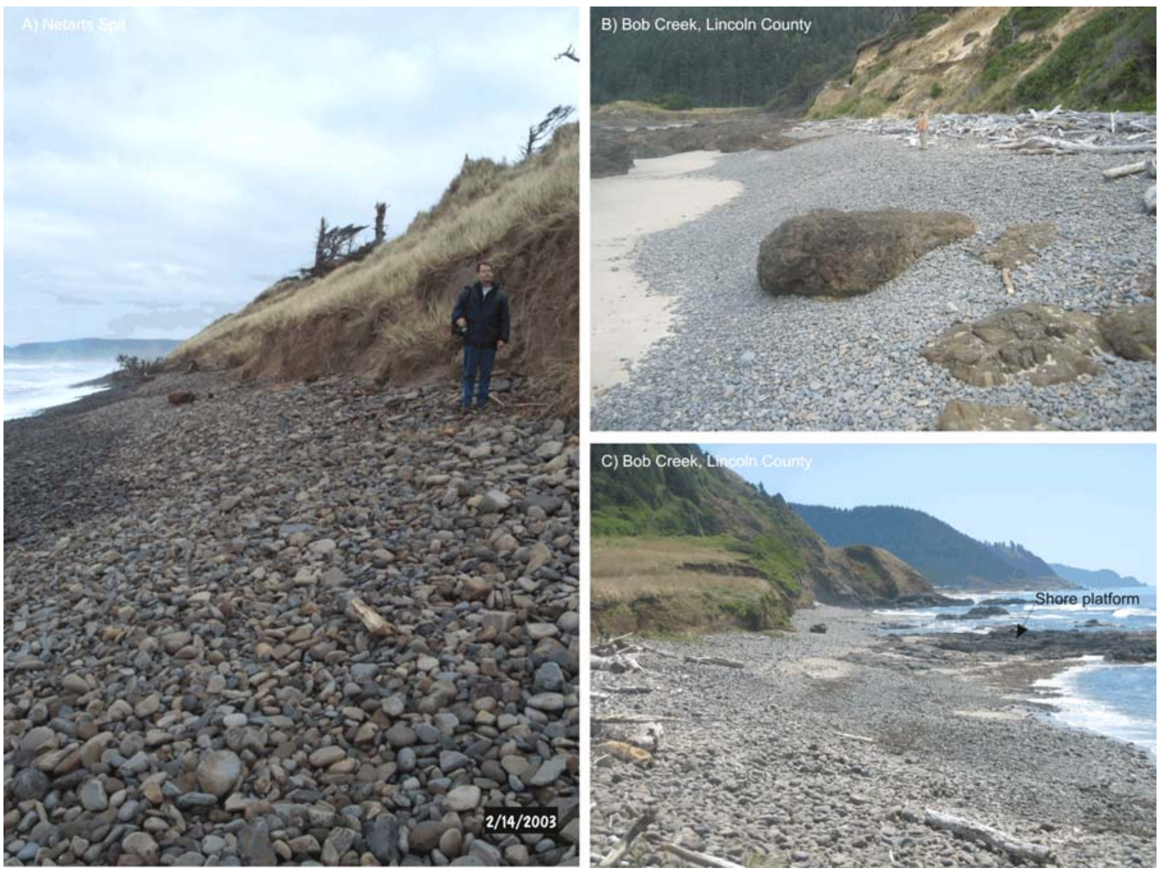

Figure 5.2: Examples of gravel beach types identified along the central and northern Oregon coast.

The southern Oregon coast gravel beaches are similar to those in the north, with the distinction that the gravels 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 gravels are probably predominantly fluvial in origin (e.g., adjacent to Brookings and at Gold Beach).

In most cases, the gravels tend to be well rounded and exhibit a wide range of sizes from fine gravel to boulders. The beaches may exhibit some evidence of cross-shore sorting with the coarsest sediments tending to accumulate in the lower portion of the gravel face, with an upward fining in the sediment sizes 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 sediments are highly mixed.

5.1 BEACH SURVEYS AND GRAIN SIZE MEASUREMENTS

A total of 27 profile lines located at 13 gravel beach study sites have been identified along the Oregon coast for assessments of their beach morphologies and grain size characteristics (Figure 5.1), with the majority of these located on the northern Oregon coast. 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 will be presented for each of the study areas, which will then be followed by a discussion of the overall results. In each example the morphology of the gravel berm and its general effectiveness in limiting erosion are described. Indicators of low erosion in the back shore 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.

5.1.1 Clatsop County

5.1.1.1 Seaside

An extensive gravel beach has developed on the north side of Tillamook Head, with the sediments having been transported north towards the town of Seaside, located at the south end of the Clatsop Plains (Figure 5.3). The gravel beach is approximately 3.3 km (2 miles) in length 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 (*Horning 2005, personal comm.*), with the gravels to the north having been 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 5.3). 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 that occurred early in 1987, released an estimated 230,000 m^3 (300,000 $yards^3$) of material onto the beach (*Horning 2005, personal comm.*). The landslide debris was rapidly redistributed along the shore, moving at an estimated 2 miles per month. By July 1987 it had formed a barrier spit across the beach near where the berm re-curves to the north (Figure 5.3). 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 to prograde seaward by some 45.4 m (150 ft).

Figure 5.3: The Seaside gravel beach showing the locations of beach profile sites and grain size sampling

Three transect lines were established at Seaside, the locations of which are shown in Figure 5.3. Results from our surveys of the gravel beach and from analyses of LIDAR data are presented in Figure 5.5. Apparent in Figure 5.5 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), decreasing in the north at profile 3 (~5.5 m (18 ft)). Of greater significance is the dramatic increase in the width of the beach to the north, increasing from approximately 54 m at profile 1 to around 130 m wide at profile 3. This equates to an increase in the volume of gravels on the beach from approximately 130 $m^3.m^{-1}$ [cubic meters per meter of beach (1400 $ft^3.ft^{-1}$)] at profiles 1 and 2 to about 430 $m^3.m^{-1}$ (4627 $ft^3.ft^{-1}$) at profile 3.

Measurements of the mean grain sizes 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 5.4, 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 gravels are classified as ‘moderately well sorted’, while 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 since one might expect to see the reverse pattern occurring as 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 recent landslide that occurred in 1987.

Figure 5.4: The gravel beach at Seaside. A) Adjacent to profile 2. The presence of logs at the crest of the beach indicates the maximum wave runup height (~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 1 ft graduations providing an insight on the size of the boulder toe at profile 1.

As can be seen from Figure 5.5, the Seaside gravel beach is dynamic, especially at profiles 1 and 3 and is clearly 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 197-98 El Niño. By the end of the winter, however, the beach had prograded seaward by some 10 to 20 m (33 – 66 ft). This was likely due to the arrival of higher storm waves from the southwest, typical of El Niño conditions, which caused a strong longshore transport gradient to develop around Tillamook Headland that eroded gravels downdrift of profile 1 and redistributed them along the shore. However, since the 1997-98 winter the gravel beach has eroded back by some 5 to 10 m (16 – 33 ft).

In contrast, profile 2 shows much smaller lateral changes, which may be due to the fact that this section of shore has an extensive sand beach in front of it, which helps to 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 point to a recent phase of seaward advance. However, erosion at profile 3 is probably less of a concern since the shore is characterized by an extremely wide gravel beach [~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 5.4), although the beach is subject to periodic wave over-topping.

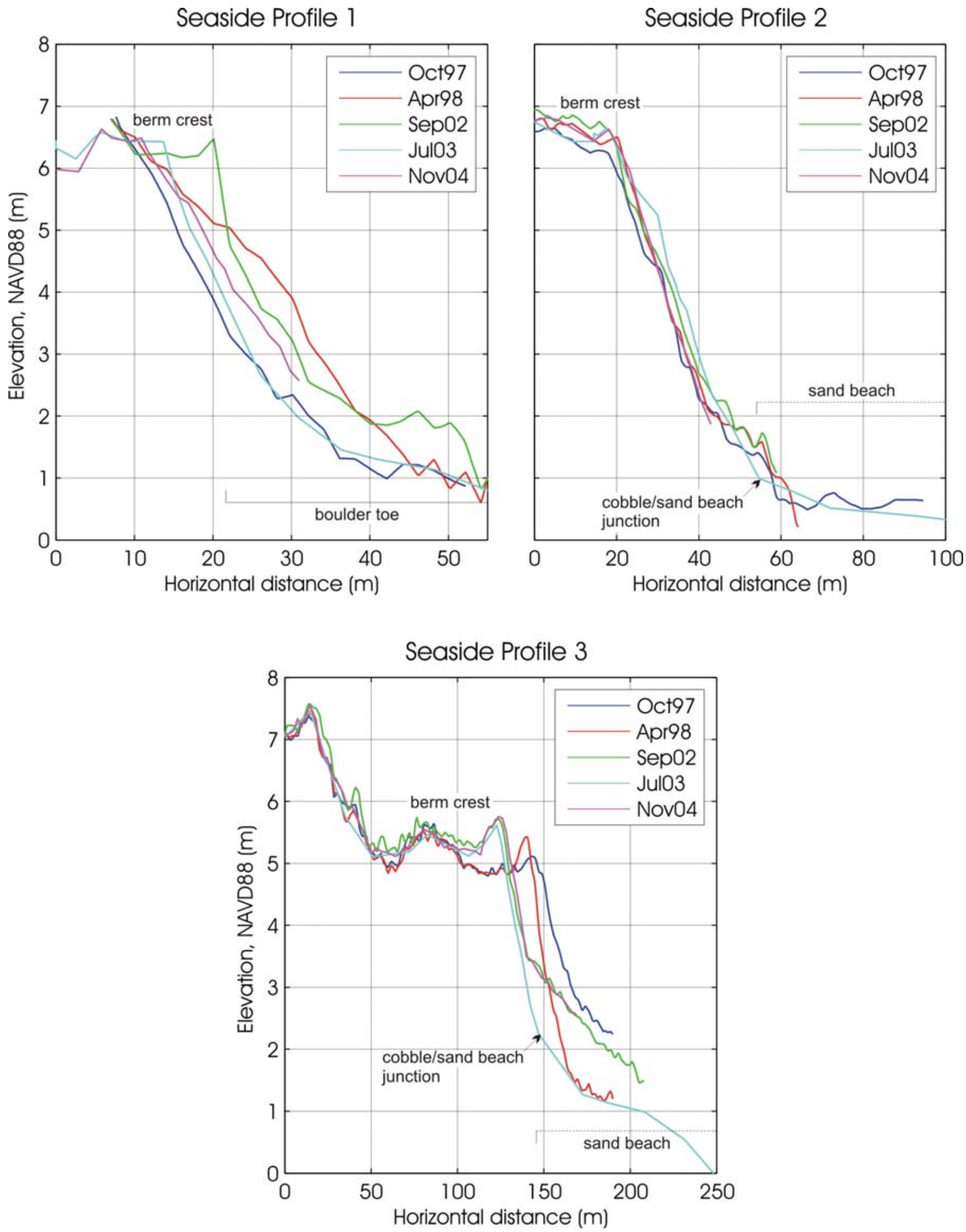

Figure 5.5: Beach profile surveys undertaken along the Seaside gravel berm. The location of the transect sites is shown in Figure 5.3.

5.1.1.2 Arch Cape and Cove Beach

The Cannon Beach littoral cell is approximately 17.8 km (11 miles) in length and extends from Cape Falcon in the south to Tillamook Head in the north. The cell may be further subdivided into two sub-cells, which includes Cove Beach located between Cape Falcon and Arch Cape, and the remaining shoreline between Arch Cape and Tillamook Head. The southern one-third of the shoreline is characterized by a composite beach that includes a gravel berm fronted by a wide sandy beach (Figure 5.6).

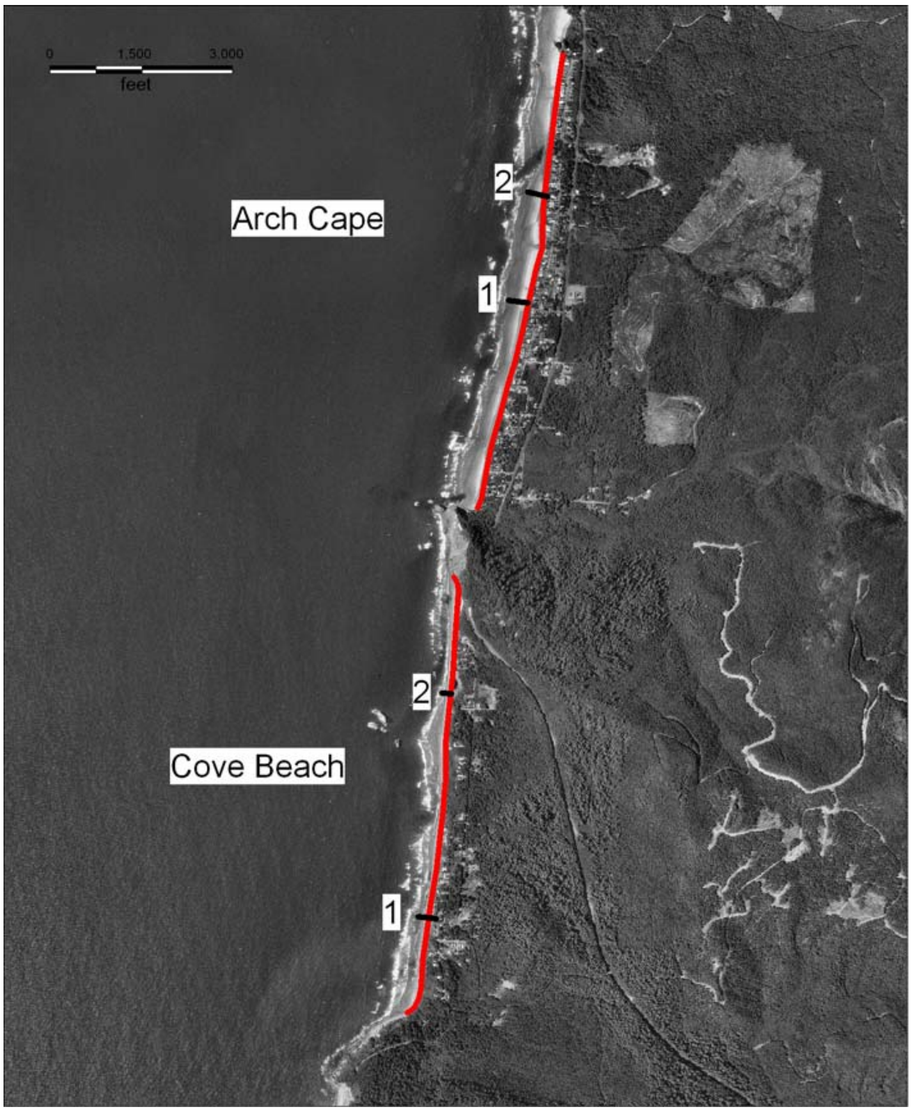

Figure 5.6: The Arch Cape and Cove Beach cobble berm showing the locations of beach profile sites and grain size sampling.

A 2.3 km (1.4 mile) long gravel beach is present along the Arch Cape shoreline (Figure 5.6). The gravel beach is approximately 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 between 30 – 40º (i.e., 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, evident 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. Nevertheless, 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, while their sizes are slightly smaller when compared with the Seaside gravel beaches. Mean grain sizes ($M_zØ$) ranged from –5.96Ø (62 mm) in the south, decreasing to –5.44Ø (43 mm) in the north. These sediments are classified as very coarse gravel. Although only two sample locations were measured at Arch Cape, the results suggest 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 - 22ft). However, 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 $m^3.m^{-1}$ at profile 1 to 53 $m^3.m^{-1}$ at profile 2 (495 – 570 $ft^3.ft^{-1}$). Given these low gravel volumes, we can 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 gravels.

Analyses of the beach profile data measured at Arch Cape reveal that the gravel beach has been subject to both erosion and rebuilding phases. At both study sites, the beach was in a generally degraded state following the end of the 1997-98 El Niño (Figure 5.7). 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 data having captured the vegetation on the terrace slope and to the gridding that has subsequently been undertaken to derive a digital elevation model for each LIDAR flight.

The gravel beach at Cove Beach is without doubt the most dramatic example identified on the Oregon coast. Along much its length the gravel beach fronts an actively eroding bluff, to the extent that at least two homes have had to be moved landward, while several other homes are now threatened (Figure 5.8a). This suggests that the gravel beach does not appear to be providing significant protection to the backshore, raising the question as to why. At the north end of the beach, the gravels form a barrier beach that has impounded a lake behind it. However, the site is clearly subject to frequent over-topping, evident by the numerous logs and debris along the crest of the berm and on its landward side leading into the lake (Figure 5.8b).

