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Net Shore-Drift and Artificial Structures within Grays Harbor, Willapa Bay, and Mouth of the Columbia River, Washington

B. Patrice (Berenthine Patrice) Thomas

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NET SHORE-DRIFT AND ARTIFICIAL STRUCTURES WITHIN GRAYS HARBOR, WILLAPA BAY, AND MOUTH OF THE COLUMBIA RIVER, WASHINGTON

by

B. Patrice Thomas

Accepted in Partial Completion of the Requirements for the Degree Master of Science

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NET SHORE-DRIFT AND ARTIFICIAL STRUCTURES WITHIN
GRAY'S HARBOR, WILLAPA BAY, AND MOUTH OF THE
COLUMBIA RIVER, WASHINGTON

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
B. Patrice Thomas
May 1995
ABSTRACT

Net shore-drift, the overall result of sediment transport in the littoral zone, was studied along the shore within Grays Harbor, Willapa Bay, and mouth of the Columbia River, Washington. The length and direction of drift cells, which are discrete sediment compartments, was delineated using geomorphologic and sedimentologic indicators. Eight drift cells were identified in Grays Harbor, seven within Willapa Bay, and three along the section of the Columbia River shore studied. Drift cell lengths range from 200 m to approximately 6 km with an average of 1.5 km. Net shore-drift directions vary considerably with maximum fetch identified as the most important factor in sediment transport. Local fetches within the embayments are responsible for transport within one-half of the drift cells, while open ocean fetch accounts for transport in one-third of the drift cells. Transport within the remaining one-sixth of the drift cells is most likely due to a combination of local and open ocean fetch. The sediment within the drift cells is mainly derived from re-working of sand dunes along the shore. The majority of the shore in the study areas is characterized by no appreciable net shore-drift. This lack of drift is due to extensive tidal flats, salt marsh vegetation in close proximity to the shore, and a lack of appropriate sediment in these estuarine environments.

The extent of structures along the shore of these areas was also identified. Human modification along the shore includes the use of jetties, groins, bulkheads, and breakwaters. All of these structures consist of riprap. In a few locations, other materials were used in conjunction with the riprap. Shore defense structures are most extensive along the section of the Columbia River studied but are also prevalent along the shore within Grays Harbor and Willapa Bay. The largest structures are the massive jetties at the mouth of the Columbia River and at the entrance to Grays Harbor.
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This thesis is dedicated to Jake Wilson and my family; Tom, Nanette, Tasha, and Glenn Thomas. They have been extremely supportive, patient, and encouraging through all phases of my graduate work.
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INTRODUCTION

Objective of the Study

The shore is widely recognized as a valuable resource. Currently, 50% of the nation lives within 75 km of the coast. By 2010, this number is expected to grow to 75% of the population (Williams et al., 1991). The shore is popular for a multitude of reasons including recreation, shipping, and development opportunities. However, as greater numbers descend upon the shore, the threat to the coastal ecosystem increases, since natural processes acting upon the shore are increasingly affected. As a result, it becomes necessary to manage the activities along the coastal sector in order to protect and preserve it. Effective management of the shore requires a thorough understanding of the complex processes involved. The main coastal process is longshore transport. This process involves the movement of sediment along the shore, which can be divided into littoral drift cells.

The erosional nature and increased development along much of the coast, as well as an expected increase in the rate of global eustatic sea-level rise, emphasizes the need for understanding the dynamics involved. Littoral drift cell mapping and documenting of structures along the shore is essential information for local coastal planning, management of the intertidal zone for fish and shellfish resources, engineering and construction of shoreline structures, and growth management decisions.

This study documents the net shore-drift directions within Grays Harbor, Willapa Bay, and mouth of the Columbia River using a field-oriented approach based on geomorphologic and sedimentologic indicators. The study areas are located in
southwest Washington (Figure 1). The extent of structures, including groins, bulkheads, seawalls, and jetties, was also determined along the same sectors. No attempt was made to measure or predict the volume of sediment transported within the drift cells or to quantify the effects of the structures on sediment transport.

Background

The Washington Shoreline Management Act of 1971 divided primary responsibility for developing and implementing coastal-zone planning programs between local and state governments (Terich, 1987). The U.S. Coastal Zone Management Act of 1972 (CZMA) established federal regulations concerning the management of the shore. All coastal states were encouraged to use federal financial aid to develop coastal management guidelines that met the federal regulations (Terchunian, 1988). The Washington Department of Ecology (DOE) is in charge of administering and implementing the CZMA in Washington state.

Shortly after the CZMA was passed by Congress, the DOE began a comprehensive inventory of the state's shore in order to provide governments of coastal counties with relevant information regarding the shore. The culmination of this project was the publication of a 12 volume set titled the Coastal Zone Atlas of Washington (Washington State Department of Ecology, 1977). These reference books contain net shore-drift data as well as information pertaining to slope stability, land use information, coastal flooding, and critical faunal and floral areas. This information is divided on a county by county basis but does not include volumes for Grays Harbor and Pacific counties.
Figure 1. Regional location map of western Washington. GH=Grays Harbor, WB=Willapa Bay, CR=Columbia River (from Chrzastowski, 1982).
The net shore-drift information for these atlases was derived by a method called wave-hindcasting. This mathematical modeling procedure incorporated data from wind recording stations to determine the direction of dominant wave approach and the resulting shore-drift (Chrzastowski, 1982). However, wind data are often limited along the coast. As a result, the data are often extrapolated from inland stations. These stations may not represent the conditions found along the coast due to topographic effects, which may result in inaccurate net shore-drift information.

Short term studies, such as those using artificial tracers or sediment traps, are also subject to error in studying net shore-drift (Johannessen, 1993). These methods only record the drift direction during the length of the study, which may not represent the long-term direction of drift.

In order to update the net shore-drift directions of the Coastal Zone Atlases, graduate students at Western Washington University under the direction of M.L. Schwartz began studying the shore using field observations of geomorphologic and sedimentologic indicators. These methods have proved reliable for a number of researchers. Besides the many theses completed along the Washington shore (Keuler, 1979; Jacobsen, 1980; Chrzastowski, 1982; Blankenship, 1983; Hatfield, 1983; Harp, 1983; Taggart, 1984; Mahala, 1985; Bubnick, 1986; Johannessen, 1993), additional studies by the U.S. Geological Survey (Hunter et al., 1979; Keuler, 1988) and others (Morelock et al., 1985; Schwartz and Anderson, 1986) have successfully employed this method. The principles regarding the use of geomorphologic and sedimentologic indicators for net shore-drift determinations have been summarized by Jacobsen and Schwartz (1981).

It was thought that all of the state's shore had been studied in terms of net shore drift (Canning and Shipman, 1992). However, the shore-drift within Grays Harbor, Willapa Bay, and mouth of the Columbia River had yet to be determined. There have
been no previous investigations of net shore-drift in these areas. The Coastal Zone Atlas series did not include Pacific or Grays Harbor counties. Graduate students at Western Washington University completed net shore-drift studies along the ocean shore of Pacific and Grays Harbor counties but did not include the embayments of Grays Harbor, Willapa Bay, and mouth of the Columbia River in their studies. This study completes the series of net shore-drift studies of the Washington shore.

Documentation of structures was not included in the past net shore-drift investigations of the state’s shore. References may have been made to structures if they affected the transport of sediment along the shore. The Coastal Zone Atlas series included documentation of structures along the shore based on 1976 data (Washington State Department of Ecology, 1977). However, due to the increased prevalence of shore structures, the DOE recently funded an investigation to document current structures along the Thurston County shore. This study is a component of the DOE’s comprehensive Coastal Erosion Management Strategy made possible by a federal grant from the CZMA. Thurston County was selected as an initial study site due to the availability of relevant information already in computer file format (Morrison et al., 1993). The DOE intends to expand their shore-structure inventory to include all of the coastal counties in Washington. This study adds to the inventory by documenting structures for portions of Grays Harbor and Pacific counties.
PHYSICAL ENVIRONMENT

Geography

The three areas of study; Grays Harbor, Willapa Bay, and mouth of the Columbia River, are located in the southwest corner of Washington state (Figure 1). Grays Harbor is located in Grays Harbor county, while the mouth of the Columbia River and Willapa Bay are found in Pacific county. The total shore length within Grays Harbor is approximately 170 km at high tide, while Willapa Bay encompasses approximately 280 km at high tide (Washington State Department of Natural Resources, 1974). The eastern limit of the study area along the Columbia River shore was Grays Point (Figure 2). The shore length for the Washington side of the Columbia River for this sector is approximately 50 km.

Estuaries

The study areas are estuarine environments. The definition of estuaries has been debated in the past, but it is generally agreed upon that they are semi-enclosed bodies of water, with a free connection to the open sea, and within which seawater is measurably diluted with freshwater derived from land drainage (Pritchard, 1967). The Chehalis River is the main freshwater source for the Grays Harbor estuary. Willapa Bay does not have one large river that dominates in terms of freshwater input; instead, it has a number of smaller flows including the Naselle, Bear, Willapa, Nemah, and Palix Rivers. The Columbia River is the third largest river in the United States and is the main freshwater contributor to the Columbia River estuary (Phipps, 1990).
Figure 2. Map of the study areas.
Estuaries can be classified according to many different characteristics including salinity, tidal range, and morphologic differences. Classification based on morphologic differences has the most relevance to this study since morphology directly influences the processes operating within a given estuary. Pritchard (1967) recognizes four distinct estuary types: drowned river valleys, tectonically-produced estuaries, bar-built estuaries, and fjord-type estuaries. Drowned river valleys are the most common type of estuary and form by a rise in sea level relative to the land, commonly as a result of the release of ice-held water. The majority of present-day estuaries formed in this way during the Flandrian transgression which occurred at the end of the last glaciation. Estuaries in this category are also commonly referred to as coastal plain estuaries or ria coasts (Schubel, 1982). If sea level invades the land due to subsidence of the shore, a tectonically-produced estuary is formed. Bar-built estuaries are a result of longshore transport building a spit that partially encloses an embayment and therefore limits the exchange of freshwater with the sea. This type of estuary tends to be shallow (Schubel, 1982). Fjords are glacially-overdeepened valleys that often have a sill at their mouths which restricts the mixing of water within the fjord and the adjacent sea.

According to this classification system, the Columbia River estuary is a drowned river valley. Tongue Point, Oregon, is generally regarded as the eastern boundary of the estuary (Figure 2). Therefore, Grays Point, located roughly north of Tongue Point in Washington, was selected as the easternmost limit of this study area. The embayments of Grays Harbor and Willapa Bay are bar-built estuaries that also exhibit some of the characteristics of drowned river valleys (Erickson and Sawyer, 1973). Grays Harbor is formed by the Westport Peninsula to the southwest and the Ocean Shores Peninsula to the northwest, while Willapa Bay is bordered on the west by the Long Beach Peninsula (Figure 2). The large barrier spits that partially enclose these two estuaries are a result of littoral drift along the ocean side. This process is
believed to have been active throughout the latter portion of the Quaternary on these massive landforms (Phipps, 1990). The majority of the sediment for these features has been derived from bed load transported by the Columbia River. The sediment has been traced to north of Ocean Shores (Scheidegger and Phipps, 1976).