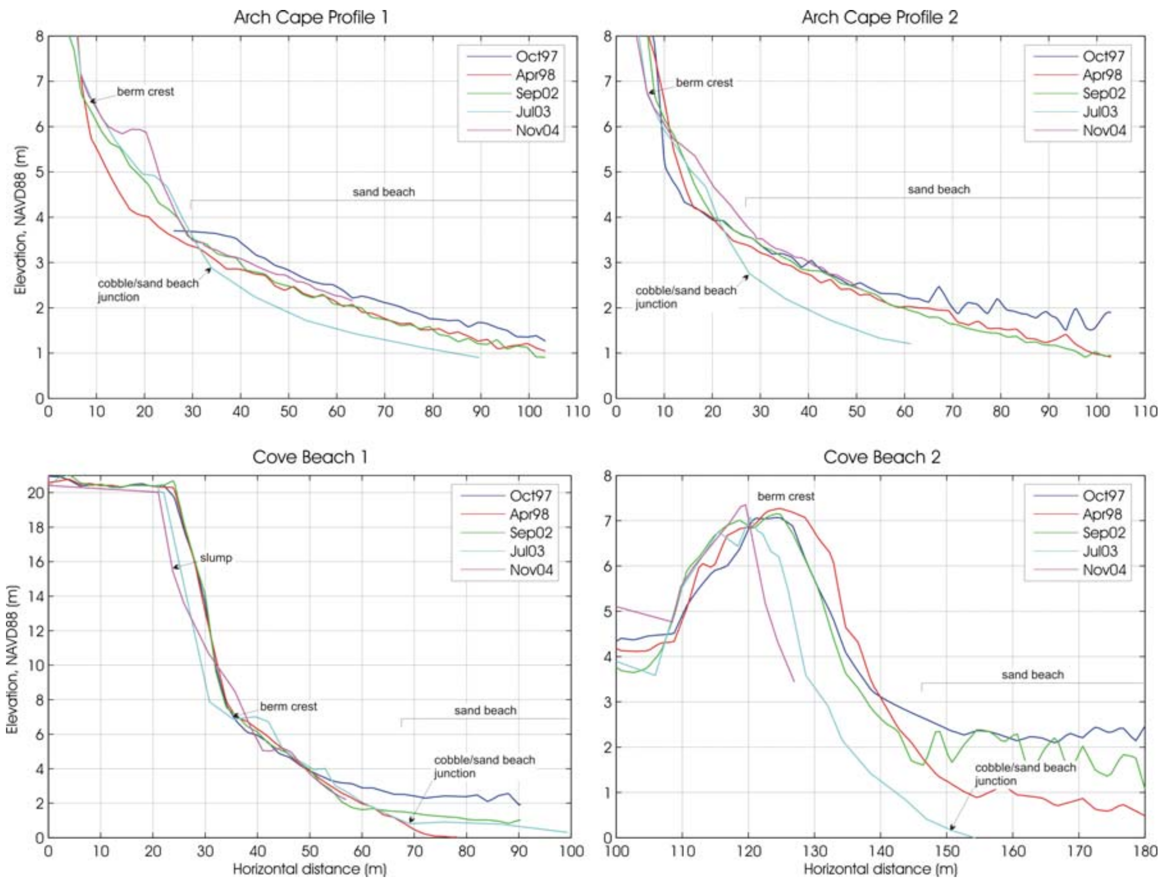

Figure 5.7: Beach profile surveys undertaken along the Arch Cape and Cove Beach gravel beach. The location of the transect sites is shown in Figure 5.6.

Figure 5.8: 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.

The beach is actively being fed by gravels from the south end of the cell in the form of landslides off Cape Falcon (Figure 5.9a), while the south-central portion of Cove Beach is primarily supplying sand and colluvial material to the system. As the material is released from Cape Falcon, the sediments are then rapidly transported northward along the beach where they are assimilated into the gravel beach (Figure 5.9a). 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 gravels. This feature of Cove Beach may be a function of the most recent major El Niño that occurred in 1997-98, which resulted in "hotspot" erosion at the south end of the Cannon Beach cell (i.e., Cove Beach), so that the sand was removed to the north (i.e., towards Arch Cape and Cannon Beach), and has simply not returned.

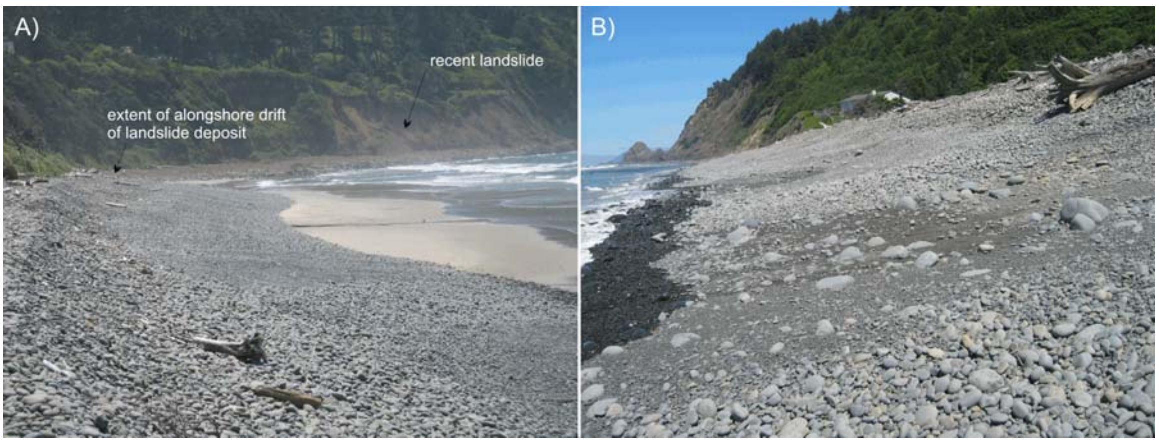

Figure 5.9: A) Sediments from a recent landslide (probably occurred during the 2002/03 winter) off of Cape Falcon have moved some 100 –150 m along the beach. B) Photo showing the extremely steep nature of the gravel beach at the north end of the shore.

The gravel beach is characterized by having a wide range of grain sizes, from coarse sand and granules to large cobbles (see page iv, opposite the Table of Contents, for an example of cross-shore sorting of sediments at Cove Beach). The sediments are classified as 'well sorted', indicating 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, increasing to –6.19Ø (73 mm) in the north. Based on our two surveys of the area, the mean crest elevation of the gravel beach reaches about 7.0 m (23 ft) high, while the width of the gravel beach ranges from 33 m (108 ft) at profile 1 to around 45 m (148 ft) at profile 2. The volume of gravel contained in the beach averages 104 m^3 per linear meter of shoreline at profile 1 increasing to 160 $m^3.m^{-1}$ at profile 2 (1119 – 1722 $ft^3.ft^{-1}$). These volumes are comparable to parts of the Seaside gravel beach. Another interesting feature of the beach at Cove Beach is the steep nature of the beach profiles. As shown in Figure 5.9B, the gravel slope at Cove Beach is extremely steep and ranges from 12.6º at profile 1 to 23.8º at profile 2.

Figure 5.7 shows the results of our recent surveys of the beach, including analyses of the 1997, 1998 and 2002 LIDAR surveys. The profiles reveal a number of interesting characteristics. 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 run out zone that probably occurred during the 2003/04 winter. The surveys also indicate that the bluff has eroded by about 3 to 5 m (10 – 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 been retreating, having eroded landward by some 12 m (39 ft) since 1998 (Figure 23). Much of this reflects the rolling over the barrier as the wave runup overtops the beach crest during storms, carrying sediment up and over the barrier and depositing it along the back edge of the ridge.

5.1.2 Tillamook County

5.1.2.1 Manzanita/Neahkanie

The Rockaway littoral cell is bounded in the north by Neahkahnie Mountain and by Cape Meares in the south. The total shoreline length is 28 km (17.4 miles), the bulk of which is comprised of sand beaches. However, the shoreline also contains two short gravel beach sections located respectively in the north along the toe of Neahkahnie Mountain and in the south, adjacent to the community of Cape Meares.

The Neahkahnie gravel beach is approximately 1.5 km (0.9 miles) long, Figure 5.10, and is highest in the north adjacent to the headland and progressively decreases in elevation to the south. In July 2003, three survey transects were established along the southern half of the beach (Figure 5.10). 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 (~50 m (164 ft)) and decreases in width to the south; 27 m (88.6 ft) wide at profile 2 and 12 m (39 ft) by the time one reaches profile 1. South of profile 1 there is no obvious evidence of the gravels having migrated farther to the south (Figure 5.11). This would imply that gravel transport, which is to the south, diminishes rapidly by the time one reaches the southern-most beach profile. However, historical photos indicate that the gravel beach at Neahkahnie was far more extensive in size, having previously extended south of the city of Manzanita. While some of these materials may have been mined at some point, it is believed that most of these latter gravels probably still remain on the beach, having been 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 5.11).

Grain size statistics measured at Neahkahnie reveal that the beach is characterized by having some of the coarsest gravels identified along the Oregon coast. In part this is due to the inclusion of a much higher proportion of boulders in the beach, a testimony to the size of the landslides that have been occurring off of Neahkahnie Mountain (Figure 5.11). Mean grain sizes ($M_z Ø$) 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)). Apart from the northern cobbles, which were classified as poorly sorted due to the inclusion of a higher proportion of boulders in the gravels, the southern two profile sites tended to be better sorted due to fewer boulders in the sediment matrix.

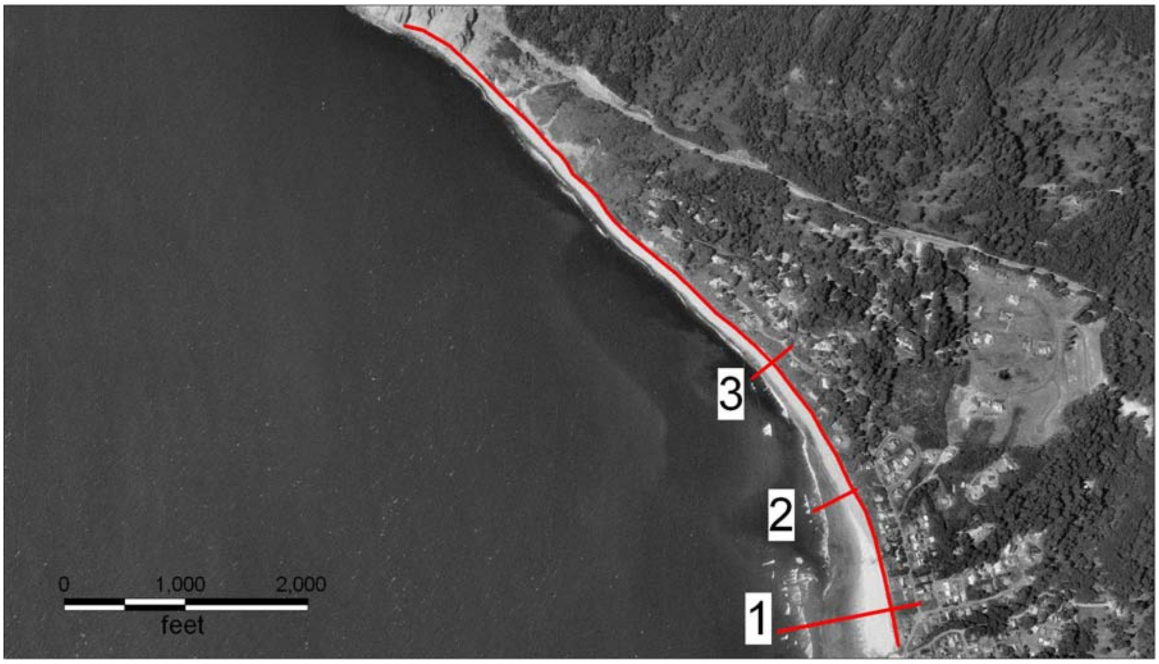

Figure 5.10: The Neahkahnie gravel beach showing the shoreline configuration, locations of beach profile sites and grain size sampling

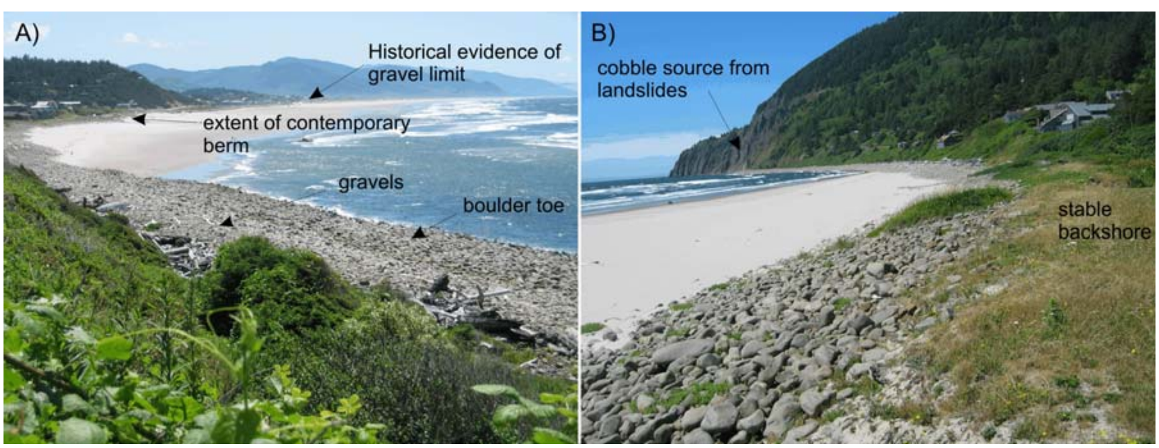

Figure 5.11: A) Much of the Neahkahnie gravel berm gains significant additional protection and stability from having a toe composed of boulders. Photo taken overlooking profile 3 and is looking towards the south. Note the historical limit of gravels identified adjacent to the town of Manzanita B) A well-vegetated backshore provides evidence of the stability of the gravel berm.

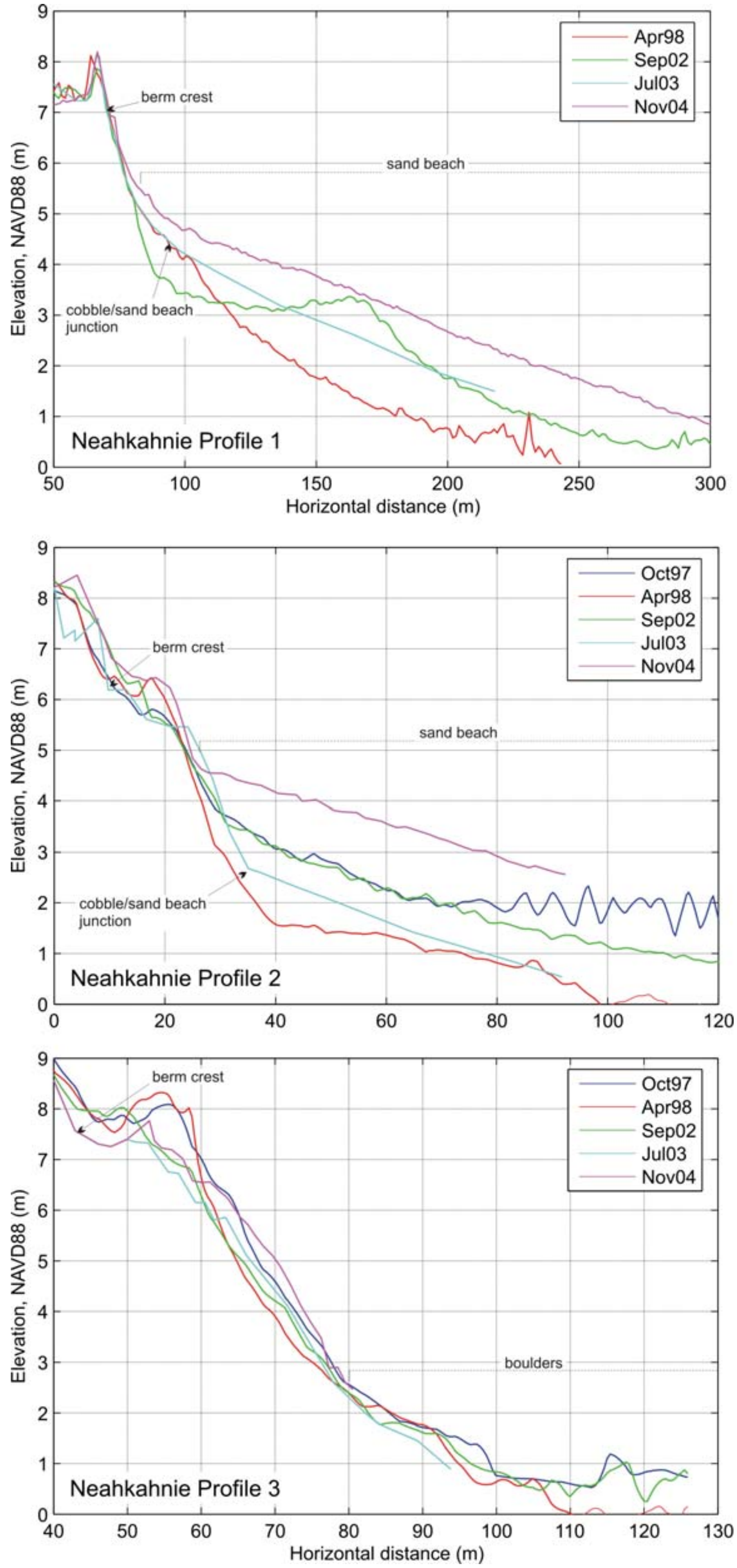

Figure 5.12: Beach profile surveys undertaken along the Neahkahnie gravel beach. The location of the transect sites is shown in Figure 5.10.

Results from the beach surveying are shown in Figure 5.12. Consistent with other beach gravel sites, the largest morphodynamic response on the beach profiles is due to the seasonal variability in the elevation of the sand beach, which varies by some 1 – 2 m (3 – 6 ft), while the gravel beach typically varies by less than 1 m (3 ft) in elevation. Horizontal variability (i.e., erosion or accretion) is clearly much less at Neahkahnie when compared with the other sites, with most of the variability being no more than a few meters. Of importance though is the fact that the gravel beach is stable with no evidence of long-term shoreline retreat. This is particularly apparent in Figure 5.11B, 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, which will be discussed later in the discussion section. Beach slopes are again consistent with the other sites, varying between 7.5º to 9.0º. The volume of gravel in the beach is greatest at profile 3 (177 m^3 per meter of beach (1905 $ft^3.ft^{-1}$)), and decreases substantially to 40 $m^3.m^{-1}$ (430 $ft^3.ft^{-1}$) at profile 2, and 51 $m^3.m^{-1}$ (549 $ft^3.ft^{-1}$) at profile 1.

5.1.2.2 Cape Meares/Short Beach

The Cape Meares gravel beach is approximately 2.3 km (1.4 miles) in length and is located on the north side of the headland, adjacent to the community of Cape Meares. The southern portion of the beach is actively 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. While the berm extends some 2.3 km (1.4 miles) along the beach, gravel can be identified up to several kilometers from the main berm, providing testimony to the large northward transport of gravel along the shore (Figure 5.13).

Results from the beach surveying are shown in the top two plots of Figure 5.14. The southern profile crosses a small erosional scarp that is about 1.5 m (5 ft) high, while the northern profile crosses a gravel barrier spit. While the scarp indicates that the south end of the gravel beach has been subject to erosion in the past, the backshore receives significant additional protection from the accumulation of logs along the crest of the beach that is likely serving an important role in mitigating much of the incident wave energy across the gravel beach.

As can be seen in Figure 5.14, the beach crest elevation is highest in the south at profile 1, reaching 6.8 m (22 ft), but decreases significantly to 5.8 m (19 ft) in the north. Furthermore, the slope of the gravel face is steepest in the south (~8.8º) and decreases to 6.9º at profile 2. Interestingly, the northern gravel profile 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 gravels on the beach. For example, the sediments are classified as 'small cobble' and have mean grain sizes that range from –6.4Ø (87 mm) to –6.7Ø (100 mm), while the sediments are 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 subject to more persistent overtopping. Evidence for this included numerous logs along the crest of the beach and landward, and debris from a recent storm.

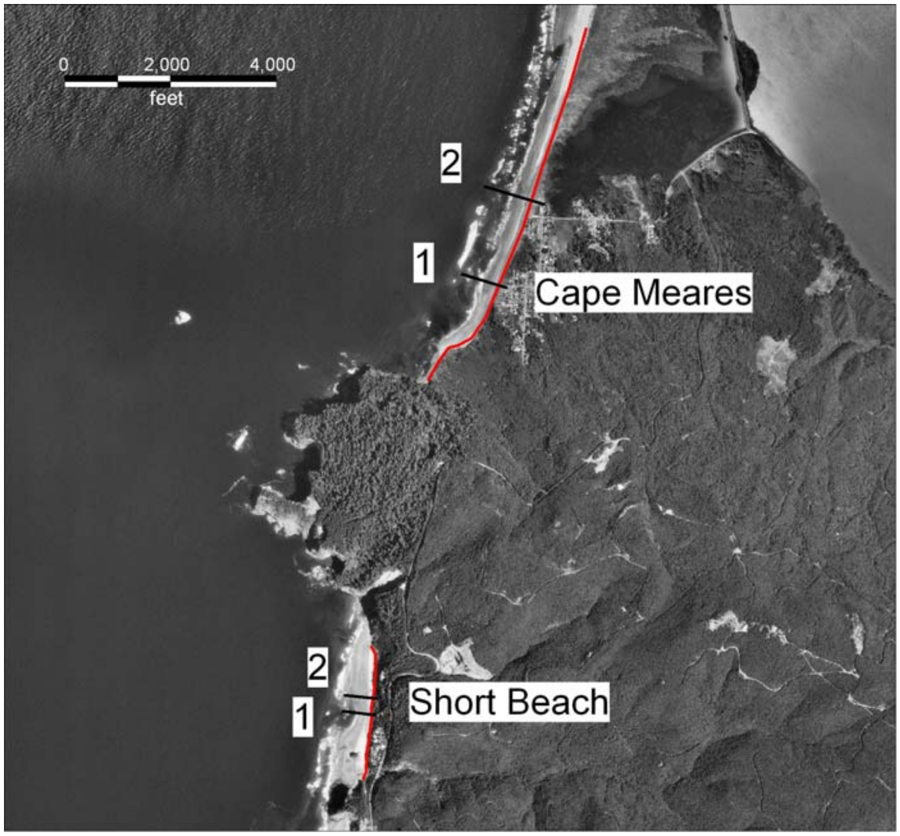

Figure 5.13: The Cape Meares and Short Beach gravel beaches showing the shoreline configuration, locations of beach profile sites and grain size sampling

In addition, it is apparent from Figure 5.14 that the gravel beach initially eroded landward between 1997 and 1998 (i.e., in response to the major 1997/98 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 1998/99 winter, 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 sediments having been transported inland.

Apart from lowering of the berm crest, the beach did not recede landward. This tends to reinforce the view concerning the level of resistance provided by natural gravel beaches. Since September 2002, the crest of the gravel beach has slowly been aggrading, having rebuilt itself by 0.25 m (0.8 ft).

To the south of Cape Meares is another gravel beach located at Short Beach (Figure 5.13). The beach is a composite beach type (**e**), characterized by a prominent gravel deposit and fronted by a wide dissipative sand beach. Although there is evidence of the backshore having experienced some 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 miles) long. However, the beach has similar morphological characteristics to other sites along the coast (Figure 3.2, left). Mean grain sizes ($M_zØ$) at Short Beach were found to be uniform at both study sites (~-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 ranged between 20 to 27 m (66 – 89 ft), while the gravel volume is estimated to be about 54 m^3 per meter of shoreline (581 $ft^3.ft^{-1}$).

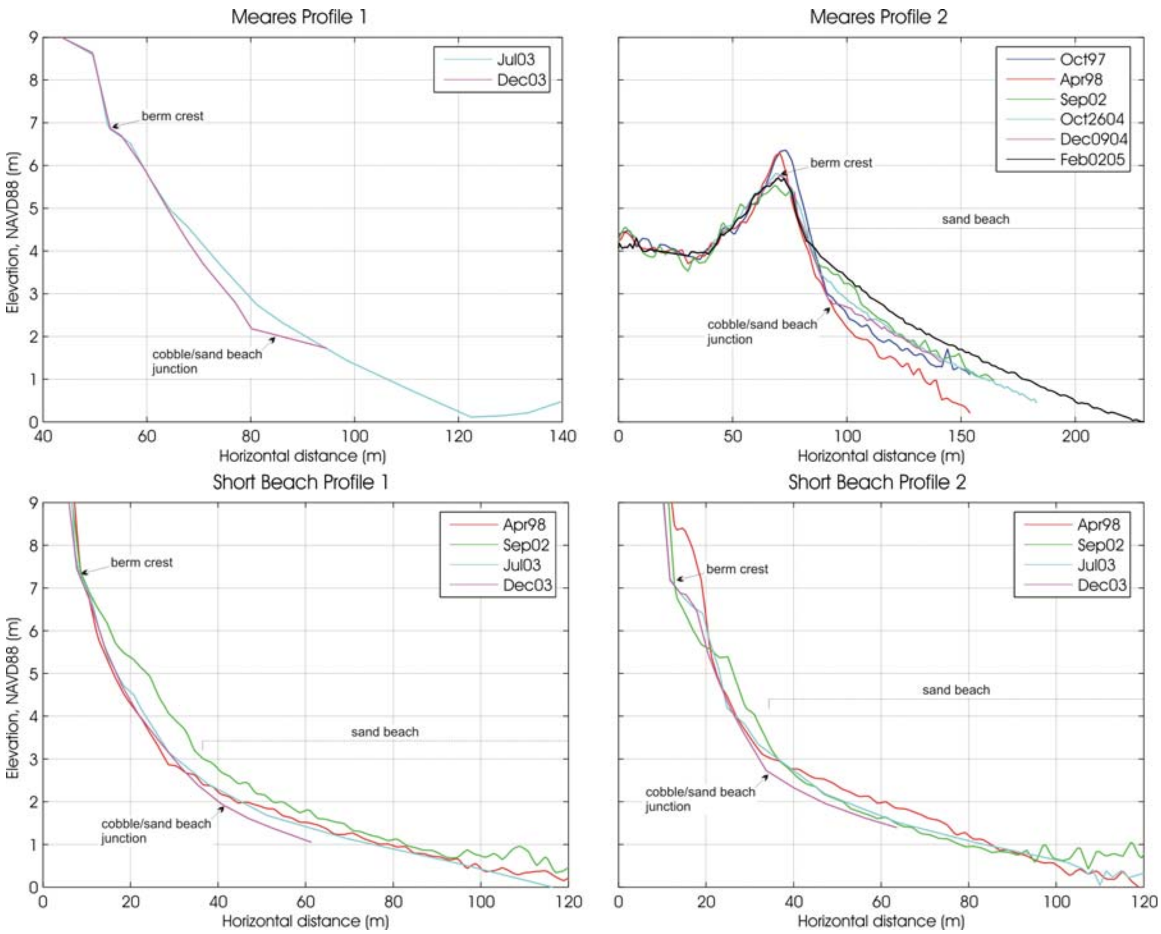

Figure 5.14: Beach profile surveys undertaken at Cape Meares and Short Beach. The location of the transect sites is shown in Figure 5.13.

Measured crest elevations along Short Beach were found to be some of the highest on the coast and varied around 7.3 m (24 ft) NAVD'88, while the beach slopes are steep (~11º). Apparent from Figure 5.14 is that the crest of the gravel beach appears to have been as high as 8 m (26 ft), and was likely lowered to ~7 m (23 ft) following the major 1998/99 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 and as a result had prograded seaward by several meters. However, this response has now been reversed so that the beach has essentially reverted back to a state similar to what it was like in April 1998.

5.1.2.3 Oceanside/Cape Lookout State Park

The Netarts littoral cell is approximately 12 km (7.5 miles) in length and is located between Cape Lookout in the south and Cape Meares in the north. Gravel beach deposits exist at a number of locations including Cape Lookout State Park (CLSP) located at the south end of the cell (Figure 5.15), Oceanside in the north, and Short Beach (described above). All three beaches are characterized as composite beaches (category **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 back shore and has been stable for at least several decades (based on historical photos of the area going back to the 1920s), while the beach at CLSP has experienced significant erosion and shoreline retreat during the past 30 years (Figure 5.16).

Figure 5.15: The Oceanside and Cape Lookout gravel beaches showing the shoreline configuration, locations of beach profile sites and grain size sampling.

Figure 5.16: A) The Oceanside gravel beach. Note the well vegetated bluff face, which indicates that this site has been stable for some time. B) The gravel beach at CLSP. 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.

Despite the high rates of shoreline retreat observed on Netarts Spit, it is worth noting that erosion of the dune fronted by a gravel beach was typically some 20 – 40% lower when compared with the pure sand beaches farther north on the spit, reinforcing the view that gravel beaches can be effective at mitigating the incoming wave energy and 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.

To-date, the dynamic revetment has performed extremely well (*Allan, et al. 2003; Komar, et al. 2003; Allan and Komar 2004*), having survived several major storms including a number of events that resulted in the dynamic revetment and artificial dune being over-topped. Research on the response of the dynamic revetment at CLSP is ongoing and includes repeated beach surveys, sediment tracing and measurements of the wave runup on the structures.

The Oceanside gravel beach (Figure 5.16) is approximately 0.5 km (0.3 miles) in length and has a crest elevation that ranges from 5.5 to 6.0 m (18 – 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 – 55.7 mm), while the sediments were again described as well sorted. Monitoring of the Oceanside profiles commenced in November 2002 as part of the CLSP dynamic revetment study initiated by Allan and Komar and has been ongoing ever since. Results from the beach surveys indicate that the gravel beach is narrow, with a width that ranges from 6 – 8 m (20 – 26 ft), while the beach slopes (11 - 13º) are comparable to the other gravel beaches described above. The volume of gravel contained on this beach is small and ranges from 11 – 14 m^3 per meter of shoreline (118 – 151 $ft^3.ft^{-1}$). Despite its small gravel volume, however, the beach at Oceanside has been characterized by only minor morphological changes and no erosion of its backshore, which suggests that other factors are likely contributing 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 experienced along the southern 3 km (1.9 miles) of the Netarts Cell (Figure 2.4) is related to the occurrence of major El Niños that contribute to hotspot erosion along the south end of several of Oregon's littoral cells. While some of the eroded sand is removed offshore to form nearshore bars, a large portion of the sand is transported to the north where it accumulates offshore from Oceanside (*Revell, et al. 2002*).

Significant dune erosion and hence the release of large volumes of sand is also occurring along the northern half of Netarts Spit. For example, Allan, et al. (*2004*) indicated that approximately 1.1 million m^3 (1.5 million $yard^3$) of sand have been eroded from the northern 4.5 km (2.9 miles) of the spit between 1998 and 2002. As a result, it is apparent that there has been a considerable injection of sand into the coastal system. Furthermore, there is good evidence that indicates that significant quantities of sand are accumulating offshore from Oceanside, to the extent that it is now affecting the operation of the town's sewer outfall (i.e., the diffuser head is periodically being buried). Accordingly at Oceanside, the accumulation of sand 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.

The Netarts gravel beach extends from Cape Lookout northwards for about 2.8 km (1.7 miles). The natural gravel beach is characterized by crest elevations that range from about 4 to 7.2 m (13 – 23.6 ft), while the average elevation is 5.6 m (18.4 ft). In contrast, the constructed dynamic revetment 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, since this portion of the berm was constructed to a lower crest elevation [initially ~5.0 m (16.4 ft) and now ~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) wide. 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 ranged from -6.2Ø (73.5 mm) on the natural gravel beach to -6.5Ø (90.5 mm) on the dynamic revetment. Accordingly, beach slopes are very similar to the other study sites, with the slopes varying around 10.4º to 11.4º. Finally, the volume of gravel contained in the beach ranges from 24 m^3 (258 $ft^3.ft^{-1}$) per linear meter of shoreline on the natural gravel beach to an average of 66 $m^3.m^{-1}$ (710 $ft^3.ft^{-1}$) on the dynamic revetment.

Analyses of the response of the natural cobble beaches and dynamic revetments sites has revealed that both areas respond in a similar fashion. At the north end of the dynamic revetment, the structure initially lost 5.2 m^3 per meter of shoreline (56 $ft^3.ft^{-1}$) of cobbles between July 2001 and February 2002 with most having been eroded from the lower portion of the gravel face. After February 2002 the structure did not lose any appreciable volume until early in the 2002-03 winter, when a series of large storms between

November and December 2002 resulted in the loss of an additional 6.1 $m^3.m^{-1}$ (66 $ft^3.ft^{-1}$) of gravels. While 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 was reversed, however, between December 2002 and late January 2003, when the north end of the dynamic revetment received an injection of gravel [+12.9 $m^3.m^{-1}$ (139 $ft^3.ft^{-1}$)], which caused the structure to prograde seaward by 3.5 to 5.0 m (11 – 16 ft). The dynamic revetment did not change significantly following the 2002-03 winter, although the upper portion of the structure continued to accumulate some gravel between March and June 2003 as material was moved up the gravel beach. With the onset of the 2003-04 winter, the north end of the structure once again entered an erosional phase, although some gravel again 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 experienced little change over the first two winters (*Allan, et al. 2003*). Recently, however, the south end of the structure received an injection of gravel [+3.2 $m^3.m^{-1}$ (34 $ft^3.ft^{-1}$)] as a slug of material moved across the structure in response to a series of storms early in October 2003. Given that this response extended towards the center of the structure, the volume of additional gravel that accumulated along the southern half of the structure is approximately 125 m^3 (163 $yard^3$). The source of this material is believed to be the natural gravel beach to the south of the structure, which has been steadily loosing sediments since monitoring began.