Geologically, estuaries tend to be very young. Most have developed since the latest post-glacial rise in sea-level inundated coastlines and drowned the mouths of river valleys (Brown et al., 1989). Sea-level stabilized about 6,000 years ago. Estuaries also tend to be short-lived, since they are net receivers of sediment from both the land and sea (Nordstrom, 1992). They generally persist for only a few ten thousands of years (Scheidegger and Phipps, 1976).

Estuaries have often been neglected by humankind. However, they have recently been recognized as being one of the most complex and productive ecosystems in the world (Hennessey, 1994). They support a multitude of organisms and include migratory bird habitats and spawning grounds for many fish (Nordstrom, 1992). Over 210 species of birds, several of them endangered or threatened, have been identified at Willapa Bay alone (Erickson and Sawyer, 1973). In addition, estuaries are valuable in terms of shipping, residential, water-related industries, and recreation uses. However, estuaries are also very vulnerable environments since they tend to concentrate pollutants (Hennessey, 1994). Effluents, such as raw sewage, are commonly disposed of in rivers that drain into estuaries or are deposited directly into the estuary itself. This results in massive de-oxygenation of the estuary due to increased bacterial populations and results in a decline in the productivity of the ecosystem (McLusky, 1971). While Willapa Bay has been recognized as the cleanest estuary along the west coast of the United States, Grays Harbor and the Columbia River have been degraded by pollution, resulting in lower productivity within these estuaries (Erickson and Sawyer, 1973). The National Estuary Program has been proposed to protect and enhance water quality
and the coastal environment of estuaries since humans tend to have a great impact on this delicate ecosystem (Imperial et al., 1992).

The economy of Pacific and Grays Harbor counties is connected mainly to the timber and fishing/shellfish industries, tourism, and some agriculture, including dairying and cranberries. The estuarine environment is especially important since Pacific oysters from Grays Harbor and Willapa Bay account for over 50% of all oysters harvested along the entire west coast of the U.S. and nearly 20% of the nation’s total harvest (NOAA, 1990).

The shores of estuaries; Grays Harbor, Willapa Bay, and the mouth of the Columbia River specifically; are characterized by extensive tidal flats and salt marshes (Figure 3). These tidal flats are composed of silt and clay and have a very shallow gradient. As a result, wave power tends to be relatively low in estuaries. Beaches comprise only a small portion of an estuarine shoreline and tend to be small, not highly visible, but extremely important to the ecosystem. The main factors affecting these beaches are essentially the same as those that form in open-ocean environments (Nordstrom, 1992). These include tidal range, bathymetry, fetch, and sediment source. The amount of sandy material from nearby sources is the most critical factor in determining the size of the beach (Ward et al., 1989). Despite their high ecological and recreational value, these beaches have not been granted the same status as wetlands and benthic environments within the estuary (Nordstrom, 1992).

One fairly recent problem in the estuaries of western Washington, particularly Willapa Bay, is the influx of *Spartina alterniflora*. This vigorous plant has been around for more than 100 years but has only recently made rapid advances in the territory it now covers. In 1990, it was estimated that *Spartina* covered approximately 1200 acres of intertidal lands in Willapa Bay and was continuing to flourish (Aberle, 1990). It is
Figure 3. Extensive tidal flats and marsh vegetation associated with estuarine environments. View is from the southern end of Willapa Bay looking north toward Long Island. Canadian geese on the tidal flats for scale.
extremely difficult to remove permanently the salt-tolerant plants, which are currently endangering shellfish production areas and migratory bird feeding habitats.

Climate

Climate is an important factor in studying net shore-drift since it affects the weathering of rock outcrops. The coastal climate of southwest Washington is similar to those of other mid-latitude, west coast marine areas (Erickson and Sawyer, 1973). Two semi-permanent pressure systems that originate over the Pacific Ocean affect this area (Harris, 1954) (Figure 4). The East Pacific High dominates from May to September while the Aleutian Low is found from October to March (Hopkins, 1971). These pressure systems influence the general wind patterns of the region. The Aleutian Low produces high intensity winds from the south/southwest during December to March (Figure 5). These winds tend to be highly variable in direction and velocity, ranging between 70 and 110 kph at times but usually not exceeding 50 kph. Summer winds are connected to the East Pacific High and tend to be more gentle in their intensity, duration, and direction (Ruef, 1975). These winds usually blow from the north (Figure 5) (Downing, 1983). Overall, the prevailing wind direction usually shifts in a counterclockwise direction from south in the winter, east in the spring, north by early summer, and back to west in the fall (Ruef, 1975).

The marine weather system’s influence on this region results in a relatively moderate climate throughout the year. Summers tend to be cool and relatively dry, while winters are usually cloudy and wet with a fairly mild temperature. The mean annual temperature is close to 10° C with a winter average around 5° C and a summer
Figure 4. Mean atmospheric pressure systems in the Northeast Pacific (from Hopkins, 1971).
Figure 5. Typical seasonal wind patterns over western Washington (from Downing, 1983).
average near 20° C. The rainy period extends from October through April during which most of the average regional precipitation of 200 cm a year falls (Ruef, 1975).

Fog is fairly common in this area especially during spring and summer (Hazeltine, 1956). In this area, it usually results from warm air over the land rising and being replaced by cool, moist ocean air (Figure 6). At night, the air temperature drops, causing the moisture in the air to condense. This process results in the formation of advection fog or low-lying, flat stratus clouds in the area (Renner, 1993). Radiation fog may also occur in the study areas (Figure 6).

Geology

Along the east margin of the study areas, lie the Willapa Hills. This area has moderate elevation with an average of less than 700 m. The hills consist mainly of Tertiary rocks including Eocene sandstone, shale, and basalt; Oligocene marine sandstone and basalt; Miocene Columbia River basalt; and Pliocene conglomerate (Easterbrook and Rahm, 1970). Igneous intrusions and faults cut the Tertiary rocks in the southwestern sector of the Willapa Hills (Erickson and Sawyer, 1973; Walsh et al., 1987).

One of the most prevalent geologic aspects within the study areas are uplifted terraces along the edges of Willapa Bay and Grays Harbor (Figure 7). These Quaternary deposits mantle the Tertiary bedrock and lie in a fairly continuous strip from Grays Harbor to Willapa Bay (Easterbrook and Rahm, 1970). The terraces are composed of semi-consolidated Pleistocene estuary deposits consisting predominantly of mud (Clifton, 1983). The deposits are very similar to those presently being deposited in Grays Harbor and Willapa Bay. According to amino-acid dating, the
Figure 6. Processes of fog formation. Diagram A shows the formation of advection fog; B depicts the formation of radiation fog (from Renner, 1993).
Figure 7. Uplifted 13 m high terrace composed of ancient estuarine deposits. Note the tree across the beach and the sea stacks indicating erosion of the terraces. View is looking north from the eastern side of Willapa Bay.
oldest of the units is almost 200,000 years old, while the youngest is about 100,000 years old (Kvenvolden et al., 1979). This stratigraphic record represents sea level fluctuations during the time frame indicated. The deposits formed at or very close to sea level and have since been uplifted by regional tectonic forces. Shipman (1989) has stated that the total amount of vertical movement in southwest Washington is very slight. According to Adams (1984), the terraces represent an average uplift rate of less than 0.1 mm/yr for the coast. The present uplift rates for the study areas range from 0 mm/yr at Aberdeen to .5 mm/yr at Astoria (Phipps, 1990).

A convergent plate boundary exists to the west of the study areas (Figure 8). The Juan de Fuca plate is subducting beneath the North American plate at an average rate of 4 cm/yr (Atwater, 1987). Evidence of former large subduction earthquakes in this region has been found in the recent estuarine deposits of these areas. Atwater (1987) has found at least six well-vegetated lowlands buried in the sedimentary record of the past 7,000 years. Each of these lowlands is overlain by intertidal mud. It is believed that they are a result of coseismic subsidence, ranging from 0.5 to 2.0 m, that accompanied large tectonic events in the recent past. Several of the buried lowlands are directly overlain by a thin sand layer that most likely represents deposition by a tsunami (Reinhart and Bourgeois, 1989). Based on these findings and others, the recurrence interval for large subduction-related earthquakes in southwest Washington is thought to be about 400 years (Heaton and Hartzell, 1987).

“Ghost forests” and buried stumps of western red cedar and Sitka spruce found in the study areas also support the occurrence of past earthquakes. Death came rapidly for these trees as indicated by analysis of their growth rings. It is believed that they died approximately 300 years ago due to submergence in brackish water (Atwater and Yamaguchi, 1991).
Figure 8. Plate tectonic setting of the Pacific Northwest (after Rogers, 1988).
In Grays Harbor and Willapa Bay, unconsolidated sediments dominate along the shore (Walsh et al., 1987). Bedrock rarely crops out along these coastal sectors. However, this is not the case along the Columbia River where several rocky headlands, including North Head, are evident (Figure 2). The majority of these headlands are basalt and are associated with volcanic rocks believed to be pre-Miocene in age (Weissenborn, 1969).

Oceanography

The main driving force of coastal processes is waves (Ritter, 1986). In terms of oceanography, waves are caused by any disturbance of the water. These sinusoidal, undulating forms (Figure 9) may exist on the interface between any two fluids of different density. However, this report will deal only with those that travel on the surface of the sea between the hydrosphere and atmosphere. The three primary natural causes for waves are wind, earthquakes, and the gravitational pull of the moon and sun (Ritter, 1986). Tides and wind-induced waves affect the beach continuously and will be discussed in greater detail in the following paragraphs. Earthquakes are generally infrequent and unpredictable events that do not always generate a wave. Therefore, this type of wave, known as a tsunami or seismic sea wave, does not have a sustained effect on the shore and, as a result, will not be dealt with in this paper.

Essentially, waves represent energy moving through the water (Terich, 1987). If they reach the shore, all or part of the waves' energy may be expended on the shore. Therefore, the bathymetry of an area is also important because it has a direct impact on wave speed and consequently on the waves' energy potential.
Figure 9. Vertical components of two successive idealized ocean waves (after Brown et al., 1989).
Wind-Induced Waves

The most common type of wave is that generated by the wind (Fox, 1983). The energy of the wind is transferred to the ocean water due to frictional stress between the two fluid layers (Brown et al., 1989). Once formed, these waves grow as a result of a pressure contrast that develops between their leeward and windward slopes (Mahala, 1985). The size and variety of these waves depends on three factors: the velocity of the wind, the fetch or distance over which the wind blows, and the duration or length of time that the wind blows (Ritter, 1986). Wind-generated waves are important since they induce the process of shore-drift.