Sediment tracing of tagged gravels and analyses of grain size statistics along Netarts Spit confirm that gravel is being transported from south to north (*Allan, et al. 2003*). In fact, the loss of sediments south of the dynamic revetment is now beginning to pose a problem for OPRD since erosion of the backshore deposits has increased significantly (~ -3 m/year (-10 ft/year), 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 gravels will be required in order to maintain the integrity of such structures.

5.1.3 Lincoln County

5.1.3.1 Cummins and Bob Creek/Muriel Ponsler State Park

The region between Cape Perpetua and Heceta Head is comprised of a series of small pocket beach littoral cells, many of which contain gravel beach deposits. However, 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 the waves to break offshore on the reefs, thereby mitigating much of the incident wave energy. This is often further aided by the presence of a wide sand beach at several sites that also serve to mitigate the incoming waves.

Furthermore, unlike the north coast beaches, the central coast gravel beaches are much smaller in size and volume, typically averaging only several hundred meters in length. The exception is the gravel beach adjacent to Muriel O. Ponsler scenic waypoint, which is almost 3 km (1.9 miles) in length. Figure 5.17 identifies the locations of six representative profile lines selected between Cummins Creek and Heceta Head, while Figure 5.18 describes the morphological response of the beaches over the past several years.

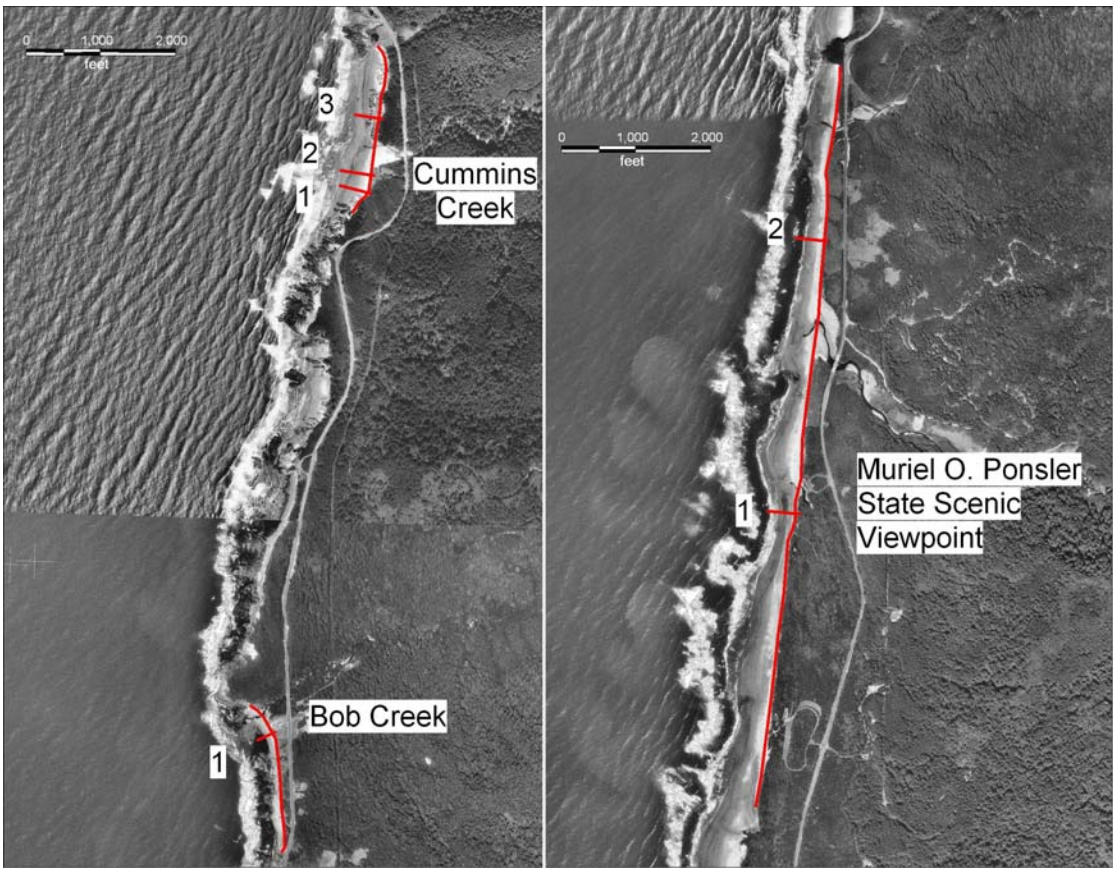

Figure 5.17: Gravel beach study sites on the Central Oregon coast. Left figure shows the locations of beach profile sites and grain size sampling locations for Cummins and Bob Creek, while the right figure is of the gravel beach adjacent to Muriel O. Ponsler State Scenic viewpoint.

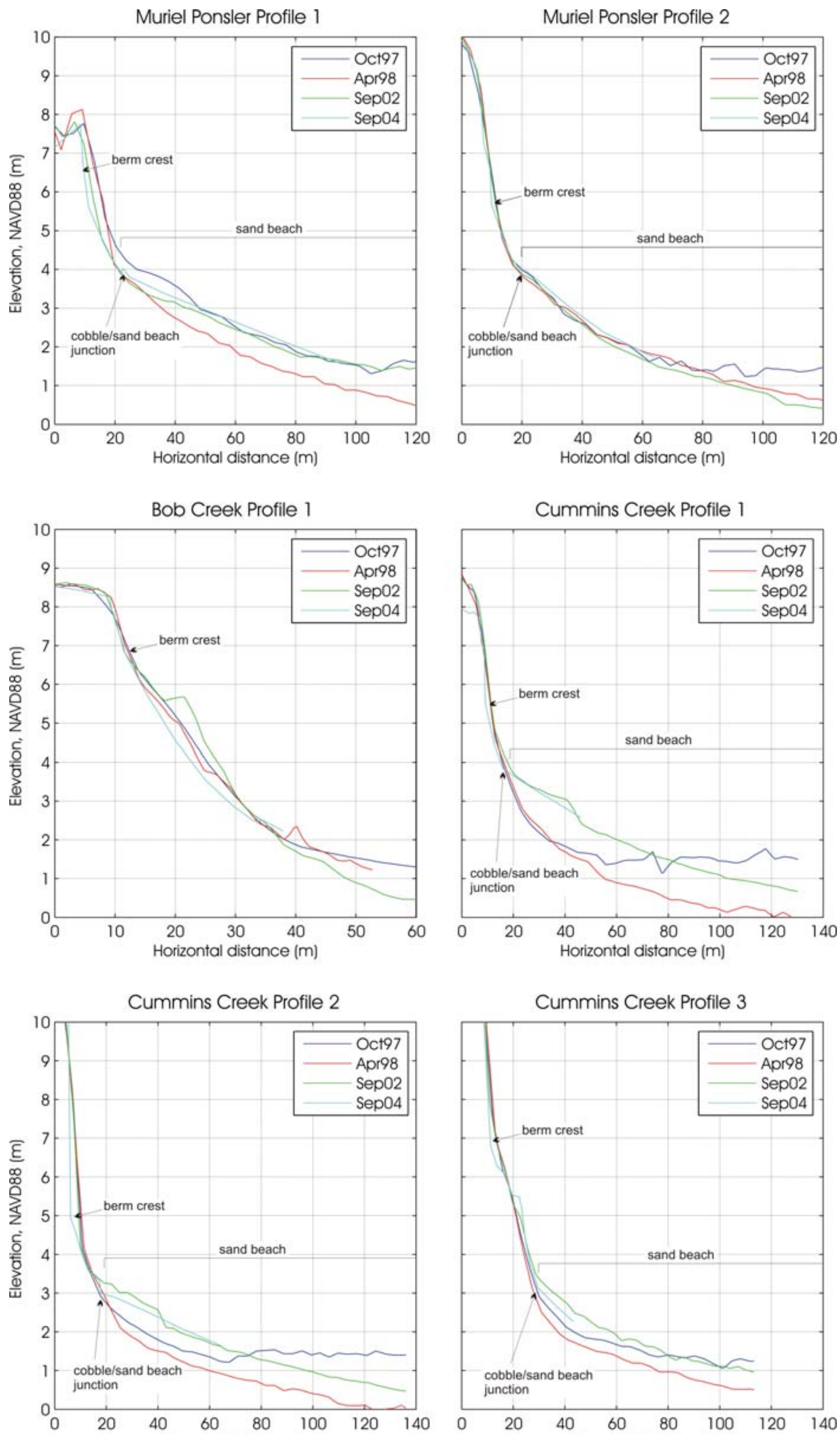

Figure 5.18: Beach profile surveys undertaken at Cummins Creek, Bob Creek and adjacent to Muriel O. Ponsler State Scenic Viewpoint. The location of the transect sites is shown in Figure 5.17.

Gravel beach widths were found to range from several meters up to 26 m (85 ft) wide, while the average width was approximately 14 m (46 ft) compared with 40 m (131 ft) on the north coast. As a result, the volume of gravels contained on the central coast beaches tended to be significantly lower, with the majority of the beaches containing less than 40 m^3 per linear meter of beach (430 $ft^3.ft^{-1}$). Despite their relatively small dimensions, however, the beaches are still characterized with crest elevations that are comparable to those on the north coast, ranging from 5 to 7.2 m (16 – 24 ft). Apart from the large gravels identified at profile 2 (-6.65Ø (100 mm)) adjacent to the Muriel O. Ponsler viewpoint, mean grain sizes (M_zØ) at the remaining study sites were uniform and ranged from –5.77Ø (55 mm) to –5.96Ø (62 mm). The predominant beach slopes tended to be much the same as those on the north coast averaging 11.5º.

Figure 5.18 reveals that the largest changes at each of the study sites is the seasonal variability in the sandy portion of the beach, which typically varies by 1 – 2 m (3 – 6 ft) vertically, while the gravel beaches have tended to experience only minor morphological change. Despite these small changes it is apparent from Figure 5.17 that each of the six profile sites have experienced some degree of erosion during the past several years. The erosion is worse at Muriel Ponsler 1 and at Cummins Creek 2, both sites having eroded landward by up to 5 m (16 ft) since 1997, while the gravel beaches at the other profile sites indicate only minor erosion.

Both Muriel Ponsler 1 and Cummins Creek 2 contain very small volumes of gravel, while Cummins Creek 2 is also characterized with a very low crest elevation. The larger erosion observed at these sites is probably largely a function of the low gravel volumes contained in the gravel beaches. In addition, neither of these sites receives any protection from an offshore reef and is thus almost entirely dependent on its sand beach to mitigate much of the incoming wave energy.

5.1.4 Curry County

5.1.4.1 Hooskanaden Creek/Brookings

Oregon's coastal geomorphology changes markedly south of Port Orford, with the beaches increasingly dominated by rocky shorelands, coarse sand or boulder beaches (Figure 5.19). While many of the beaches contain some gravel material, invariably the volume of gravel on the beaches is negligible. Thus 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. These sites included Hooskanaden Creek, located about 20 km (12 miles) north of Brookings, and Sport Haven Park located adjacent to the Chetco River. Figure 5.20 identifies the location of each of the study sites, while Figure 5.21 depicts the beach survey data. Unfortunately, only one survey period is shown in Figure 5.21. At the time of the survey we did not have a GPS system for surveying in the locations of the transects. Thus, it was not possible to include LIDAR data in these plots for comparative purposes. Furthermore, there is no LIDAR data for 1997 and 1998 for this part of the coast.

Figure 5.19: (Left) A mixed sand and gravel beach south of Port Orford that is backed by a small amount of gravels. (Right) A coarse sand beach merges into a boulder beach near Humbug Mountain.

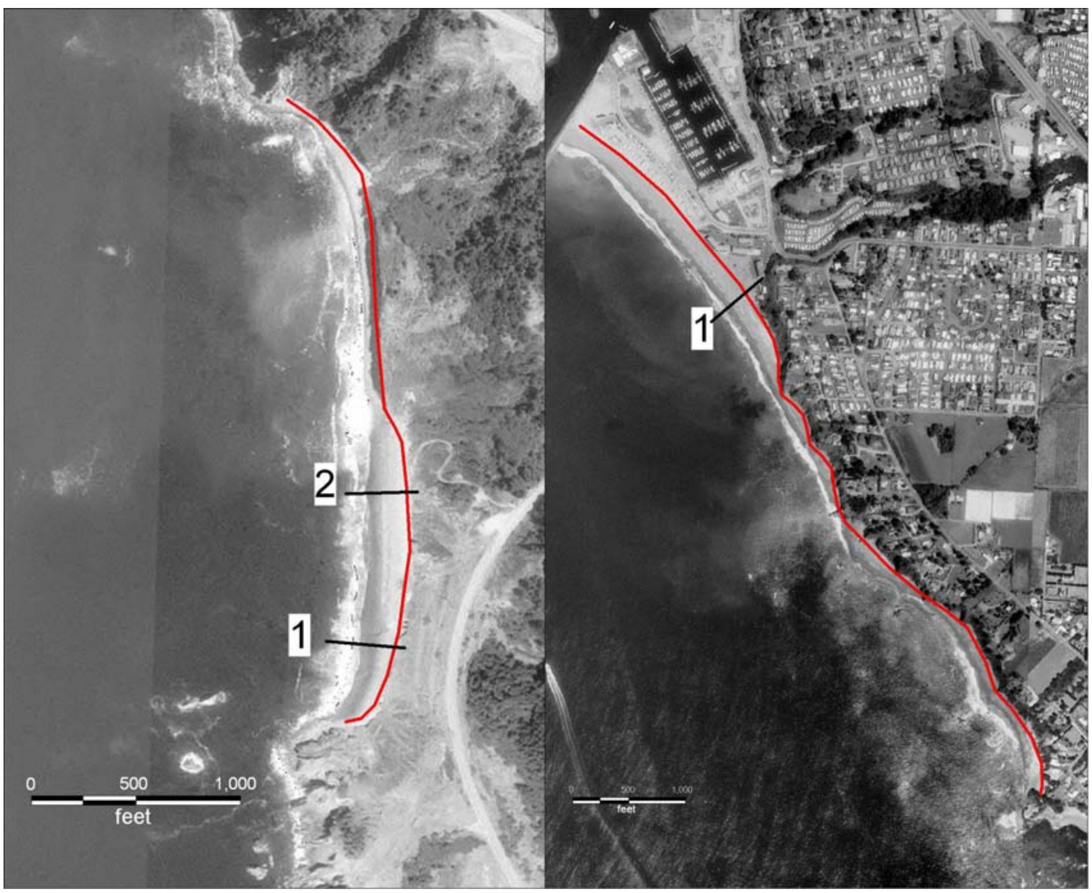

Figure 5.20: Gravel beach study sites on the Southern Oregon coast. Left figure shows the locations of beach profile sites and grain size sampling locations for Hooskanaden Creek, while the right figure is of the gravel beach at Sport Haven Park, Brookings.

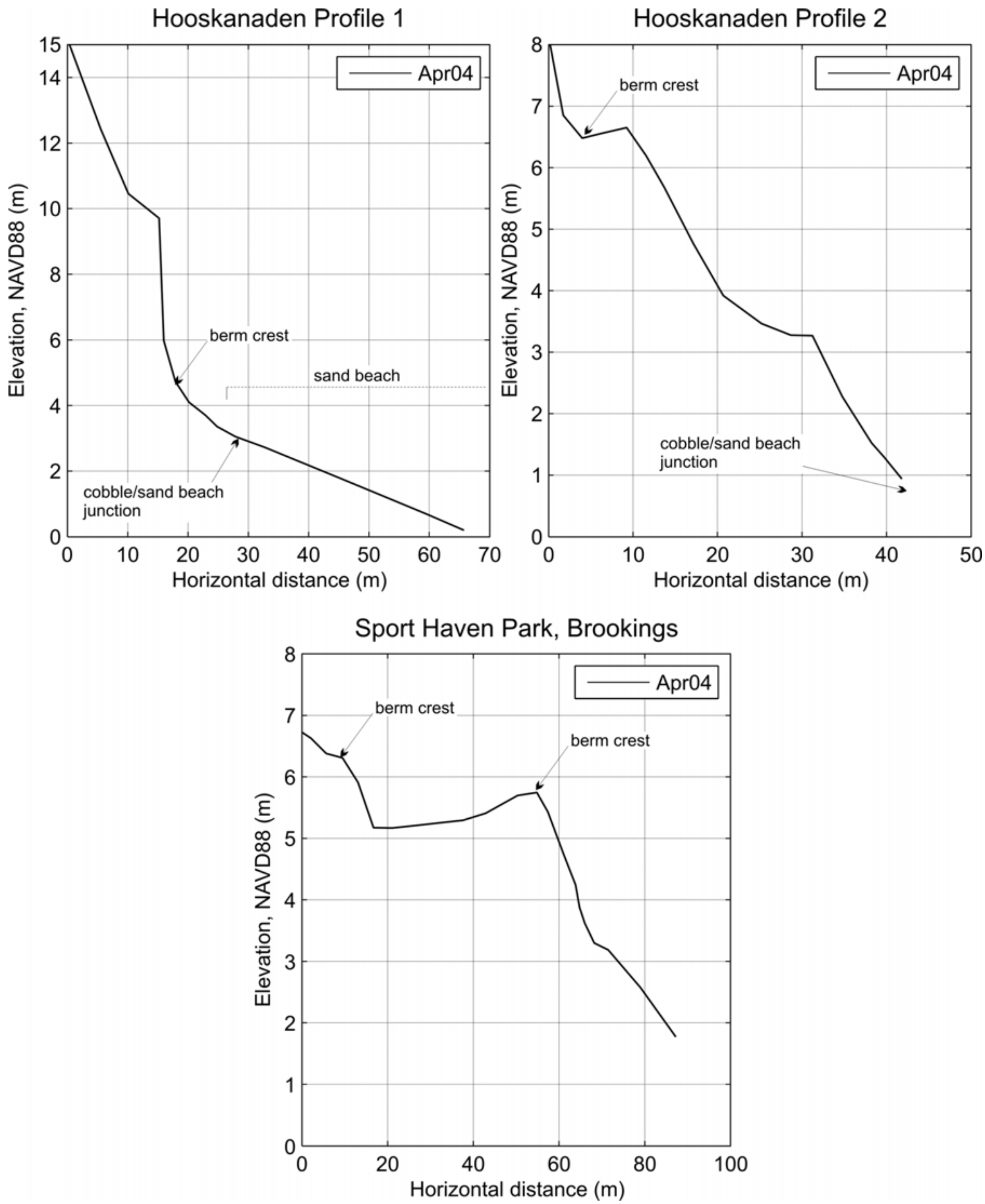

Figure 5.21: Beach profile surveys undertaken at Hooskanaden Creek and at Sport Haven Park adjacent to Brookings. The location of the transect sites is shown in Figure 5.20.

Hooskanaden Creek is a 1 km (0.6 miles) long gravel and sand beach. A significant gravel beach exists along the northern two-thirds of the shore (profile 2, Figure 5.21), while the southern most portion has been depleted of its gravels and is now experiencing erosion (profile 1, Figure 5.21). The site is particularly relevant to this study, as U.S. Highway 101 is located adjacent to the beach, having been built on fill that is now being eroded by ocean waves. At the time of our site visit in April 2004, ODOT crew were in the process of removing approximately 3 - 4.5 m (10 - 15 ft) of part of the Hooskanaden Culvert, a testimony to the amount of erosion that has been taking place 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 mean grain size ($M_zØ$) identified at Hooskanaden Creek is –6.8Ø (112 mm), which reflects large cobbles, and the sediments are described as well sorted. However, despite the coarse nature of the sediments on the beach, the slope of the two profile sites is typically less steep when compared with those sites in the north, averaging only 8.8º. 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), while the width of the gravel beach is less than 20 m (66 ft) wide.

The south end of the beach is characterized by an extremely small volume of gravels that averages about 7 m^3 per linear meter of beach (75 $ft^3.ft^{-1}$). 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, and the width of the gravel beach is approximately 40 m (131 ft). Thus the volume of gravels on the beach in the north is significantly greater, reaching approximately 120 $m^3.m^{-1}$ (1291 $ft^3.ft^{-1}$).

These data suggest that the gravels from the south end of the beach are probably being stripped out and transported northwards along the shore where they are accumulating around profile 2 and farther to the north. The removal of the gravels 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 gravels in the north and placing them in the south in front of the culvert, raising the existing gravel beach crest elevation of 4.7 m (15 ft) to approximately 6.5 m (21 ft) and increasing the overall gravel volume accordingly.

The final site of interest is Sport Haven Park, located on the south side of the Coquille River mouth. Due to the presence of a wide gravel beach deposit at Sport Haven Park (Figure 5.21), characterized by at least two gravel ridges with elevations that range from 5.7 m (18.7 ft) to 6.3 m (20.7 ft) and a well vegetated backshore, this beach is considered to be stable. The beach is of interest in that it is characterized by the smallest sediments of all the study sites with a mean grain size ($M_zØ$) of -4.9Ø (30 mm), which is classified as coarse pebbles. Accordingly, the beach slopes at Sport Haven Park tends to be slightly lower (~8.8º) when compared with other gravel study sites. Beach crest elevations are only slightly lower when compared with other sites on the Oregon coast and reached 5.7 m (18.7 ft), while the width of the gravel beach was the second largest reaching some 70 m (230 ft) wide. Thus the volume of gravel contained in the beach was found to be large, reaching 189 $m^3.m^{-1}$ (2034 $ft^3.ft^{-1}$), the second highest identified on the coast.

5.2 DISCUSSION OF GRAVEL BEACH MORPHOLOGIES AND DYNAMIC REVETMENT DESIGN CHARACTERISTICS

The previous sections have described and documented the morphological characteristics of gravel beaches along the Oregon coast. Based on this analysis, several variables have been recognized that characterize the morphology of Oregon's gravel beaches and have been summarized in Table 5.1 for comparative purposes. These variables include the elevation of the gravel beach, slope of the gravel face, the sand beach slope (if present), the width of the gravel beach, gravel volumes, and the mean grain sizes identified at each study site. Table 5.1 also includes summary data expressed as averages of all the available data, and as averages based on discernable 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 5.1 also identifies those sites that exhibited evidence of recent backshore erosion (identified by the shaded italics), which suggests that the gravel beaches at those locations are generally ineffective at mitigating the 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 indicated in the previous section, evidence for backshore erosion was clearly apparent in the field as either a prominent erosion scarp or as an over-steepened bluff face that lacked any vegetation. In almost all the cases, the field observations were also supported by analyses of the LIDAR data, which demonstrated evidence of shore retreat.

Intuitively, one might expect to see some difference in the morphological characteristics of the beaches between those that are eroding and those that are stable. This is certainly not always the case in Table 5.1. For example, although five of the eroding beach profile lines exhibit crest elevations that are less than 6.0 m (19.7 ft) the other five do not, with the Cove Beach site having a beach crest of 7.0 m (23 ft). Similarly, there is no clear pattern in the beach slopes and grain-sizes identified along the coast. Perhaps more convincing is the fact that seven of the eroding 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 is probably an important consideration when designing a dynamic revetment for the Oregon coast. This will be discussed in more detail later in this section.

As indicated in Table 5.1, the mean crest elevation identified for Oregon's gravel beaches is on the order of 6.4 m (21 ft), while the standard deviation is ±0.7 m (2.3 ft), giving crest elevations that range from 5.7 to 7.1 m (19 – 23 ft). In addition, there is some suggestion that the north coast gravel beaches are on average higher [average ~6.6 m high (22 ft)] compared with the central and south coast sites, which average about 5.9 m (19 ft) in height. Clearly there are exceptions to this pattern, with a number of the south coast sites characterized by elevations that are more comparable to the 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 5.22), as demonstrated at Seaside, Arch Cape, Cove Beach and Neahkahnie. These plots were derived by walking the crest of the gravel beach using a Trimble

5800 GPS surveying system. Also included in Figure 5.22 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 5.3), to around 6.3 m (21 ft) at profile 2 (Figure 5.22). 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 5.22), from a low of 5.0 m (16 ft) south of profile 2 (Figure 5.10) 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 the incoming wave energy. Accordingly, the swash of the waves is able to reach much higher elevations in these areas, pushing the gravels up the beach face. At each of these sites the mean crest elevation is consistent with those presented in Table 5.1.

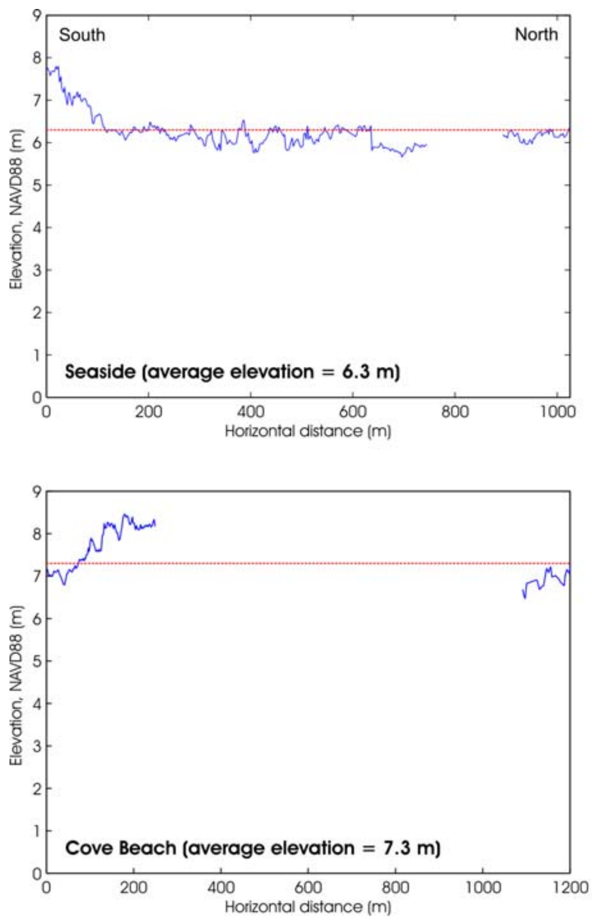

Figure 5.22: Alongshore variability in the crest elevation of the gravel beaches at four of the study sites on the northern Oregon coast. Data was derived using RTK-DGPS.

Table 5.1: Summary gravel beach morphology information for beaches along the Oregon coast

Profile (N = 27)	Gravel Beach Crest Elevation (m)	Gravel Beach Slope (º)	Sand Beach Slope (º)	Width of Gravel Beach (m)	Gravel Volume ($m^3.m^{-1}$)	Grain size (Ø (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 (64.9)
Seaside 3	5.8	8.6	0.8	132	427	-6.11 (69.1)
Arch Cape 1	6.5	11.9	2.2	25	46	-5.96 (62.3)
Arch Cape 2	6.7	9.3	2.8	23	53	-5.44 (43.4)
Cove Bch 1	*7.0*	*12.6*	*1.0*	*33*	*104*	*-5.74 (53.5)*
Cove Bch 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 Bch 1	7.4	10.5	2.0	27	67	-5.81 (56.1)
Short Bch 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 Crk 1	*5.5*	*13.8*	*2.4*	*7*	*8*	*-5.96 (62.3)*
Cummins Crk 2	*4.9*	*9.4*	*1.7*	*12*	*12*	*-5.93 (61.0)*
Cummins Crk 3	*6.8*	*11.3*	*3.7*	*18*	*42*	-
Bob Creek	*6.9*	*10.0*	-	*26*	*52*	*-5.91 (60.1)*
Muriel Ponsler 1	*6.7*	*12.8*	*1.8*	*13*	*14*	*-5.67 (50.9)*
Muriel 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	5.7	8.8	5.1	70	189	-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)**
St.Dev	**±0.7**	**±3.2**	**±1.1**	**±26.1**	**±88.4**	**± -0.5**

Notes:

- Netarts Spit[a] has been derived from LIDAR beach profile data and represents an average.
- Netarts Spit[b] has been derived from beach surveys and grain size measurements undertaken by Allan, et al. (*2003*), Komar, et al. (*2003*) and Allan and Komar (*2004*).
- Items in shaded italics denote sites subject to some form of backshore erosion, while values in parentheses in the width of gravel beaches and gravel volume columns reflect averages that exclude Seaside 3 and Sport -Haven Park in the calculation.
- To convert the gravel volumes to imperial units, multiply the values by 10.76 to yield cubic feet per foot of shoreline.

Figure 5.23 is a comparative plot of the change in gravel beach crest elevations, based on the 1997, 1998 and 2002 LIDAR data; they reflect information extracted from transects spaced 100 m apart in a Geographical Information System. The sites presented in Figure 5.22 are again the focus here, with the exception that Cove Beach and Arch Cape have now been combined into a single plot. The purpose of these data is to better understand both the temporal and spatial response of the gravel beaches with respect to how high and low the beach may aggrade or erode.

With the exception of Cove Beach and Arch Cape, the response of the gravel beach is generally minor, with the beach crest varying in elevation by about 0.5 to 1.0 m (1.6 to 3.3 ft) about a mean elevation of 6.5 m to 7.9 m (21 – 26 ft). It is possible that at Seaside and Neahkahnie, these minor morphological changes are due to the coarse nature of the sediments and the generally larger size of the gravel beaches when compared with Cove Beach and Arch Cape. Figure 5.23 also highlights the alongshore decrease in the crest of the beach, consistent with our measurements presented in Figure 5.22. However, the results for Neahkahnie indicate that farther out on the headland the elevation of the gravel beach reaches almost 10 m high (Figure 5.23).

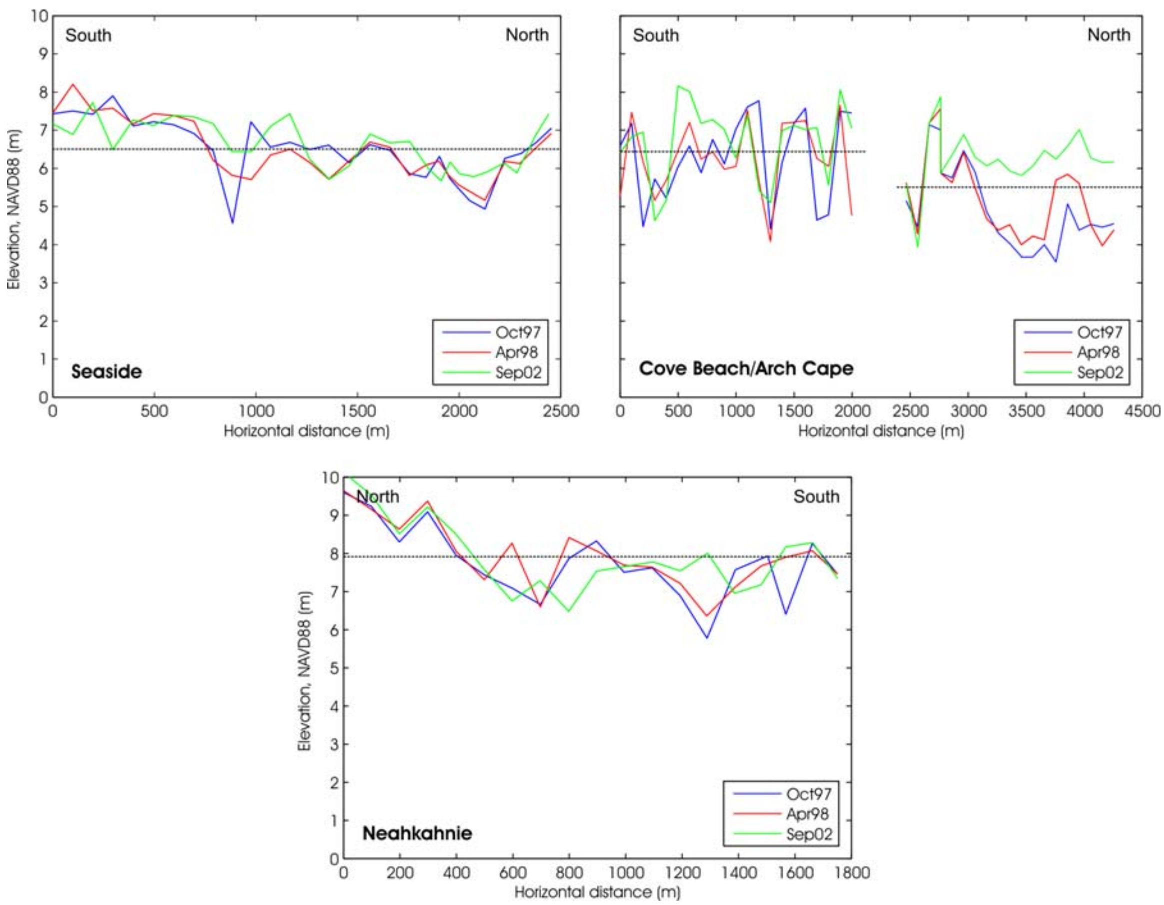

Figure 5.23: Temporal and spatial variability of the elevation of the berm crest along four selected north coast gravel beach study sites. Data derived from LIDAR.