Along open-ocean coasts, fetch is usually not a limiting factor since changes in fetch are important only up to about 1500 km (Davies, 1980). At the entrances of the study areas, ocean swell may have an effect on the shore. However, within the embayments, fetch tends to be quite limited and therefore controls the magnitude of wind-induced waves (Nordstrom, 1992). As fetch increases, wave period and wave height also increase. The height and period increase to a certain maxima, above which they do not change significantly (Johannessen, 1993). In fetch-limited environments, the wind is able to generate the largest possible waves in a fairly short amount of time. Keuler (1979) demonstrated this process in his calculations for waves affecting the shore of Skagit county (Table 1).

Tides

Tides are waves with an extremely long wavelength (Figure 9): one half the distance around the Earth (Bascom, 1980). This type of wave is due to the gravitational attraction between the earth, sun, and moon that results in the displacement of marine water (Wood, 1982). The moon, being closer to the earth, exerts a greater force upon the earth; about twice
Table 1. Significant wave heights for typical velocity, fetch, and duration (from Keuler, 1979).

<table>
<thead>
<tr>
<th>FETCH (km)</th>
<th>SIG. WAVE HT. FOR GIVEN WIND DURATION (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 Hours</td>
</tr>
<tr>
<td>VEL= 5.4 m/s (12 mph)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>.15</td>
</tr>
<tr>
<td>10</td>
<td>.24</td>
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<tr>
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<td>.27</td>
</tr>
<tr>
<td>30</td>
<td>.27</td>
</tr>
<tr>
<td>50</td>
<td>.27</td>
</tr>
<tr>
<td>VEL= 8.1 m/s (18 mph)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>.40</td>
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</tr>
<tr>
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<td>1.07</td>
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</tbody>
</table>
that of the sun’s influence (Ward et al., 1989). This lunar influence results in approximately two high tides and two low tides daily. The gravitational effect of the sun may complement or detract from that of the moon (Ritter, 1986). When the earth, moon, and sun are aligned, which is referred to as syzygy, the greatest tides occur as a result of the addition of gravitational forces (Figure 10). This occurs approximately twice a month during the new and full moons. When the sun and moon are at right angles to each other in relation to the earth, their gravitational effects are out of phase resulting in a minimum tidal range (Figure 10). These low-range tides are termed neap tides and occur in association with the first and third quarter phases of the moon (Fox, 1983).

Much of the west coast of North America, including Grays Harbor, Willapa Bay, and the mouth of the Columbia River, experiences semi-diurnal mixed tides (Mahala, 1985). Essentially this means that within approximately 24 hours, two highs and two lows occur. All of these tides are unequal, with the lower of the two lows referred to as lower low water and the higher of the two highs termed higher high water (Keuler, 1979). The long-term means of these highest and lowest tides are abbreviated as MHHW and MLLW, respectively.

The majority of Washington’s Pacific coast has a spring tidal range that typically falls between 3 and 4 m (Mahala, 1985). Davies (1964) classified tidal regimes according to the spring tidal range as follows: microtidal is less than 2 m, mesotidal ranges from 2 - 4 m, while macrotidal is greater than 4 m. According to Davies’ classification, the study areas are mesotidal environments. The Columbia River’s maximum semi-diurnal range of 3.6 m supports this classification (Sherwood and Creager, 1990).

Tides are important to the littoral regime because a continuous change in water level results in migration of the wave attack. This tidal fluctuation is one of the main
Figure 10. Tide-producing forces. The gravitational attractions produced by the moon and sun combine at times of new and full moon to increase the range of the tides, and counteract each other at first and third quarters to reduce the tidal range (from Mahala, 1985).
factors in determining the configuration of the beach profile of an area (Inman and Filloux, 1960). If two coastal areas are similar in all aspects except tidal range, the shore with the larger tidal range will generally have less coastal erosion (Rosen, 1977). A slower rate of erosion affects the rate of net shore-drift along a coastal sector (Chrzastowski, 1982). Tides also initiate currents that flow into and out of the often constricted embayments of estuaries, facilitating the exchange of water.

**Bathymetry**

The speed at which waves travel are directly affected by the water depth of the particular area. In general, if the water depth is less than one half the wavelength, the wave will slow down due to interaction with the bottom topography (Brown et al., 1989). Wave power tends to be diminished in estuarine environments due to shallow water. In some areas of Willapa Bay and Grays Harbor, tidal flats extend more than a kilometer from shore (Clifton, 1983). At higher levels of the tide, these areas are covered but only to a very shallow depth. In addition, marsh plants often dissipate wave energy before reaching the shore.

The waters along southwest Washington are notorious in the shipping business since almost 2,000 vessels have been claimed during the past 300 years partly due to numerous shoals in the area. Shoals are very common near the mouths of embayments due to deposition by tidal currents. These features tend to dissipate any open ocean waves that enter an estuary (Nordstrom, 1992).
METHODS

Principles of Net Shore-Drift

The process of shore-drift is due to the combined effects of longshore drift and beach drift. Longshore drift occurs in the nearshore zone as a result of waves striking the beach at an angle. These waves create a longshore current that transports sediment parallel to the coast due to wave fronts deflecting the nearshore water circulation in one direction (Bird, 1984). Beach drift, also a result of waves approaching the shore obliquely, is a zig-zag motion of sediment transport. As a wave breaks on the shore, the swash, or forward surge of the water, drives sediment diagonally up the beach face. The backwash, or return flow of the water, carries sediment down the beach face at right angles to the shoreline due to the effect of gravity (Figure 11). Successive waves repeat this process and transport sediment down the beach. Shore-drift is also commonly referred to as longshore transport (Komar and Inman, 1970: King, 1972), longshore drift (Bird, 1984), or littoral drift (Ingle, 1966; Ritter, 1986).

As long as the winds approach from the same direction, the alongshore transport direction of sediment remains the same. If the prevailing and predominant wind directions differ, there may be temporary reversals in the shore-drift direction. Net shore-drift is closely tied to the predominant and prevailing winds. In relation to coastal studies, prevailing winds are those that occur most frequently, while predominant winds are those that have the most effect on the shore in a particular area (Jacobsen and Schwartz, 1981). While the direction of shore-drift may vary daily or seasonally, net shore-drift is the long-term, overall result of this process.
Figure 11. Diagram illustrating net shore-drift (from Chrzastowski, 1982).
Drift cells are an important principle associated with net shore-drift (Inman and Masters, 1994). A drift cell may also be referred to as a coastal sediment compartment, drift sector, littoral drift cell, coastal cell, or other various combinations of these words. With respect to sediment transport, drift cells are partially or wholly compartmentalized zones resulting from changes in shore or wind orientation, water depth, artificial structures, or other factors. An idealized drift cell consists of three areas: its origin at a source of sediment supply, a central transport zone, and a terminus which is a site of deposition (Figure 12). The origin is often at a river mouth or an area of higher wave energy where long-term erosion of material takes place. The zone of transport is where sediment is moved along the shore by shore-drift processes. Sediment may be added to the cell in this zone as a result of stream input or erosion of intervening headlands. Essentially, wave energy in this stretch is sufficient to move the sediment supplied to the cell. The terminus of a drift cell is identified as an area of sediment deposition. Deposition of sediment may occur onshore or offshore in this location. The boundaries of drift cells are often broad zones rather than distinct contacts, since the direction or energy of wind-generated waves may vary over time. These borders may have been artificially modified due to development along the shore.

Designation of a drift cell includes the direction and length of net shore-drift. The net shore-drift direction is identified from the zone of origin to the zone of the terminus (Figure 12). Length is the average alongshore distance of sediment transport. When referring to drift cells, the terms downdrift and updrift are commonly used. Downdrift refers to a location closer to the terminus of a cell, while updrift indicates closer proximity to the origin of the drift cell.

Drift cells described in this study were identified through systematic field investigations of the shore within the study areas. Field work was conducted mainly during August and September 1994. Selected sites were re-visited during fall 1994.
Figure 12. Idealized net shore-drift cell (after Inman and Masters, 1994).
Walking of the shore at low tide provided optimal conditions for observing net shore-drift indicators. A 3.6 m motorized aluminum boat was used to reach the shore of Long Island. This 200 hectare island is a part of the Willapa National Wildlife Refuge and is accessible only by private boat.

Sedimentologic and geomorphologic indicators resulting from shore-drift processes were identified to delineate the boundaries of a net shore-drift cell and sediment transport within it. When the limits of a drift cell and its direction were identified, a number was assigned to it and it was drawn on the base map in its proper location. Data were recorded on a chart for later reference. Written descriptions were kept in a journal.

This method is a key component in mapping net shore-drift and has been employed in numerous studies along the shore, including those by the U.S. Geological Survey (Hunter et al., 1979; Keuler, 1988), by researchers at Western Washington University (for example, Jacobsen and Schwartz, 1981; Johannessen, 1993) and others (Morelock et al., 1985). These indicators can be divided into two categories: drift-trend and site-specific. Drift-trend indicators tend to occur over the length of the drift cell, while site-specific indicators are those that are present at a particular location within the drift cell. A single indicator is not sufficient to delineate the boundaries and direction of net shore-drift; rather, a number of indicators are necessary for identification.

Where no appreciable net shore-drift (nansd) occurs, shore-drift processes no longer operate. This may be a result of extremely low wave energy, bedrock outcrops projecting into deep water, or artificial modification of the shore. Since the study areas are estuarine environments, much of the shore is subject to low wave energy.
Aerial photographs of the areas were supplied by the Department of Ecology to aid in investigations of the shore. These included selected oblique views and color infrared from the 1:24,000 series.

**Drift-Trend Indicators**

Drift-trend indicators are those that occur over a significant length of the shore. Gradual changes in sedimentologic and geomorphologic features can indicate the direction of net shore-drift. These features may be due to changes in the amount of wave energy reaching the beach or changes in the composition of the beach. Wave energy reaching the beach often decreases in the direction of net shore-drift for one or more of the following reasons: a broader beach that acts as a buffer to waves, waves approaching the shore at a more oblique angle, or more incoming wave energy absorbed by a progressively shallower or wider nearshore zone (Johannessen, 1993). Drift-trend indicators are useful in identifying the origin or terminus of drift cells as well as the direction of net shore-drift.

Near-linear coasts with uniform sediment type and input seem to produce the most consistent drift-trend indicator patterns (Johannessen, 1993). A drift-trend pattern may repeat itself within a drift cell due to input of new sediment, but the overall trend of indicators can be indicative of net shore-drift direction. Drift-trend indicators include the presence of the following.

1. Sediment size gradation. The mean sediment size tends to decrease in the direction of net shore-drift as a result of decreasing wave energy (Jacobsen and Schwartz, 1981). The fine sediment in effect outruns the coarse sediment. A beach at the origin of a drift cell consists predominantly of coarser grains, while downdrift the sediment tends to have an increasingly higher proportion of finer grains (Figure 13) (Self, 1977).
Figure 13. A series of photographs displaying sediment size gradation.
A) Primarily composed of granules and pebbles near the cell origin.
B) Mixed sand and granules midway through the cell.
C) Primarily sand near the terminus of the drift cell.
2. Beach width. As a result of generally higher energy conditions near the beginning of a drift cell, beaches there tend to be narrow and erosional (Jacobsen and Schwartz, 1981). A gradual widening of the beach occurs downdrift due to accumulation of sediment. The development of a broader beach and backshore, often with one or more berms present around the high tide level, is commonly associated with this widening.