Of interest is the response of the gravel beach at Cove Beach and Arch Cape. As shown in Figure 5.23, the gravel beach at Arch Cape 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 these gravels may have originated, as there is no evidence for a loss of gravels elsewhere along the beach. Apart from landslides, one likely possibility is that the sediments may have been located farther offshore on the lower beach face, where they were buried beneath the sand. With the arrival of the large winter storm waves during the 1998/99 winter, the sand beach would have been lowered exposing the gravels. Since gravels tend to remain on the beach face due to their larger size, it is likely that the sediments were carried onshore and up onto the gravel face due to the high swash velocities associated with the extreme 1998/99 winter waves.

The above analysis suggests that a design crest elevation of 7.0 m (23 ft) is probably the minimum height a dynamic revetment should be constructed for 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 the total water levels (wave runup + tides) that are achieved during extreme storms. One might expect to see a correlation between the height of the 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 the available sediments, the velocity of the swash uprush and how high the swash reaches on the gravel beach.

As indicated in Section 4.0 on methods, wave runup can be calculated empirically (Equation 4-1), using a model developed for the Oregon coast by Ruggiero, et al. (*2001*). The model requires information on the deepwater wave heights and peak spectral wave periods and the slope of the beach. The addition of the wave runup plus the tidal component provides a measure of the total water level (T_{WL}).

Wave statistics were derived from the Newport buoy for the period 1988 to 2004, while tide data covering the same period was obtained from the Newport tide gauge located in Yaquina Bay. Because gravel beaches on the Oregon coast are of the composite type, being comprised of a gently sloping sand beach that is backed by a steep gravel slope, determining an appropriate slope to use was not straightforward. The approach adopted here was to use a composite beach slope (i.e., average slope), based on both portions of the beach. For the purposes of this study we used a 10.9º gravel slope and a 1.7º sand beach slope, which resulted in a composite slope of 6.3º. The hourly total water levels (T_{WL}) were subsequently calculated using a script developed in MATLAB. From these data, we derived a maximum total water level for each of the winter months, since this is the period when the beaches are most susceptible to change. An extreme value analysis was subsequently undertaken using the Coastal Engineering Design & Analysis System (CEDAS) software developed by U.S. Army Corps of Engineers. The best-fit distribution curve is presented in Figure 5.24 and represents a Weibull fit with k = 2.0.

The calculated total water levels presented in Figure 5.24 are estimated to range from 8.1 m (27 ft) for an annual event to about 12.5 m (41 ft) for a 100-year storm. However, due to the limited 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 the calculated extreme total water levels and the preferred height of the gravel beaches presented in Table 5.1, although some of the heights shown in Figure 5.22 and 5.23 are close to the annual extreme event. Removing the effects of the extreme events that occurred during the 1998-99 winter from the extreme value analysis, produced 100-year water levels that were about 11.5 m (37.7 ft), which is still unreasonably high, while the annual T_{WL} drops to ~7.8 m (25.6 ft), much closer to the preferred heights of the gravel beaches.

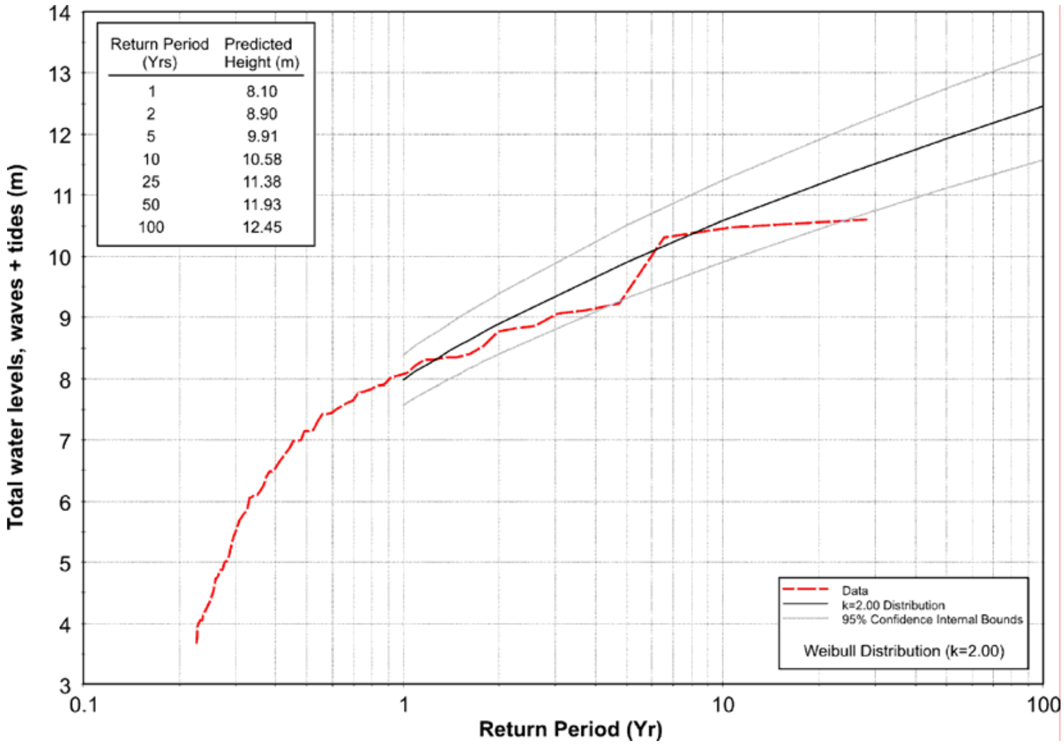

Figure 5.24: An extreme value analysis of total water levels (combined wave runup and tidal elevations) performed for gravel beaches on the Oregon coast (N = 76)

While the extreme value analysis is tending to over-predict the T_{WL}'s, this process is probably also being enhanced by the Ruggiero, et al. (*2001*) wave runup model, which was originally derived for Oregon's dissipative sand beaches and not for gravel beaches. As a result, the wave runup model is likely over-estimating the true T_{WL} for Oregon's gravel beaches. In addition, it is important to bear in mind that the Ruggiero, et al. wave runup model is based on a 2% runup exceedence 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 and even 8 m elevations (*Komar, et al. 2003; Allan, et al. 2003*). However, these events are probably not as common as implied in Figure 5.24. An ongoing objective of our work at CLSP is to undertake measurements of wave runup, which may be used to develop a suitable empirical runup model for coarse beaches on the Oregon coast.

Figure 5.25 presents a histogram plot of the hourly total water levels, binned at 0.1 m (0.3 ft) intervals, and a cumulative frequency plot of the calculated total water levels. As can be seen in the figure, the calculated total water levels (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 5.25, for 25% of the time the total water levels exceeded an elevation of 4.8 m (16 ft), and for 10% of the time they exceed an elevation of 5.6 m (18 ft). For 5% of the time, the T_{WL} exceeds an elevation of 6.0 m (20 ft), and exceeds 7.0 m for only 1% of the time. Accordingly, these latter results suggest that it is probably reasonable to construct a dynamic revetment to an elevation of 7.0 m (20 ft). However, it is important to appreciate that such a structure would be periodically over topped. One approach for minimizing any potential impacts on the backshore associated with such events is to create a berm with a broad crest, or to utilize an artificial dune such as that which was constructed at CLSP.

In addition to identifying a preferred design crest elevation for dynamic revetments, it is also necessary to assess the beach slopes and gravel grain sizes. As can be seen in Table 5.1, there is little variation in the slopes of the gravel beaches and grain sizes along the Oregon coast, with the mean slope averaging 10.9º (i.e., a 1-on-5.2 slope). The average mean grain size is approximately –6.05Ø (66.3 mm), which is classified as 'small cobble.' This is not a surprise, since the beach slope and mean grain size are closely related (*Komar 1998*).

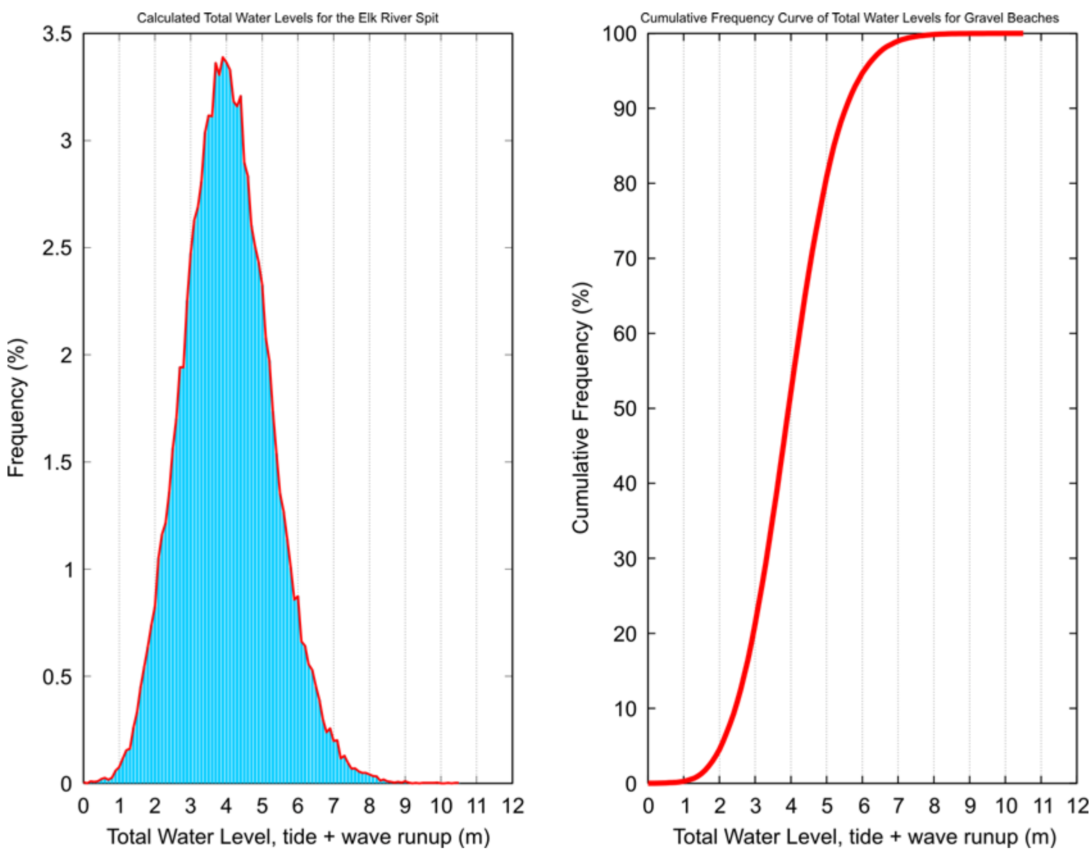

Figure 5.25: Calculated winter total water levels for gravel beaches based on an average beach slope (S = 0.110) expressed as a frequency distribution and a cumulative frequency curve (N = 55,504). Note: data span the period from January 1988 to December 2004.

A summary plot of grain size distribution curves for each study site is presented in Figure 5.26. 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. The advantage of this approach is that one can quickly identify those study sites that may be influenced by a mixing of different sediment populations such as sand, gravels and boulders. In contrast, sediments that are normally distributed will plot as a straight line on Figure 5.26, while sites subject to a mixing of sediment populations will be characterized by inflections on the lines. Included in Figure 5.26 are the average mean grain sizes identified for each shoreline segment.

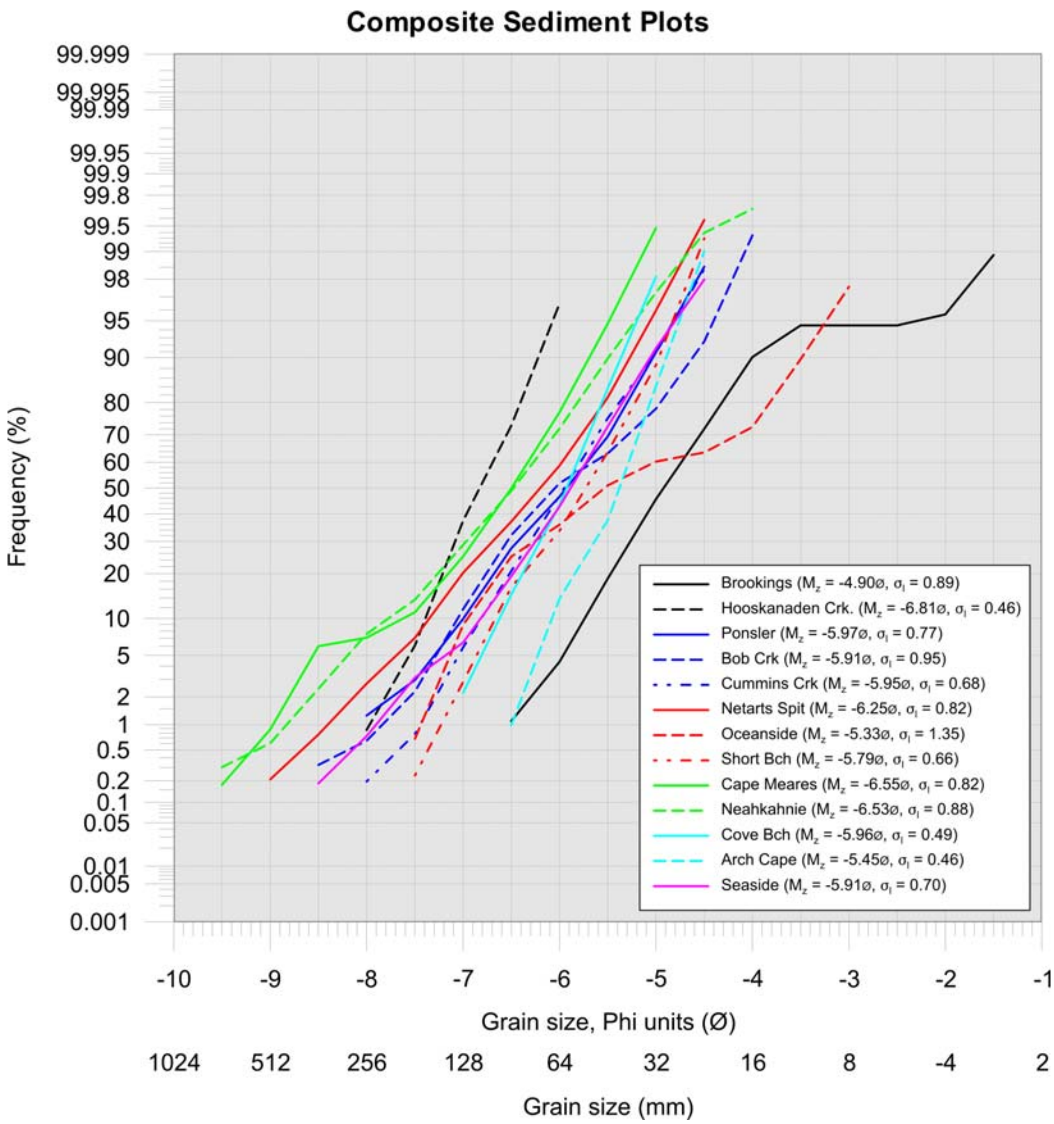

Figure 5.26: Grain size distribution curves derived for various gravel beach sites along the Oregon coast

As can be seen in Figure 5.26, the majority of the study sites sampled are characterized by straight lines, which indicates uniform sediment populations dominated by gravels 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 at Cape Meares), which reveal grain size populations that are composed of a mixture of predominantly coarse gravels and a tail of boulder-size clasts. At the other end of the spectrum, the Brookings site is dominated by a mixture of gravels, with a long tail of granules and coarse sand that are likely related to both the fluvial origins of the sediments and the different lithologies that characterize this part of the Oregon coast. Although subtle differences in the grain size distributions can be identified, they are unlikely to complicate the choice of a preferred grain size. Accordingly, we recommend a mean grain size that is no less than –6.0Ø (64 mm) in size.

Although the slopes of the gravel berms appear to be uniform, Table 5.1 indicates that the same cannot be said for the slopes of the sand beach that fronts the gravel berms. As indicated in Table 5.1, the north coast sand beach slopes average about 1.7º, while the central to south coast study sites are characterized by beaches that are steeper (~3.1º). In all likelihood this 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 the mixed sand and gravel beach categories (**b** and **c**) described previously. However, these latter 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, since the latter provides additional dissipation of wave energy thereby providing some element of protection to the dynamic revetment.

Finally, it is useful in the design of dynamic revetments to examine the predominant widths and volumes of the gravel beaches. Table 5.1 indicates that the mean gravel beach width is 31 m (102 ft), while the mean gravel volume is ~81 m^3 per meter (872 $ft^3.ft^{-1}$) of shoreline. However, these data are likely skewed by the extremely wide gravel beaches at Seaside on the north coast and Sport Haven Park on the south coast. Thus separate estimates of the average widths and gravel volumes are also included in Table 5.1. These latter results indicate a mean width and volume of 25 m (82 ft) and 63 $m^3.m^{-1}$ (678 $ft^3.ft^{-1}$) respectively. Furthermore, there is also a regional difference in the width and volumes of the gravel beaches (Table 5.1), with the central to south coast study sites characterized by values that are respectively 35% and 57% 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 gravels. Figure 5.27 presents a step-wise linear regression that has been fitted to these data with the width of the gravel beach being the independent variable. As can be seen in the figure, both parameters are highly correlated ($R^2 = 0.95$). This is useful since it essentially 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 shown to be uniform along the coast).

Figure 5.27 also identifies those sites that have been experiencing erosion (highlighted in red). Ignoring Cove Beach, the general pattern suggests that sites subject to lower gravel volumes (< 50 $m^3.m^{-1}$) and gravel beach widths <20 m wide tend to be eroding (e.g., the central coast beaches) while sites characterized by higher values are generally more stable. The Cove Beach site is considered to be an exception since this site has no sand beach present in front of the gravel face. Accordingly, at Cove Beach the first line of defense is the gravel beach and, as can be seen in Figure 3.2, the beach is subject to waves at all tidal elevations and will therefore tend to be more responsive to waves and currents.

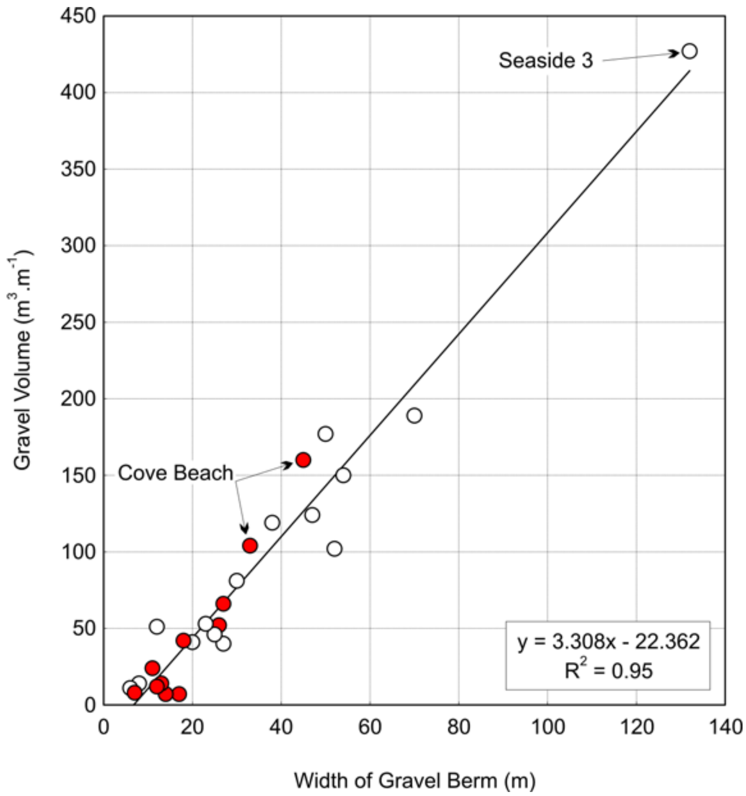

Figure 5.27: A step-wise linear correlation between gravel volume and gravel beach width derived for the Oregon coast. Solid color points are those sites that are currently experiencing erosion.

6.0 COBBLE SOURCES

The purpose of this component of the study was to investigate potential sources of cobble-sized rock, both naturally rounded and crushed quarry rock, and to discuss the logistics involved in moving it to coastal project sites. Data has been extracted from departmental databases, site visits, and by personal and telephone interviews with rock quarry operators, sand & gravel producers, port officials, and rail officials. Material source locations and operator contact information are included in the Appendix.

The effective use of cobble-sized gravels [~-6Ø (64 mm)] as a dynamic revetment to slow beach erosion at Cape Lookout State Park, Tillamook County, 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, as opposed to a conventional riprap revetment or seawall, which remains static in the face of sustained ocean wave attack and mitigates the energy largely by mass.

The construction of the dynamic revetment at Cape Lookout State Park involved the relocation of approximately 5340 m^3 (~7000 $yards^3$) of naturally sub-rounded to rounded particles of basalt that were obtained from two locations on Netarts Spit; 3058 m^3 (4000 $yards^3$) were derived north of the completed dynamic revetment while an additional 2294 m^3 (3000 $yards^3$) came from the south end of the cell adjacent to Cape Lookout. While OPRD was able to derive gravels locally, the same cannot be said for other potential project sites, raising the obvious question of where to obtain suitable gravels and how one might transport the sediments to a point of interest. In general, suitable round rock sources are not common along the Oregon coast, nor is extraction likely to be permitted from those few occurrences (mainly fluvial sources) that do exist. In contrast, roughly equi-dimensional, 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.

6.1 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 sediments in this size range are generally oversized for most applications and are typically crushed to smaller size fractions. Some operations produce unscreened material (“pit-run” or “quarry-run”) but most 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, while much larger clasts are stored for such purposes as constructing riprap revetments. Further sizing is rarely done, so these latter particles may range up to large boulders (i.e., intermediate axis widths that are on the order of 20” to 30” wide).

Round rock particle size is a function of source rock characteristics and erosion and transportation processes. Cobble-sized round rock can be generated in reaches of high energy streams, at sites of sea cliff erosion, and by glaciers and glacial floods. All such deposits occur in Oregon but few accessible sources are located near the coast. Examples include glacial flood deposits in Columbia County and alluvial deposits along the eastern margin of the Willamette Valley where major tributaries debouch onto 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 the rock as close as possible to finished product sizes and to minimize 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-sized 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 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 would be willing to effect such changes for a 10,000 ton project, others would not.

6.2 TRANSPORTATION AND HANDLING

Truck transportation would be necessary at some point for any coastal project requiring cobbles, either to the project from a near-coast source or to the project 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, any material source north of the beach could not have utilized a fully loaded truck/trailer because of the load limits on the bridge crossing Spencer Creek.

Rail transportation could possibly be used for some projects, especially if round rock from inland sources is required. Large volumes of rock could be moved more quickly and at lower cost than by truck, but the number of loading and unloading facilities is much 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, since 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, an approach used by the Port of Tillamook Bay Railroad to deliver 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 the time requirements this could be done only from a siding.

Barge transportation could be used to move rock from sources on the Columbia River or 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. There is also regular traffic of dedicated vessels along the coast carrying aggregate to southern California from British Columbia and gypsum from Mexico northward to various wallboard plants including one at Rainier, in Columbia County. 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-sized round rock. Systems designed to move smaller particles with a relative high angle of repose may not be able to contain larger round cobbles that could roll off conveyor belts, especially at steep conveyor angles.

6.3 COBBLE SOURCES

Most potential coastal project sites are within 30 miles of a rock quarry that could produce cobble-sized stone, assuming that crushed stone would be satisfactory (Figures 6.1 and 6.2). Nearly 40 quarries are listed in the accompanying database that are either currently active or have produced for at least two of the last five years. Inactive sites were included because operation can be sporadic, even for some large volume quarries, if they are dependent on only very 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 by 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 a year 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-sized material in the deposit. No variations in operating procedures can increase the number of cobbles present, and few deposits are cobble-rich. If a coastal project requires round cobbles, sources farther afield may have to be considered.

Only three near-coast sites appear to have potential for sufficient volume of round cobbles (Figure 6.2). All are owned by LTM, Inc. of Medford and none is in full production. The Elk River site, about four miles north of Port Orford, and the Broadbent site, about five miles south of Myrtle Point, were not yet permitted or in production in the Spring of 2004, and the permit application for the dredging operation on the lower Umpqua has been rejected. Inland sources containing cobbles are located near the Interstate 5 corridor in Jackson, Josephine, Douglas, and Linn Counties (Figures 6.1 and 6.2). All have varying access to rail. Operations near the Columbia River in Columbia County (Figure 6.1) have both rail and barge access and one company can also source cobbles by barge from its pits near Tacoma. While 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.

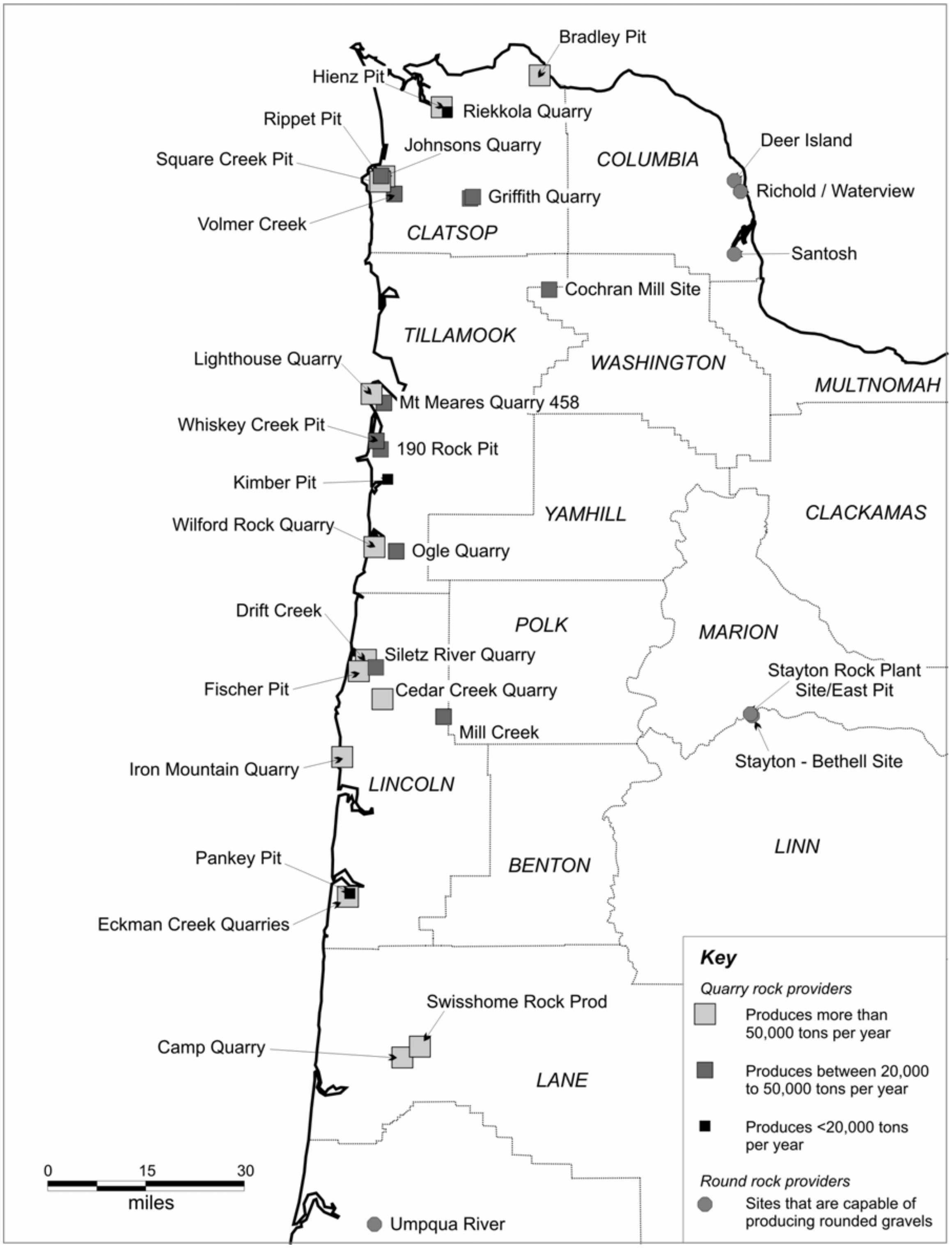

Figure 6.1: Location map of active rock quarry sites and quarries capable of producing rounded gravels on the central to northern Oregon coast

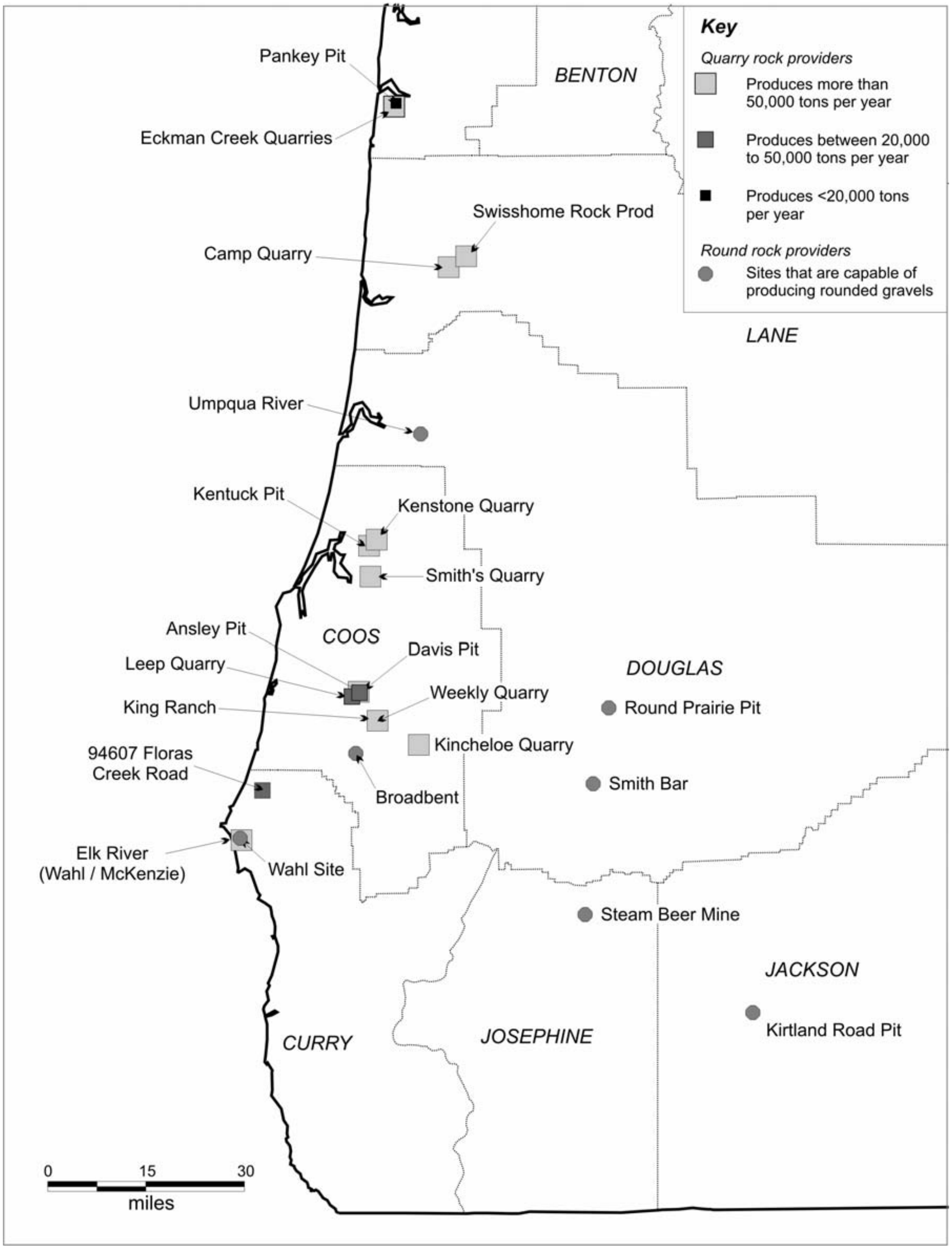

Figure 6.2: Location map of active rock quarry sites and quarries capable of producing rounded gravels on the central to southern Oregon coast

One other factor – aesthetics – may be of concern to some. Cobble and pebble beaches in Oregon are composed primarily of dark colored rocks – typically basaltic material. Cobbles from Cascade and Coast Range drainages would also be predominately dark, but Columbia River glacial flood deposits and alluvial and glacial deposits farther north can contain lighter colored stone including granite.

6.4 COSTS

Understandably, few operators are willing to commit to material or transportation costs without a specific project description, but from conversations with several producers and transportation companies the following generalizations can be made. These are only approximations.

Material cost would currently 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, transportation costs by truck average about $0.75 per ton per mile for hauls of a few tens of miles (*Mr. Tony Snyder, ODOT, personal comm. 2005*). However, this cost is dependent on a variety of factors including travel time, distance of travel, equipment type and on the type of road surface and may therefore vary accordingly. 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, approximately 210 miles 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, 85 highway 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, or possible demurrage fees, nor local handling and truck transport to the project site. Truck transport from Scappoose to Newport, approximately 150 highway miles, would be about $38 per ton.