3. Bluff morphology. As stated previously, the beach at the origin of a drift cell is usually quite narrow, providing very little protection to the bluff base in stormy periods. As a consequence, the bluff tends to be nearly vertical and bare of vegetation (Keuler, 1979). Progressing downdrift, the bluff usually becomes more vegetated with a gentler slope as a result of a wider beach and backshore that provide increased protection at the bluff base.

4. Log-spiral beaches. Log-spiral beaches, or headland bay beaches, as defined by Yasso (1965) are those with a "seaward concave plan shape that lies in the lee of a headland" (Figure 14). The headland causes a wave shadow in its lee as the predominant waves approach it. Wave refraction and some diffraction occur in the wave shadow and cause a local reversal in the direction of net shore-drift within the lee area (Jacobsen and Schwartz, 1981). Therefore, sediment size and beach slope increase with increasing distance from the headland.
Figure 14. Plan view of Halfmoon Bay shoreline and fitted logarithmic spiral (from Yasso, 1965).
Site-Specific Indicators

Site-specific indicators are those that are found at a particular location within a drift cell and include the following features.

1. Objects interrupting shore-drift. Any large and fairly solid structure located across the foreshore will obstruct shore-drift. Obstructions may cause a horizontal and vertical offset of the shoreline due to the updrift accumulation of sediment against the barrier. Erosion occurs downdrift due to the depletion of sediment (Figure 15). In general, the longer the obstruction has been in place, the greater the amount of sediment accumulation and erosion. Groins and jetties are among the many obstacles that may interrupt net shore-drift.

2. Spit growth. Spits are depositional landforms that grow in the direction of net shore-drift (Bird, 1984). They usually indicate the terminus of a drift cell. The visible portion of a spit is built atop a larger, submarine platform. Growth of the platform always precedes growth of the subaerial portion of the spit (Meistrell, 1972). Spits may be hooked at their end due to wave refraction carrying sediment around the terminus of the feature (Evans, 1942).

3. Identifiable sediment. In some areas, an unusual sediment or mineral may indicate net shore-drift. This sediment may be natural, such as an unusual rock type, or manufactured, as in the case of brick (Figure 16) (Jacobsen and Schwartz, 1981). The identifiable sediment is transported like any other sediment within the cell and therefore will be found downdrift of its source area. As with objects interrupting net shore-drift, the longer the time that the sediment has been transported, the more likely that it indicates net shore-drift rather than seasonal drift.
Figure 15. Relationship between wave approach and longshore drift of sediment. Note the accumulation of sediment on the updrift side and the erosion on the downdrift side of the groin (from Ward et al., 1989).
Figure 16. Peat as an identifiable sediment. Photograph was taken mid-way through drift cell GH-1.
4. Stream diversion. The mouths of streams may be diverted in the direction of net shore-drift as a result of sediment deposited on the updrift side and eroded on the downdrift side of the stream outflow. If the sediment builds up faster than the stream is able to carry it away, the stream channel becomes displaced. The amount of diversion may vary from a few meters to several kilometers at different sites (Jacobsen and Schwartz, 1981).

5. Plan view of river deltas. River deltas and intertidal fans tend to act as obstacles to shore-drift. As a result of net shore-drift, these features become asymmetrical. The updrift side of a delta or intertidal fan often has a broader, prograded foreshore that tapers in the updrift direction. The downdrift side is more rounded and blunt in plan view (Komar, 1973; Chrzastowski, 1982). Although it is possible to observe this phenomenon in the field, air photos taken at mean lower low water (MLLW) show it more clearly.

6. Presence of nearshore bars. Depending on the conditions, wave action occasionally builds oblique bars in the intertidal or shallow subtidal zone. These bars are composed of sand and gravel and are oriented roughly perpendicular to the principal direction of wave approach (Johannessen, 1993). Although nearshore bars can be a valuable indicator, they are not as reliable as other indicators due to their ephemeral nature and the large variety of other bar types (Greenwood and Davidson-Arnot, 1979).

Structures

The shore is a dynamic system that is constantly changing in response to natural forces. Most coastal engineering structures have been built to address these changes.
More specifically, the majority of artificial modifications to the shore are those dealing with sediment transport along the shore (Bird, 1993). Human interference with shore processes results in changes to the entire system.

One of the most obvious processes occurring along the shore is erosion. Coastal erosion occurs within the strip of land and sea floor immediately adjacent to the coast (Jolliffe, 1982). Presently, almost all of the world’s shore is experiencing erosion (Ward et al., 1989). On its own, shoreline erosion does not present a hazard, but in a cultural context it is a serious problem (Shipman, 1995). When development has occurred along the shore, erosion may threaten a property owner’s investment.

There are three choices when confronted with an erosion problem: take no action, relocate endangered structures, or take positive action to halt or minimize the erosion (U.S. Army Corps of Engineers, 1981). Property owners generally feel compelled to take positive action (Shipman, 1995), which may include beach nourishment, vegetative controls, or building structures along the shore to minimize erosion. Beach nourishment and vegetative controls are often referred to as "soft solutions" while structures are often called "hard solutions". The most common type of shoreline stabilization in the past has been in the form of structural control, which will be the type dealt with in this report (Pilkey and Wright, 1988).

Cape Shoalwater on the northern side of the entrance to Willapa Bay indicates that erosion is occurring in southwest Washington. Schwartz and Terich (1985) reported that a 3.2 km recession has occurred in the last 90 years. Cape Shoalwater is believed to be the most active coastal erosion site along the Pacific coast of the United States (Terich and Levenseller, 1986).

Deposition is another coastal process that has resulted in the construction of structures along the shore. While most property owners would be happy to have new land accreting to theirs, deposition of sediment in channels often poses navigation
problems. As a result, structures are often constructed at the mouths of inlets or harbors to inhibit the transport of sediment along the shore. Many of these structures are also built to increase the flow velocity of the water within the channel in the hope that it will scour out the sediment that is deposited.

Structures have been built along the shore to mitigate erosion, prevent deposition, or provide protection from waves for thousands of years (Bruun, 1993), but it has only been since the Industrial Age in the mid-18th century that man has been able to invest large sums in marine structures (Silvester and Hsu, 1993). However, the complex processes occurring along the shore were poorly understood, and these early attempts often resulted in significant changes to the shore (Silvester and Hsu, 1993). Even with a more thorough understanding of coastal processes, coastal stabilization methods are often short-sighted attempts to subdue and "organize" nature (Erickson and Sawyer, 1973). It seems to be man's inherent disposition to attempt to control nature rather than live in harmony with it.

The major types of shore structures include jetties, breakwaters, seawalls, bulkheads, and groins. Structures described in this report will follow the classification according to the Glossary of Coastal Engineering (U.S. Army Corps of Engineers, 1972). A jetty is a structure that extends into a body of water and is designed to prevent shoaling of a channel by littoral materials or to direct and confine the stream or tidal flow. A groin is a shore protection structure that is built to trap littoral drift or retard erosion of the shore. It is usually constructed across the beach perpendicular to the shoreline. A structure protecting a shore area, harbor, anchorage, or basin from waves is referred to as a breakwater. A bulkhead retains or prevents sliding of the land; a secondary purpose is to protect the upland against damage from wave action. A seawall separates land and water areas and is primarily designed to prevent erosion and other damage due to wave action. In much of the literature on coastal engineering
structures, the terms seawall and bulkhead are used interchangeably. However, there is a distinct difference between the two as indicated by their definitions, and therefore they will be treated as separate categories within this report.

The documentation of structures was conducted in conjunction with investigations of the net shore-drift of the study areas. Structure sectors were assigned an identification letter and drawn in along the relevant base map sections. Descriptions of the structures in this report will include type, construction material(s) used, location in relation to the shore, and length of the structure. It is important to note that structures tend to “smooth out” the shore rather than follow the small crenulations associated with a high tide shore.

Effects of Structures

It is not clearly understood exactly what physical effect structures have along the shore. Macdonald et al. (1994) have identified six general categories that have the potential to be impacted by shore protection measures. These include sediment impoundment, narrowing of the beach, modification of groundwater flow, loss of beached organic debris, and modification of beach substrates. They state that the relative degree of response depends on the structure, wave energy, and other factors at the site. The categories of sediment coarsening, groundwater modification, and loss of organic debris have received limited attention in the literature.

Silvester and Hsu (1993) state that waves reflect from seawalls and apply double the amount of energy to the seabed adjacent to their faces. This results in greater scouring at the base of the seawall, which creates conditions for collapse of the structure (Figure 17). In effect, the seawalls change a dissipative beach into a reflective
Figure 17. Scouring at the base of a seawall. Diagram A shows scour depth (erosion) that may occur following construction of a seawall (from Kraus, 1988). Diagram B shows a potential effect of a seawall failure (from Terich, 1987).
beach, which aggravates pre-existing erosion (Rosenbaum, 1976). Findings by Terich and Schwartz (1993) and Weggel (1988) support erosion associated with seawalls, especially when structures are located on the beach face. McDougal et al. (1987) found that depth of scour erosion at the ends of the seawall is generally about 10% of the seawall length. This leads to general lowering of the entire beach profile and may result in “end-wall” effects that could require further stabilization (Figure 18). In addition, structural activity in one area may have a significant affect on an area far removed from the original site (Bruun, 1993). The structures may impact adjacent unprotected beaches with greater beach scarping and erosion. Research by Komar and McDougal (1988) predicts that the total alongshore length of erosion is approximately 70% of the structure’s length.

Groins and jetties cause accumulation of sediment on the updrift side of the structure due to interruption of longshore transport. A corresponding amount of erosion occurs on the downdrift beach due to “sediment starvation” (Terich, 1987). Inappropriately located groins may aggravate erosion problems of adjacent properties due to reduction of longshore transport (Downing, 1983). In terms of the spacing of jetty pairs, it is important to consider the average volume of water that flows in and out of the area during a 12.4 hour tidal cycle. The spacing will help to ensure adequate flow to scour sediment from the channel (Bascom, 1980).

Although it does not guarantee 100% success, understanding the processes at work is essential in order to determine the most effective treatment for a coastal erosion or deposition problem. Location, shape, and orientation of a structure are all important so that wave energy is reflected or absorbed (Bascom, 1980). The cost, availability of materials, and local regulations involved are also considerations.
Figure 18. End wall effects (from Macdonald et al., 1994).
Sea-Level Rise

Tide stations around the world indicate a current global eustatic sea-level rise of approximately 1.2 mm/yr due to glacial melting and thermal expansion of the oceans (Phipps, 1990). In a particular area the relative sea-level rise may differ significantly from this value due to subsidence or uplift of the land. There is generally widespread agreement that global warming and sea-level rise will continue during the coming century. In fact, the majority of researchers believe that the rate of sea-level rise will increase due to a phenomenon referred to as the “greenhouse effect”.

The earth’s temperature is determined mainly by the amount of sunlight it receives, the amount of sunlight it reflects, and the extent to which its atmosphere retains heat (Titus, 1988). When the composition of the atmosphere is changed, it will have an effect on the amount of heat that is retained. Carbon dioxide, methane, and chlorofluorocarbons are a few of the substances that are termed “greenhouse gases” as a result of their ability to absorb the sun’s radiation rather than reflect it. The proportion of these gases has already increased in Earth’s atmosphere and is expected to continue to increase (Bird, 1993). It is believed that this will cause a general warming of the climate, which will melt more glacial ice and also cause expansion of the marine water. As a result, the rate of sea-level rise is expected to increase.

There has been debate on the rate of increase that can be expected. There is still enough water in the polar glaciers of Greenland and Antarctica to raise sea-level more than 70 m (Titus, 1988). However, this would take tens of thousands of years even if the earth were to warm substantially. Due to the many variables involved, it is impossible to predict the exact amount of sea-level rise. As a result, the minimum and maximum values of rise according to numerous researchers are summarized in Table 2. If present trends continue, an average estimate of sea-level rise within the next 100 years is 1 m (Bird, 1993).
Table 2. Compilation of data on predicted maximum and minimum rates of sea-level rise. Values are given in centimeters for 25 year intervals (from Schwartz, 1990).

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<td>9.5 - 15.5</td>
</tr>
<tr>
<td>2100</td>
<td>56.2</td>
<td>345.0</td>
<td>12.0 - 18.0</td>
</tr>
</tbody>
</table>
These increases may appear insignificant at first, but even a rise of only 0.3 m may cause shoreline recession distances of more than 35 m (Figure 19). Even higher recession rates in marsh and other low-shore areas can be expected (Bruun, 1962). The Bruun Rule explains this process for beaches that are in equilibrium. This theory states the relationship between sea-level rise and erosion (Schwartz, 1967). As sea-level rises, erosion of the upper beach occurs. The eroded sand is deposited in the nearshore zone so that the original beach profile is restored (Figure 20). In effect, there is an upward and landward migration of the beach profile resulting in a coastline that recedes beyond the limits of submergence. This model has been supported by investigations along the Great Lakes shore, along the east coast of the United States, and by laboratory studies. The Bruun Rule was developed for beaches in equilibrium and research has shown that it does not apply to beaches that are not in equilibrium (Bird, 1993).

Effects of Sea-Level Rise on Structures

Any rise in sea level may greatly impact the shore in the form of inundation, erosion, and salt water intrusion (Titus, 1988). The structures along the shore will be affected as well if they were designed for lower sea-levels. As sea-level rises, the structures will either need to be raised and extended laterally or abandoned. In rural areas, it will probably be most cost-effective to let nature take its course, while the most likely response in urbanized areas will be to try to maintain the present coastline (Bird, 1993). Maintenance will be done by constructing sea walls or adding to the existing structures. The predicted cost of maintaining the present U.S. coastline for a one m rise in sea level is $500 billion (Bird, 1993).
Figure 19. Relationship between vertical sea level rise and horizontal shoreline movement (erosion). Note a small amount of rise in water level can lead to a major amount of shoreline erosion (from Ward et al., 1989).
Figure 20. The Bruun Rule: a rise in sea level causes beach erosion. If the sea rises .3 m, so will the offshore bottom. Erosion of the beach (area b) provides the necessary sand for the bottom (area b') (from National Research Council, 1987).
RESULTS

Preface

Net shore-drift and structure information are presented separately for each of the study areas. Information for Grays Harbor and Willapa Bay is presented clockwise from north to south, while the Columbia River sector is described from west to east. Maps are divided into northern and southern sections for Willapa Bay and Grays Harbor, while the Columbia River section is presented on one map (Figure 21). Expanded views of selected maps are also included due to great detail in these areas. Discussion of drift cells includes features that aided in their identification, direction of net shore-drift, and length. The fetch direction is also included. Sediment size descriptions are according to the Wentworth classification system (Figure 22). Structure sectors are described according to their type, construction material used, length, and location on the shore (Figure 23).

Drift cells and structure segments are identified by two letters according to the study area. For example, Grays Harbor would be labeled GH. Drift cells are numbered sequentially, while structure sectors are followed by a letter in alphabetical order (Figure 24). Therefore, the first drift cell within Grays Harbor would be labeled GH-1, while the first structure sector would be identified as GH-A. Willapa Bay drift cells and structure sectors are designated by WB, and the Columbia River features are labeled beginning with CR.

Structure segments and drift cells are identified on maps created from ARC-INFO. These maps were originally based on the U.S. Geological Survey 1:100,000 series. However, the maps were reconfigured to best highlight the study areas and are,
Figure 21. Map of the study areas showing divisions of base maps.
<table>
<thead>
<tr>
<th>GRAIN SIZE IN MM</th>
<th>WENTWORTH SIZE CLASSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>256</td>
<td>Boulder</td>
</tr>
<tr>
<td>64</td>
<td>Cobble</td>
</tr>
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<tr>
<td>2.00</td>
<td>Granule</td>
</tr>
<tr>
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<td>Very Coarse Sand</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>0.0625</td>
<td>Very Fine Sand</td>
</tr>
<tr>
<td>0.0039</td>
<td>Silt</td>
</tr>
</tbody>
</table>

**Figure 22.** Wentworth sediment size classification system.
Figure 23. Cross-section of the beach environment with relevant terminology. Note M.L.L.W. is an abbreviation for mean lower low water (from Ingle, 1966).
Zone of long-term drift divergence; an erosional zone and origin of two diverging cells.

Direction and length of net shore-drift. The line begins at the initial indication of a net drift direction. The arrowhead is positioned at or near the long-term drift cell terminus, a depositional zone.

The cell identification. The letters correspond to the study area. The number is a sequential reference to the various drift cells beginning with the northernmost cell and continuing clockwise around each study area. A letter following the dash represents a structure sector.

WB-8

nansd

Acronym for “no appreciable net shore-drift”. Such a condition may occur due to factors such as no sediment supply, a shore artificially filled or otherwise modified out to deep water, or a shore of very low wave energy.

xxx

Structure sector. Indicates artificial structures along the shore.

Figure 24. Explanation of map symbols.
therefore, each at a slightly different scale. A legend on each map identifies the scale for that map. Drift cells are identified by arrows parallel to the shore, while structure segments are represented by an X X X symbol along the shore. A divergence zone, representing an area of origin of two drift cells, is identified by a dashed line. No appreciable net shore-drift is identified by the acronym “nansd” on the maps (Figure 24). Each map is located at the end of the description section for that particular area.
Grays Harbor

Map GH-1 (Figures 25 and 26)

Structure sector GH-A  The North Jetty of Grays Harbor extends to the southwest for roughly 2.5 km and consists of large riprap. This structure extends downward into the water so that no natural shore exists. Riprap continues from the northeastern end of the North Jetty in the form of a submerged breakwater. It extends to the northeast to the tidal inlet near the Oyhut Wildlife Area, a distance of approximately 2.0 km. This structure is located offshore for approximately 1.5 km with the remaining .5 km situated on the foreshore. The total length along the shore of this structure is 4.5 km.

Drift cell GH-1  This drift cell begins at the northeastern end of the North Jetty, extends to the east, and terminates in a spit. Sediment transport occurs shoreward of the submerged breakwater described in structure sector GH-A. At the origin of the drift cell, 1.6 m high vegetated dunes are being eroded. A peat layer near the beginning of this drift cell is also being eroded with pieces of peat found for about 100 m to the east of the outcrop. Beach width increases significantly to the east. Grain size decreases slightly eastward with sand-sized grains to granules found near the origin and medium to fine sand near the terminus. The drift cell terminus is a flat, unvegetated spit in front of the riprap that extends to the east. A large fetch across the open ocean drives sediment transport in this cell, which is roughly 2.5 km in length.

Drift cell GH-2  This drift cell is located entirely on Damon Point, which is a spit extending to the east. The origin of the drift cell is at the tidal inlet near the Oyhut Wildlife Area. Its terminus is near the northeastern end of Damon Point. Drift cell GH-2 extends to the east, wraps around the eastern end of the spit, and then extends to
the north for a short distance. Near the origin, erosion of the backshore is evident. Beach width increases to the east with concentric beach ridges visible midway through the cell. A slight decrease in grain size to the east is apparent; granules and sand-sized grains are evident at the origin while only sand-sized grains are found near the terminus. Sediment transport in this 1.8 km drift cell is a result of an open ocean fetch on the west with refraction occurring around the end of the spit.

Structure sector GH-B A riprap seawall extends for about .4 km along the road at the origin of drift cell GH-2. The riprap is located on the backshore which appears to have been severely eroded. Sediment transport in GH-2 occurs seaward of this structure.

Structure sector GH-C A small riprap seawall protects the parking lot and trail near the origin of drift cell GH-3. It is situated on the foreshore where it extends along the beach for about 5 m.

Drift cell GH-3 This short drift cell originates near the northeastern tip of Damon Point, extends to the west, and terminates in a spit extending to the northwest. Vegetated 1.8 m high dunes are eroding at the origin of this cell. Beach width increases slightly to the west with a beach ridge evident midway through the cell. The terminus of the cell is a small, unvegetated, slightly hooked spit. Sand-sized grains are prevalent throughout drift cell GH-3. Net shore-drift within GH-3 is due to an easterly local fetch. This drift cell is roughly .5 km long.

Drift cell GH-4 Slight erosion of the .7 m high bank indicates the origin of this west-trending drift cell, which terminates at the Ocean Shores Marina jetty. Beach width increases to the west in this drift cell. A slight decrease in grain size to the west is
evident. Grain size ranges from granules and coarse sand near the origin to fine sand at the terminus. The terminus for drift cell GH-4 is a small bay on the south side of the Ocean Shores Marina where sediment is accumulating. An easterly local fetch drives net shore-drift within this 1.5 km long drift cell.

Structure sector GH-D The Ocean Shores Marina is protected by two riprap jetties each about 200 m in length. The southern jetty at the marina is effective in blocking sediment transport, resulting in the terminus of drift cell GH-4 at this location. A riprap bulkhead extends fairly continuously for approximately 1.8 km northward from the northern jetty at the Ocean Shores Marina. This bulkhead is built on the upper foreshore with sediment transport in GH-5 occurring bayward of the structure. Near the southern end of the bulkhead are several badly-eroded piling groins located across the foreshore.