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

6.5 DATABASES

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

Quarry rock lists 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. Located west of the approximate crest of the Coast Range

Each quarry site is ranked incrementally by annual production, obtained by dividing total production by the number of years of production. The increments are: less than 20,000 tons per year; 20,000 to 50,000 ton per year; and more than 50,000 tons per year. The larger operators would be more likely able to produce 10,000 tons of a specialty product, cobble-sized material, without major impact on their normal operation.

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.

7.0 CONCLUSIONS

The standard approach commonly adopted for preventing the erosion of coastal properties and other forms of infrastructure is to utilize "hard" engineering solutions such as riprap revetments, seawalls, or even bulkheads, which essentially thwart the effects of waves through their shear size and mass. There is a growing concern, however, over the potential impact such structures may have on the beach, particularly in terms of impounding sediments contained behind the structures. In addition, the structures essentially fix the coast in place, so that any prevailing long-term increase in mean sea level results in a progressive narrowing and loss of the beach width over time. Important for minimizing such negative impacts is the testing of innovative "soft" engineering alternatives that attempt to replicate nature by slowing the erosion to an acceptable rate while eliminating or reducing scour and beach sediment losses.

Researchers have long recognized 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. As a result they have been suggested as a form of shore protection. Such structures are variously termed "dynamic revetments," "cobble berms" or "rubble beaches." The approach essentially involves the construction of a gravel beach at the shore, in front of the property to be protected. As observed by Ahrens (*1990*) and Ward and Ahrens (*1991*), the dynamic structure is effective in defending properties because the sloping, porous cobble beach is able to disrupt and dissipate the wave energy by adjusting its morphology in response to the prevailing wave conditions. Apart from their resilience to ocean waves, dynamic revetments are also significantly easier to construct than a conventional riprap revetment or seawall. This is strongly aided by the fact that the particle sizes used in the construction are smaller and generally less expensive than the large armor stones, and placement of the gravels does not require any special attention.

In 1999, the OPRD constructed a dynamic revetment at Cape Lookout State Park on the northern Oregon coast, providing 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 a number of events that resulted in the dynamic revetment and artificial dune being over-topped. Damage to the structure has been minimal, suggesting that these types of structures may be a viable alternative to "hard" engineering solutions in the Pacific Northwest. There remain a number of uncertainties, however, concerning the physical design of such structures and the acquisition of suitable quantities of gravels to construct a dynamic revetment.

This study had two key objectives. The first was to undertake an assessment of the geomorphology of gravel beaches along the Oregon coast, with emphasis on identifying the 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 was 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 sediments 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, characterized by well-vegetated backshores. Most of the stable gravel beach sites can be found on the northern Oregon coast, while sites exhibiting evidence of backshore erosion tended to be concentrated on the central to 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 was no clear discernable 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 – 23 ft), while the recommended berm crest height should be no less than 7.0 m (23 ft).

- Given that the height of gravel beaches is regarded to be a function of the maximum runup achieved by waves during storms, analyses were undertaken to compare the heights of the beaches measured on the Oregon coast with the calculated total water levels – T_{WL} (wave runup plus tidal elevation) – using a model developed for dissipative sand beaches by Ruggiero, et al. (*2001*) and incorporating a composite beach slope of 6.3º. An extreme value analysis was subsequently performed on the monthly maximum T_{WL} values, which revealed extreme T_{WL}'s 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 over-predicts T_{WL}'s on gravel beaches. Accordingly, further efforts should be directed at developing a suitable empirical model to predict the runup of waves on coarse beaches, which encompasses Oregon's typical situation of a wide dissipative gently sloping sand beach that is backed by a steep sloping gravel beach.

- Although the extreme value analysis on the T_{WL} did not yield any meaningful correlation with the heights of the gravel beaches, a cumulative frequency plot of the hourly T_{WL}'s revealed that 5% of the time the T_{WL} exceeded an elevation of 6.0 m (20 ft), and only 1% of the time the 7.0 m height was exceeded. Accordingly, these results suggest that 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 periodically over topped, as has occurred on occasion at CLSP (*Komar, et al. 2003; Allan, et al. 2004*). One approach for minimizing any potential impacts on the backshore associated with such events is to create a dynamic revetment with a broad crest, or to utilize an artificial dune such as that which 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, and the sorting of the sediments was generally classified as well sorted to moderately well sorted. Based on this study, we recommend using particles with a mean grain size of -6.0Ø (64 mm). These sediments are classified as small cobble.

- 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, and 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 width of the gravel beaches and their volumes revealed that the north coast gravel beaches tended to exhibit wider beaches [~28 m (~92 ft)] and correspondingly larger volumes of gravel [~77 $m^3.m^{-1}$ (~830 $ft^3.ft^{-1}$)] when compared with the central to south coast gravel beaches, which were characterized by widths and volumes that were respectively 35% to 57% 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, based on an understanding of a design berm width.

In addition to the above conclusions, we recommend some consideration of the potential impact of longshore drift be included in any project design on the Oregon coast. Our review of the literature has highlighted several studies (e.g., Cape Lookout State Park, Oregon; Vancouver, Canada; Flathead Lake, Montana) which document the important role of longshore currents in transporting large quantities of sediment out of a project area. Accordingly, we recommend that a procedure for periodic maintenance be included in the project design, which may include returning some portion of those sediments transported out of the project area or periodically introducing additional new sediments as the gravel volume decreases. Alternatively, one could also evaluate an engineering solution such as a low weir-type groyne constructed across the dynamic revetment, which could reduce the rate of along-shore gravel transport (at least until the gravel begins to over-top the groyne).

Perhaps a major constraint that likely limits the adoption of dynamic revetments as a viable engineering solution on the Oregon coast is the identification of suitable gravel sources that could be utilized in the construction and maintenance of such structures. In an effort to address this issue, this study undertook an assessment of the spatial distribution and operational capabilities of quarry sites along the Oregon coast and west of the Willamette Valley. These data have been summarized in graphical form in Figures 6.1 and 6.2, and are provided as a searchable GIS database. Our main findings include the following:

- Our review of existing gravel quarries capable of producing rounded particles appear to reinforce the perception that these types of gravels are scarce in Oregon, being much more common in Washington State. Only five gravel quarry sites could be identified on the central to northern Oregon coast capable of producing "rounded" gravels in the -6Ø (64 mm) range, 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 44). In contrast, there are potentially seven sites on the south coast that could provide suitable sediments for the construction of a dynamic revetment, with the Elk River, Broadbent and Umpqua sites closest to the coast (Figure 6.2).

- Quarries capable of producing crushed gravels of a particular size are relatively more common, a number of which are located adjacent to major towns or transportation hubs (e.g., Astoria, Tillamook, Newport, and Coos Bay). As indicated in Figures 6.1 and 6.2, a significant number of these quarries are capable of producing ~50,000 tons of crushed rock annually. However, production of cobble-sized 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, 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).

- There are no quarries capable of producing crushed rock south of Port Orford. Accordingly, the construction of a dynamic revetment at Hooskanden Creek for example would have to utilize existing sediments on the beach (e.g., there is an abundance of gravels that have accumulated north of profile 2), or would have to be imported from an alternative source.

- 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 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 costs average about $0.75 per ton per mile for hauls of a few tens of miles. However, transportation costs are dependent on a variety of factors including travel time, distance of travel, equipment type and on 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, approximately 210 miles 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.

- 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. However, this does not include port, stevedoring, stockpiling, storage, or possible demurrage fees, nor 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.

8.0 RECOMMENDATIONS

Unresolved problems in need of further study include the following:

- Investigation of the rate at which crushed rock rounds to the appropriate diameter under varying wave conditions.

- Analyses of the along-shore 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,

- More 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 include:

    - Cape Lookout State Park, Tillamook County;
    - Spencer Creek Bridge, Lincoln County; and,
    - Hooskanaden Creek, Curry County.

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APPENDIX

APPENDIX

The following two tables list data about quarries capable of producing gravels suitable for the construction of a dynamic revetment.

Table A-1: Quarry rock

This table list 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 tons in one year of the last five years; and c) located west of the approximate crest of the Coast Range.

Site Name	Production Level	Owner	County	Address	City	State	Zip Code	Phone	Sec.	TWP	RGE	Latitude	Longitude
Road Builders	20,000 to 50,000 tons per year	Road Builder's Inc.; David & Lisa McClean	Clatsop	37222 Linda Lane	Seaside	OR	97138	503 738-5458	22	5N	8W	45.9036	-123.658
Kimber Pit	less than 20,00 tons per year	Kimber, Eugene	Tillamook	25000 Sandlake Road	Cloverdale	OR	97112	503 965-6670	21	3S	10W	45.2947	-123.911
Wilford Rock Quarry	more than 50,000 tons per year	D.K. Quarries, Inc.	Tillamook	PO Box 10	Otis	OR	97368	541 994-8584	7	5S	10W	45.1477	-123.952
Riekkola Quarry	less than 20,00 tons per year	Riekkola Quarry; Jon Riekkola	Clatsop	91640 Youngs River Road	Astoria	OR	97103	503 440-0257	18	7N	8W	46.0897	-123.728
Leep Quarry	20,000 to 50,000 tons per year	Roseburg Resources Company	Coos	PO Box 1088	Roseburg	OR	97470	541 679-3311	30	28S	12W	43.1150	-124.163
Volmer Creek	20,000 to 50,000 tons per year	Osburn Brothers Rock	Clatsop	PO Box 2069	Gearhart	OR	97138	503 738-7709	14	5N	10W	45.9128	-123.891
Griffith Quarry	20,000 to 50,000 tons per year	Bayview Transit Mix, Inc.	Clatsop	PO Box 619	Seaside	OR	97138	503 738-5466	22	5N	8W	45.9055	-123.652
Pankey Pit	less than 20,00 tons per year	Cedar Creek Quarries, Inc.	Lincoln	PO Box 730	Newport	OR	97365	541 265-9441	33	13S	11W	44.3980	-124.028

Site Name	Production Level	Owner	County	Address	City	State	Zip Code	Phone	Sec.	TWP	RGE	Latitude	Longitude
94607 Floras Creek Road	20,000 to 50,000 tons per year	Stonecypher Ranch, Inc.	Curry	PO Box 328	Sixes	OR	97476	541 348-2432	2	31S	15W	42.9120	-124.437
Cochran Mill Site	20,000 to 50,000 tons per year	Port of Tillamook Bay	Washington	4000 Blimp Blvd.	Tillamook	OR	97141	503 842-2413	34	3N	6W	45.7047	-123.417
Mill Creek	20,000 to 50,000 tons per year	Plum Creek Timberlands, L.P.; Andrew Dobmeier	Lincoln	PO Box 216	Toledo	OR	97391	541 336-3819	24	9S	9W	44.7806	-123.740
190 Rock Pit	20,000 to 50,000 tons per year	Fallon Logging Company, Inc.	Tillamook	PO Box 637	Tillamook	OR	97141	541 994-5976	32	2S	10W	45.3592	-123.933
Davis Pit	20,000 to 50,000 tons per year	Davis, Gary	Coos	54962 Brady Road	Myrtle Point	OR	97458	541 572-2597	21	28S	12W	43.1230	-124.139
Siletz River Quarry	20,000 to 50,000 tons per year	Kauffman, Morris E.	Lincoln	PO Box 124	Lincoln City	OR	97367	541 994-2422	7	8S	10W	44.8872	-123.948
Whiskey Creek Pit	20,000 to 50,000 tons per year	S-C Paving Company	Tillamook	PO Box 535	Tillamook	OR	97141	503 842-7541	20	2S	10W	45.3778	-123.946
Drift Creek	more than 50,000 tons per year	Devils Lake Rock Company	Lincoln	2300 SE Highway 101	Lincoln City	OR	97367	541 994-3641	1	8S	11W	44.9042	-123.978
Camp Quarry	more than 50,000 tons per year	Mapleton Rock Products, Inc.	Lane	PO Box 63	Mapleton	OR	97453	541 268-0300	34, 35	17S	10W	44.0430	-123.866
Ogle Quarry	20,000 to 50,000 tons per year	Nesko Rock, Inc.	Tillamook	723 Evans Street	McMinnville	OR	97128	503 472-8571	15	5S	10W	45.1392	-123.886
Mt Meares Quarry 458	20,000 to 50,000 tons per year	Shiloh Forest Enterprises, Inc.	Tillamook	1500 Netarts Highway West	Tillamook	OR	97141	503 842-8438	28, 29	1S	10W	45.4597	-123.923
Rippet Pit	20,000 to 50,000 tons per year	Howard E. Johnson & Sons Construction Co.	Clatsop	85029 Hwy 101	Seaside	OR	97138	503 738-7328	4	5N	10W	45.9511	-123.932
King Ranch	20,000 to 50,000 tons per year	King, Dal	Coos	54041 Weekly Creek Road	Myrtle Point	OR	97458	541 572-2640	11	29S	12W	43.0666	-124.091
Smith's Quarry	more than 50,000 tons per year	Lee Webster Excavating, Inc.	Coos	PO Box 938	Coos Bay	OR	97420	541 267-5860	27	25S	12W	43.3731	-124.106
Kentuck Pit	more than 50,000 tons per year	Main Rock Products, Inc.	Coos	96521 Kentuck Way Lane	North Bend	OR	97459	541 756-2623	34	24S	12W	43.4394	-124.110

Site Name	Production Level	Owner	County	Address	City	State	Zip Code	Phone	Sec.	TWP	RGE	Latitude	Longitude
Iron Mountain Quarry	more than 50,000 tons per year	ODOT	Lincoln	3700 SW Philomath Blvd.	Corvallis	OR	97333	541 757-4211	20	10S	11W	44.6936	-124.051
Kincheloe Quarry	more than 50,000 tons per year	Kincheloe & Sons, Inc.	Coos	PO Box 296	Myrtle Point	OR	97458	541 572-5249	36	29S	11W	43.0100	-123.958
Ansley Pit	more than 50,000 tons per year	Main Rock Products, Inc.	Coos	96521 Kentuck Way Lane	North Bend	OR	97459	541 756-2623	21	28S	12W	43.1245	-124.142
Hienz Pit	more than 50,000 tons per year	M. Nygaard Logging Company	Clatsop	PO Box 100	Warrenton	OR	97146	503 861-3305	12	7N	9W	46.1003	-123.746
Eckman Creek Quarries	more than 50,000 tons per year	Eckman Creek Quarries	Lincoln	PO Box 540	Waldport	OR	97394		33	13S	11W	44.3910	-124.033
Weekly Quarry	more than 50,000 tons per year	Coos County Highway Department	Coos	250 North Baxter	Coquille	OR	97423	541 396-3121	14	29S	12W	43.0622	-124.084
Cedar Creek Quarry	more than 50,000 tons per year	Wienert, Bob	Lincoln	PO Box 730	Newport	OR	97365	541 265-9441	4	9S	10W	44.8190	-123.927
Bradley Pit	more than 50,000 tons per year	Teevin Bros. Land & Timber Co., LLC	Clatsop	42894 Old Highway 30	Astoria	OR	97103	503 458-6671	20	8N	6W	46.1684	-123.446
Square Creek Pit	more than 50,000 tons per year	Bayview Transit Mix, Inc.	Clatsop	PO Box 619	Seaside	OR	97138	503 738-5466	4, 9	5N	10W	45.9392	-123.934
Swisshome Rock Prod	more than 50,000 tons per year	Lloyd S. Hockema, Inc.	Lane	PO Box 1085	Florence	OR	97439	541 997-7328	30	17S	9W	44.0672	-123.813
Fischer Pit	more than 50,000 tons per year	Cedar Creek Quarries, Inc.	Lincoln	PO Box 730	Newport	OR	97365	541 265-9441	14	8S	11W	44.8790	-124.000
Johnsons Quarry	more than 50,000 tons per year	Howard E. Johnson & Sons Construction Co.	Clatsop	85029 Hwy 101	Seaside	OR	97138	503 738-7328	4	5N	10W	45.9508	-123.922
Kenstone Quarry	more than 50,000 tons per year	Coos Bay Timber Operators	Coos	PO Box G	North Bend	OR	97459	541 756-6254	26	24S	12W	43.4536	-124.087
Wahl Site	more than 50,000 tons per year	LTM, Inc.	Curry	PO Box 1145	Medford	OR	97501	541 770-2960	17	32S	15W	42.8036	-124.501
Lighthouse Quarry	more than 50,000 tons per year	Shiloh Forest Enterprises, Inc.	Tillamook	1500 Netarts Highway West	Tillamook	OR	97141	503 842-8438	18	1S	10W	45.4792	-123.961

Table A-2: Round rock

This table 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 other would require truck haulage to a railhead or to the project itself.

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