Drift cell GH-5 This drift cell originates on the northern side of the Ocean Shores Marina, extends to the north, and terminates in a slightly hooked spit. Near the origin of drift cell GH-5, several piling groins (GH-D) have accumulations on their south sides and erosion on the north. These accumulations create a vertical offset of the beach surface averaging 20 cm higher on the south than on the north. An average horizontal offset landward of the shoreline of about .6 m was observed. Beach width increases significantly to the north, while a decrease in grain size to the north was evident. Granules are found with coarse sand near the origin while only sand-sized particles are evident to the north. The drift cell terminates in a spit that is slightly hooked to the west. Transport of sediment within this approximately 2.0 km long cell is related to a local fetch from the south.
An area of no appreciable net shore-drift extends from the terminus of drift cell GH-5 to the mouth of the Chehalis River. This area is characterized by marshy vegetated areas and tidal flats. No appreciable net shore-drift occurs in this area due to the lack of sand-sized sediment and the prevalence of near-shore vegetation. Point New is an eroding bluff consisting of Pleistocene estuary deposits. These deposits generally contain silt- and clay-sized grains and therefore do not provide sediment for littoral transport.

**Structure sector GH-E**  The backshore to the west of the spit indicating the terminus for drift cell GH-5 is protected intermittently by a riprap seawall for approximately 0.8 km.

**Structure sector GH-F**  A riprap bulkhead protects approximately 1.8 km of the shore beginning near Grays Harbor City and extending to the east. Highway 109 parallels the shore in this location. At high tide, the toe of the riprap extends into the water, creating an artificial shoreline.

**Structure sector GH-G**  The shore is intermittently protected by a riprap bulkhead or is an industrialized shore for approximately 8.5 km from south of the Bowerman airport, near Hoquiam, eastward to Aberdeen. Aberdeen and Hoquiam both have partially industrialized shores.

The shore southwest of the mouth of the Chehalis River exhibits no appreciable net shore-drift to the mouth of Stafford Creek. Tidal flats prevail along this section with marshy vegetation concentrated along the margins of the shore. There is no sand-sized sediment available for transport in this area.
Rennie Island, south of Hoquiam, is bordered by an area of no appreciable net shore-drift resulting from a lack of sand-sized sediment and the prevalence of marshy vegetation along its shore.
Figure 25. Map GH-1, expanded view.
Map GH-2 (Figures 28 and 29)

An area of no appreciable net shore-drift exists from the mouth of Stafford Creek to Westport. Marshy vegetation, especially within South Bay, is prevalent. Tidal flats are also common. Appropriate-sized sediment is lacking along these shores. Eroding bluffs composed of estuarine deposits are located near South Arbor but are too fine-grained to contribute sediment for littoral transport.

Drift cell GH-6 This drift cell originates on the southern side of the Westport marina facilities, extends to the southeast for roughly .8 km, and terminates in a spit. At the origin of this drift cell, erosion of 1 m high vegetated dunes is apparent, while the terminus of the drift cell, a spit, is fairly flat and unvegetated. Also near the origin, a peat layer is eroding with peat pieces found for approximately 100 m to the southeast of the outcrop. Beach width increases to the southeast in this drift cell and terminates in the southeast-trending spit. Sand-sized sediment is prevalent along the entire length of this drift cell. Sediment transport within this cell is most likely related to both local fetch from the northwest and refracted open ocean waves.

An area of no appreciable net shore-drift extends from the southeastern end of the Westport Marina facilities to the fifth groin from the west on the north end of Westhaven. No appreciable net shore-drift is a result of riprap protecting the shore in this area, as described in structure sector GH-H.

Structure sector GH-H A riprap bulkhead extends from the southern end of the Westport Marina facilities to the western side of Westhaven, a distance of almost 3 km. This structure sector also includes a riprap breakwater at the marina. Six large, riprap groins extending to the north from the northern end of Point Chehalis are included in
this structure sector as well (Figure 27). These structures create an artificial shoreline as a result of their extension into deep water.

**Drift cell GH-7** This drift cell has its source in the sand carried into the inlet from the east end of the log-spiral beach that comprises drift cell GH-8. Drift direction is identified by the accumulation of sand-sized sediment on the western side of the five western-most large riprap groins (Figure 27). Horizontal and vertical offsets of up to 1 m were observed as a result of this sediment accumulation that indicates eastward transport. This drift cell terminates at the fifth groin from the western end. Transport within this .6 km long cell is a result of a long fetch on the west across the open ocean.

**Drift cell GH-8** This drift cell originates to the west of Westhaven, extends to the southwest for roughly 1.5 km, and terminates near the South Jetty at Point Chehalis. This drift cell is located within the confines of a log-spiral beach and exhibits southwestward transport. Sediment is most likely derived from reworking of sediment that composes the spit. Beach width increases to the southwest, and a slight decrease in sediment size to the southwest was apparent. Sand-sized grains prevail in this drift cell with coarser sand found near the origin and finer sand near the terminus. Sediment accumulation on the northeast sides of two riprap groins perpendicular to the beach indicate southwestward transport. In the winter of 1993, the area to the south of the South Jetty was breached. Presently, the situation is being modified by the U.S. Army Corps of Engineers. A large volume of sand is being pumped into the breached area as a temporary measure until a more permanent solution is agreed upon. This artificial nourishment has drastically altered the drift patterns at the end of drift cell GH-8. Net shore-drift within this cell is likely a result of ocean waves from the west being refracted around the landward end of the south jetty.
Figure 27. Groins to the north of Westport. Photograph A shows an aerial view of the groins. East is to the right. Photograph B is a view looking east into Grays Harbor from Westport. Note build-up of sediment against the west sides of the groins.
Structure Sector GH-1  The South Jetty at Grays Harbor extends to the west from the beach for roughly 2.2 km and consists of large riprap.
Willapa Bay

Map WB-1 (Figure 30)

The northern side of the entrance to Willapa Bay was covered by H. Bronson’s drift cell 4-2, which extends from Cape Shoalwater into the bay and includes Graveyard Spit (Bronson, 1984).

Drift cell WB-1 This drift cell begins at a zone of divergence in front of Tokeland, extends to the northwest, and terminates about 1.0 km northwest of its origin near the tidal inlet on the southeast side of Graveyard Spit. Accumulation of sediment on the southeastern side of a wooden groin and a mixed-composition groin (boulders, concrete, pilings) indicate northwesterly transport. This accumulation has resulted in a .3 m vertical rise of the beach surface on the southeast and a roughly 1.0 m horizontal offset landward of the shoreline on the northwest of the wooden groin. The mixed composition groin has a horizontal landward offset of the shoreline of about .6 m on the northwest; a vertical rise of the beach surface of approximately .3 m was observed on the southeast. A slight increase in beach width to the northwest is also apparent. The terminus of this drift cell is located about 1.0 km to the northwest of Tokeland where the sand fades into a vegetated area of the tidal inlet. Sand-sized grains are found along the length of this drift cell. Transport within this cell is most likely due to a local fetch from the east/southeast.

Structure sector WB-A A riprap seawall protects the shore from about 100 m to the west of Tokeland to the northern side of the Tokeland marina, including the two Tokeland marina jetties. The structure is built along the foreshore with several large
riprap groins extending across the foreshore that impede, but do not totally block, sediment transport. The total length of this structure sector is 2.8 km.

**Drift cell WB-2**  
Beginning at a zone of divergence in front of Tokeland, drift cell WB-2 extends to the east and terminates at the Tokeland Marina. Fining of sediment to the east indicates easterly transport. Distinct angular cobbles are eroding from one segment of the bulkhead within this drift cell and are found about 100 m to the east. Grain size diminution of these cobbles is evident to the east. Sand-sized grains and granules are found near the origin as well as the cobbles. The grain size near the terminus is mostly fine sand. The most apparent indicator of net shore-drift direction is the accumulation of sediment on the west side of a series of large riprap groins and corresponding erosion on the east side in this drift cell. Drift cell WB-2 wraps around the end of Toke Point, with drift continuing to the north. It terminates with sediment accumulation against the small Tokeland Marina jetty, which extends to the north. Open ocean fetch is the probable driving force behind this roughly 1.6 km long drift cell which is located entirely on a spit.

An area of no appreciable net shore-drift exists from the western side of the Tokeland marina to the mouth of the Willapa River. The lack of net shore-drift here is a result of prevalent near-shore vegetation. This area is also characterized by extensive tidal flats.

**Structure sector WB-B**  
A riprap seawall roughly 20 m in length protects Highway 105 directly to the southwest of the mouth of the Cedar River. This structure is located on the backshore.
Structure sector WB-C A bulkhead composed of riprap protects Highway 105 from slightly southeast of the mouth of the Cedar River to a short distance west of Freshwater Creek, a distance of nearly 4 km. This structure constitutes an artificial shore at high tide as a result of the riprap extending into the water.

Structure sector WB-D An approximately 2.5 km long riprap bulkhead protects Highway 105 west of the North River. This structure is situated on the backshore.

Structure sector WB-E Southeast of Smith Creek, the shore in front of Highway 105 is armored with a roughly 1.8 km long riprap bulkhead. An artificial shore is created at high tide due to the extension of riprap down to the water's edge.

An area of no appreciable net shore-drift extends from the mouth of the Willapa River southwest to Wilson Point. It is a result of nearshore vegetation and tidal flats that characterize the area. In addition, there is no sand-sized sediment available for transport.

Structure sector WB-F A rock groin extends for about 100 m across the foreshore at Stony Point. Tidal flats prevail in this location.
Figure 30. Map WB-1.
Map WB-2 (Figure 31)

No appreciable net shore-drift exists from Wilson Point to the mouth of the Palix River. This zone extends from the Palix River northwestward to Goose Point and is a result of lack of sand-sized sediment, nearshore vegetation, and prevalent tidal flats.

Drift cell WB-3 This drift cell originates at Goose Point, extends to the south, and terminates about 2 km south of Sandy Point. Erosion of 13 m high bluffs prevails along much of this drift cell. The material in the bluffs consists of estuarine deposits that are generally too fine-grained to make a significant sediment transport contribution. The majority of sediment is probably derived from offshore shoals. Grain size diminution to the south as well as sediment accumulation on the north side of several large, in-place stumps indicate southward transport. Coarse sand and a small amount of granules are found at the origin of drift cell WB-3. Medium to fine sand prevails toward the terminus of this drift cell. Vertical offsets up to .4 m in height were observed on the north side of in-place stumps within this drift cell. Sediment transport at the cell origin is possibly influenced by ocean waves entering through the Willapa Bay inlet. However, essential transport for the entire cell likely remains under the influence of local fetch from the north. The total length of this drift cell is approximately 5 km.

Structure sector WB-G South of Rhodesia Beach, a .8 km long riprap bulkhead protects houses that are located on the upper foreshore. This bulkhead impedes sediment transport but does not entirely block it.
Structure sector WB-H  The upper foreshore along the road at Sandy Point has been reinforced with a riprap bulkhead for approximately 100 m. Also at this location, two rock groins are located on the tidal flats. They do not extend across the sandy stretch of shore mentioned in drift cell WB-3 and therefore do not indicate a drift direction.

An area of no appreciable net shore-drift from roughly 2.0 km south of Sandy Point extends to the mouth of the Naselle River. No appreciable net shore-drift continues around the southern end of Willapa Bay and then northward to slightly north of Nahcotta. It is a result of a well-vegetated shore, extensive tidal flats, and no sand-sized sediment available for transport.

Structure sector WB-I  Beginning at the southwestern end of the Stanley Peninsula, Highway 101 is protected intermittently by a riprap bulkhead. This structure extends for approximately 7 km to the southwest. In many locations along the length of this sector, the riprap creates an artificial shore at high tide.

Structure sector WB-J  The Nahcotta marina is protected by a riprap breakwater that extends to the east for approximately .5 km.

Drift cell WB-4  This short drift cell begins at the former site of the Willapa Camp. This site is commonly referred to as Yellow Bluffs by residents of the area. Sediment accumulating on the north side of two riprap groins indicates southwesterly transport. This sediment is beginning to prograde to the southwest over the riprap. An approximately 7.5 m high, vegetated dune is being eroded immediately to the southwest of the end of a riprap bulkhead (WB-K) at this site. Grain size diminution of particles eroding from the groins and bulkhead is evident to the south. The terminus of this .7
km long drift cell is in the small bay to the southwest of the Willapa Camp, where sediment is accumulating. Sand-sized sediment prevails in this area. A long local fetch from the north drives sediment transport within drift cell WB-4.

Structure sector WB-K  A riprap bulkhead extending for roughly 80 m exists at the Willapa Camp. This area has experienced severe erosion problems in recent times (G. Andrews, personal communication). This structure sector also includes the two riprap groins across the foreshore as discussed in drift cell WB-4.

Beginning at the northern end of the Willapa Camp, an area of no appreciable net shore-drift extends to slightly north of Stackpole Harbor. This situation occurs as a result of extensive near-shore vegetation and tidal flats.

Structure sector WB-L  Approximately 2 km of the shore in front of Oysterville is protected by a riprap seawall, which has been overgrown by brush.

Drift cell WB-5  The origin of drift cell WB-5 is located slightly north of Stackpole Harbor. Eroding dunes, approximately 1.4 m in height, and a large accumulation of fallen trees across the beach, indicate the beginning of this drift cell. Accumulation on the southern side of several of the larger trees indicates transport of sediment to the north. A northern increase in beach width also supports northward transport. The terminus of this drift cell is approximately 2.5 km to the north of Stackpole Harbor. Sediment transport in this cell is associated with a long local fetch from the south/southeast. A marshy, vegetated area located in front of the majority of this drift cell would seem to inhibit future transport of sediment in this area. The total length of sediment transport within this drift cell is roughly 1.5 km.
The area extending from the terminus of drift cell WB-5 to Grassy Island is an area of no appreciable net shore-drift. It is characterized by tideflats and marshy lowlands.

Drift cell 4-1, designated by Bronson (1984), covers the southern side of the entrance to Willapa Bay, including Grassy Island.

The east side of Long Island from Diamond Point, at the north end of Long Island, to High Point is an area of no appreciable net shore-drift. High Point is a rocky headland, one of the few locations where bedrock crops out along the shore of Willapa Bay. The zone of no appreciable net shore-drift extends northward to slightly south of Smoky Hollow on the west side of the island.

**Drift cell WB-6** This drift cell begins slightly south of Smoky Hollow, extends generally to the northwest, and terminates at the end of Jensen Point. Vegetated bluffs, averaging roughly 13 m high, are eroding at the beginning and middle of this cell while Jensen Point, at the terminus, is a fairly flat, unvegetated spit. A reduction in grain size was observed from Smoky Hollow northwestward to Jensen Point. Granules prevail in the southeastern end of this drift cell, while the spit is characterized by fine sand. An increase in beach width from southeast to northwest is also apparent. Local fetch from the south drives sediment transport within this approximately 6 km long drift cell.

The area directly behind Jensen Point is a marshy area of no appreciable net shore-drift. This is due to extensive tidal flats and vegetation in this area.
Drift cell WB-7  Drift cell WB-7 extends northward from slightly north of Jensen Point to Diamond Point; a distance of about 2.6 km. An increase in beach width to the north was observed. High (roughly 13 m high), eroding bluffs extend along almost the entire length of this drift cell except at the terminus to the southwest of Diamond Point. The beach at the base of this eroding bluff tends to be very narrow. There is an accumulation of sand at the terminus. Some sediment is probably carried offshore into the vegetated tidal flats. Sediment transport in drift cell WB-7 is related to a local southerly fetch.
Columbia River

Map CR-1 (Figures 32 and 33)

Structure sector CR-A  The North Jetty of the Columbia River consists of large riprap and extends to the southwest from the shore for almost 3 km.

The area between the North Jetty and Jetty A is mostly a rocky headland where no appreciable net shore-drift exists.

Structure sector CR-B  Jetty A extends to the south from a basaltic headland for approximately 1.2 km. It is composed of large riprap.

Drift cell CR-1  This drift cell originates on the east side of Jetty A, has eastward, then northerly net shore-drift, and terminates to the southeast of the Coast Guard Motor Lifeboat School. Slight erosion of the 1.6 m high bank near Jetty A provides some of the sediment, but the majority is probably derived from waves which drive sediment back into the mouth of the Columbia River. Beach width increases gradually to the east with concentric beach ridges evident midway through the cell. Cobbles of various composition have been eroded from Jetty A and transported to the east. This results in a particle size decrease to the east. However, the majority of sediment within this cell consists of sand-sized grains. The terminus for drift cell CR-1 is in a small bay where sediment is accumulating and gradually filling the bay. Sediment transport within this roughly .6 km long cell is a result of the large westerly fetch across the open ocean.

Drift cell CR-2  Slight erosion of the 1 m high bank indicates the origin of this short, north-trending drift cell which terminates at the Coast Guard Motor Lifeboat School.
bulkhead. Beach width increases to the north in this short drift cell. A lobe of sediment prograding to the north over the riprap of the bulkhead indicates the terminus of drift cell CR-2. Sand-sized sediment prevails within this entire drift cell. A local southeasterly fetch drives sediment transport within this 200 m long cell.

The shore from the Coast Guard Motor Lifeboat School to the northwest edge of the Chinook marina exhibits no appreciable net shore-drift. This is a result of extensive marshy vegetation, artificial structures, and tidal flats.

Structure sector CR-C  A riprap bulkhead begins on the south side of the Coast Guard Motor Lifeboat School and protects most of the small bay in which the Coast Guard facilities are located. Vegetation has overgrown the riprap in this area so that it is not readily apparent. It extends for about .8 km to the north.

Structure sector CR-D  A boat launch facility, to the north of the Coast Guard facilities, is built out over the marshy foreshore area. The parking lot area is protected by a riprap bulkhead. A short piling jetty extends to the south. The area covered by these structures is about .2 km in length.

Structure sector CR-E  The Port of Ilwaco boat basin is sheltered by two riprap jetties and a breakwater. This structure extends along the shore for roughly .8 km.

Structure sector CR-F  The road in front of the Port of Ilwaco Airport is reinforced with an overgrown riprap seawall for almost 3 km to Stringtown. This structure is situated on the backshore.
Structure sector CR-G  Approximately 1.0 km of the backshore northwest of Chinook is intermittently reinforced by a riprap seawall. A short segment of the structure is constructed of logs.

Structure sector CR-H  The Port of Chinook marina breakwater consists of riprap and parallels the shore for roughly .5 km.

Drift cell CR-3  Beginning to the southeast of the Port of Chinook marina breakwater, this cell has southeastward net shore-drift and terminates to the northwest of the Chinook county park. Recent dredgings from the boat basin channel have been deposited on the upper foreshore at the origin of this drift cell. Erosion of this material is occurring. Grain size decrease to the southeast and a slight beach width increase to the southeast indicate southeastward net shore-drift. A wooden walkway perpendicular to the shore acts as a partial barrier to shore-drift with accumulation occurring on the northwest side and corresponding erosion on the southeast side. A vertical offset, approximately 25 cm higher on the northwest than on the southeast, indicates southeastward transport of sediment. The terminus of drift cell CR-3 is an area of sediment accumulation to the northwest of the county park. Sediment transport is likely related to westerly open-ocean fetch. A local fetch from the northwest probably also influences this 1.2 km long cell.

Structure sector CR-I  The backshore of drift cell CR-3 is protected by a seawall beginning about 45 m to the southeast of the Chinook marina and extending to the northeastern side of Chinook Point. The material is predominantly riprap but also includes some concrete blocks, dead brush, and old machinery parts. The length of this structure sector is roughly 2.2 km.
An area of no appreciable net shore-drift occurs from the southeastern edge of Chinook to Grays Point. The shore here is characterized mainly by tidal flats with small, intermittent pockets of vegetation up to the northwestern side of Chinook Point. Extending from the southeastern side of Chinook Point to Knappton, there is no natural shore due to the structures along the shore. From Knappton to Grays Point, extensive vegetation and tidal flats prevent shore-drift. The shore extending to the east of Grays Point was not included in this study.

**Structure sector CR-J** A riprap bulkhead extends from the southeastern side of Chinook Point, which is bedrock, to Knappton. Along the majority of this distance, the highway closely parallels the shore resulting in an artificial shore. A few small rocky headlands interrupt this nearly continuous stretch of riprap. Roughly 1.3 km to the northeast of Cliff Point, the road diverges briefly from the shore. The riprap in this particular area is less prevalent and is slightly overgrown since the road does not need protecting. The total length of this structure sector is approximately 10 km long.
Figure 32. Map CR-1, expanded view.
DISCUSSION

Eight drift cells were identified within Grays Harbor, seven within Willapa Bay, and three along the stretch of the Columbia River studied. Fetch appears to be the most important factor controlling the direction of sediment transport since no predominant orientation of transport is evident in any of the study areas (Table 3). Local fetch appears to be responsible for sediment transport in one half of the drift cells, an open ocean fetch accounts for transport in one third, while the remaining one sixth are associated with both an open ocean and a local fetch.

The lengths of the drift cells vary from a couple hundred meters to about 6 km. The average length is 1.5 km for all of the study areas (Table 3). Willapa Bay has the longest average drift cell length: 2.6 km. The Columbia River has the shortest average length with a value of .6 km. Grays Harbor drift cells average 1.4 km in length.

The majority of the drift cells are concentrated near the inlets of the estuaries where there tends to be a greater abundance of sand. The predominant source of sediment is erosion of sand dunes. In Grays Harbor and Willapa Bay, this involves the reworking of sand comprising the barrier spits that partially enclose the embayments. Sand-sized grains were the prevalent grain size found in the majority of the drift cells.

No appreciable net shore-drift dominates in all of the study areas due to the lack of appropriate-sized sediment in the areas and the predominance of tidal flats and marshy areas characteristic of estuarine environments. In some locations, no appreciable net shore-drift was a result of structural intervention that created an artificial shore.
Table 3. Compilation of drift cell data.

<table>
<thead>
<tr>
<th>Drift Cell</th>
<th>Direction of Transport</th>
<th>Length (km)</th>
<th>Miscellaneous Features</th>
<th>Fetch</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH-1</td>
<td>East</td>
<td>2.5</td>
<td>Peat, Spit</td>
<td>Ocean</td>
</tr>
<tr>
<td>GH-2</td>
<td>East, North</td>
<td>1.8</td>
<td>Spit</td>
<td>Ocean</td>
</tr>
<tr>
<td>GH-3</td>
<td>West</td>
<td>0.5</td>
<td>Hooked Spit</td>
<td>Local</td>
</tr>
<tr>
<td>GH-4</td>
<td>West</td>
<td>1.5</td>
<td></td>
<td>Local</td>
</tr>
<tr>
<td>GH-5</td>
<td>North</td>
<td>1.8</td>
<td>Hooked Spit</td>
<td>Local</td>
</tr>
<tr>
<td>GH-6</td>
<td>Southeast</td>
<td>0.8</td>
<td>Peat</td>
<td>Local And Ocean</td>
</tr>
<tr>
<td>GH-7</td>
<td>East</td>
<td>0.6</td>
<td></td>
<td>Ocean</td>
</tr>
<tr>
<td>GH-8</td>
<td>Southwest</td>
<td>1.5</td>
<td></td>
<td>Ocean</td>
</tr>
<tr>
<td></td>
<td>Grays Harbor Average Length</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WB-1</td>
<td>Northwest</td>
<td>1.0</td>
<td></td>
<td>Local</td>
</tr>
<tr>
<td>WB-2</td>
<td>East, North</td>
<td>1.6</td>
<td>Spit</td>
<td>Ocean</td>
</tr>
<tr>
<td>WB-3</td>
<td>South</td>
<td>5.0</td>
<td></td>
<td>Local And Ocean</td>
</tr>
<tr>
<td>WB-4</td>
<td>Southwest</td>
<td>0.7</td>
<td></td>
<td>Local</td>
</tr>
<tr>
<td>WB-5</td>
<td>North</td>
<td>1.5</td>
<td></td>
<td>Local</td>
</tr>
<tr>
<td>WB-6</td>
<td>North</td>
<td>6.0</td>
<td>Spit</td>
<td>Local</td>
</tr>
<tr>
<td>WB-7</td>
<td>North</td>
<td>2.6</td>
<td></td>
<td>Local</td>
</tr>
<tr>
<td></td>
<td>Willapa Bay Average Length</td>
<td>2.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CR-1</td>
<td>East, North</td>
<td>0.6</td>
<td></td>
<td>Ocean</td>
</tr>
<tr>
<td>CR-2</td>
<td>North</td>
<td>0.2</td>
<td></td>
<td>Local</td>
</tr>
<tr>
<td>CR-3</td>
<td>Southeast</td>
<td>1.2</td>
<td></td>
<td>Local And Ocean</td>
</tr>
<tr>
<td></td>
<td>Columbia River Average Length</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average Length of Study Areas</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Spits were documented as the terminus of a drift cell in six locations (Table 3). Hooked spits were identified in two of these cases. The "hook" is a result of the refraction of waves around the terminus of the spit.

Much of the shore within Grays Harbor, Willapa Bay, and the section of the Columbia River is undeveloped; but, where there is development, structures to combat erosion are common. Structures are most prevalent along the Columbia River shore. Within Grays Harbor, the shore near the inlet is dominated by structures. Structures are also fairly common near Aberdeen and Hoquiam but are lacking along the remainder of the shore within Grays Harbor. Shore protection structures are found in a wide variety of locations along the shore of Willapa Bay. They are most prevalent along the northern and southeastern ends of the bay. Along the Columbia River, roads closely parallel the shore for much of the shore length studied. The riprap of these protected roads extends into the water of the Columbia River so that no natural shore exists in these sectors. The same is true for sections of the shore within Willapa Bay and Grays Harbor.

The location of structures, with respect to the beach, varies. The majority of bulkheads and seawalls are situated along the backshore. Along the Columbia River, the shore near Chinook is protected by a seawall on the backshore (structure sector CR-I) for almost the entire length of drift cell CR-3. However, this is not the case in drift cell WB-2, near Toke Point which is armored along its entire length by a seawall located on the foreshore (structure sector WB-A). Structures located on the backshore tend to result in minimal effects on the shore, while sediment transport is often affected when the structure is situated on the foreshore. An example of a response to interrupted sediment transport would be a lowering of the beach profile.

Riprap is the most common material used for shore-protection structures within the study areas. It was used in the construction of all of the structure sectors (Table 4).
Table 4. Compilation of structure sector data.

<table>
<thead>
<tr>
<th>Structure Sector</th>
<th>Length (km)</th>
<th>Type</th>
<th>Construction Material Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH-A</td>
<td>4.5</td>
<td>Jetty, Submerged Breakwater</td>
<td>Riprap</td>
</tr>
<tr>
<td>GH-B</td>
<td>0.4</td>
<td>Seawall</td>
<td>Riprap</td>
</tr>
<tr>
<td>GH-C</td>
<td>0.05</td>
<td>Seawall</td>
<td>Riprap</td>
</tr>
<tr>
<td>GH-D</td>
<td>0.2</td>
<td>Jetty, Bulkhead, Groins</td>
<td>Riprap, Pilings</td>
</tr>
<tr>
<td>GH-E</td>
<td>0.8</td>
<td>Seawall</td>
<td>Riprap</td>
</tr>
<tr>
<td>GH-F</td>
<td>1.8</td>
<td>Bulkhead</td>
<td>Riprap</td>
</tr>
<tr>
<td>GH-G</td>
<td>8.5</td>
<td>Bulkhead, Industrialized Shore</td>
<td>Riprap</td>
</tr>
<tr>
<td>GH-H</td>
<td>3.0</td>
<td>Breakwater, Bulkhead, Groins</td>
<td>Riprap</td>
</tr>
<tr>
<td>GH-I</td>
<td>2.2</td>
<td>Jetty</td>
<td>Riprap</td>
</tr>
<tr>
<td>WB-A</td>
<td>2.8</td>
<td>Bulkhead, Groins</td>
<td>Riprap, Concrete, Wood</td>
</tr>
<tr>
<td>WB-B</td>
<td>0.02</td>
<td>Seawall</td>
<td>Riprap</td>
</tr>
<tr>
<td>WB-C</td>
<td>4.0</td>
<td>Bulkhead</td>
<td>Riprap</td>
</tr>
<tr>
<td>WB-D</td>
<td>2.5</td>
<td>Bulkhead</td>
<td>Riprap</td>
</tr>
<tr>
<td>WB-E</td>
<td>1.8</td>
<td>Bulkhead</td>
<td>Riprap</td>
</tr>
<tr>
<td>WB-F</td>
<td>0.1</td>
<td>Groin</td>
<td>Riprap</td>
</tr>
<tr>
<td>WB-G</td>
<td>0.8</td>
<td>Bulkhead</td>
<td>Riprap</td>
</tr>
<tr>
<td>WB-H</td>
<td>0.1</td>
<td>Bulkhead, Groins</td>
<td>Riprap</td>
</tr>
<tr>
<td>WB-I</td>
<td>7.0</td>
<td>Bulkhead</td>
<td>Riprap</td>
</tr>
<tr>
<td>WB-J</td>
<td>0.5</td>
<td>Jetty</td>
<td>Riprap</td>
</tr>
<tr>
<td>WB-K</td>
<td>0.08</td>
<td>Bulkhead, Groins</td>
<td>Riprap</td>
</tr>
<tr>
<td>WB-L</td>
<td>2.0</td>
<td>Seawall</td>
<td>Riprap</td>
</tr>
<tr>
<td>CR-A</td>
<td>3.0</td>
<td>Jetty</td>
<td>Riprap</td>
</tr>
<tr>
<td>CR-B</td>
<td>1.2</td>
<td>Jetty</td>
<td>Riprap</td>
</tr>
<tr>
<td>CR-C</td>
<td>0.8</td>
<td>Bulkhead</td>
<td>Riprap</td>
</tr>
<tr>
<td>CR-D</td>
<td>0.2</td>
<td>Jetty, Bulkhead, Breakwater</td>
<td>Riprap</td>
</tr>
<tr>
<td>CR-E</td>
<td>0.8</td>
<td>Jetty, Breakwater</td>
<td>Riprap, Pilings</td>
</tr>
<tr>
<td>CR-F</td>
<td>3.0</td>
<td>Seawall</td>
<td>Riprap</td>
</tr>
<tr>
<td>CR-G</td>
<td>1.0</td>
<td>Seawall, Bulkhead</td>
<td>Riprap. Logs</td>
</tr>
<tr>
<td>CR-H</td>
<td>0.5</td>
<td>Breakwater</td>
<td>Riprap</td>
</tr>
<tr>
<td>CR-I</td>
<td>2.2</td>
<td>Seawall</td>
<td>Riprap, Miscellaneous</td>
</tr>
<tr>
<td>CR-J</td>
<td>10.0</td>
<td>Bulkhead</td>
<td>Riprap</td>
</tr>
</tbody>
</table>
The jetties are by far the most massive artificial structures within the study areas. The large structures were built at the mouth of the Columbia River and the entrance to Grays Harbor in the late 1800's and early 1900's for navigational purposes (Galster, 1989). Jetties have also been proposed for the entrance to Willapa Bay (Erickson and Sawyer, 1973).

These structures have been very effective in terms of navigational improvements. For example, at the Columbia River, the bar had migrated two miles seaward by 1950 from its pre-jetty position (Galster, 1989). These structures have also resulted in significant geomorphic changes to the entrances of Grays Harbor and the mouth of the Columbia River. These effects include sediment impoundment behind the structures such as the accretion at the North Jetty of Grays Harbor. By 1939, this accumulation had resulted in a 3.3 km seaward offset of Point Brown. These changes are evident in the historical maps of these areas (Figures 34 and 35). It is important to note that significant geomorphic changes, such as the erosion of Cape Shoalwater, have also occurred at the entrance to Willapa Bay although no jetties exist at this location.

The massive jetties have repeatedly deteriorated over the years, requiring expensive upkeep. Table 5 documents the maintenance for these large structures. The South Jetty at the Columbia River is included since the effectiveness of the structure is a result of the pairing. Jetty A and the groins north of Westport are also noted since they were constructed to prevent further migration of the channel that resulted from construction of the large jetties.

The use of groins is most common within Willapa Bay where four separate locations were identified (Table 4). The largest groins are those to the north of Westport. A small groin field was also documented near Ocean Shores in Grays
Figure 34. Geomorphic changes at the entrance to Grays Harbor.
PB, Point Brown; PC, Point Chehalis, NJ, North Jetty; SJ, South Jetty.
Dashed lines represent the approximate position of -12 m contour, stippled area represents area between mean high water and -6 m (from Galster, 1989).
Figure 35. Geomorphic changes at the mouth of the Columbia River. A, Jetty A; BB, Baker Bay; CD, Cape Disappointment; CS, Clatsop Spit; MS, Middle Sands; NJ, North Jetty; PA, Point Adams; PE, Point Ellice; PS, Peacock Spit; SI, Sand Island; SJ, South Jetty; YB, Youngs Bay. Dashed lines represent shoals, solid lines the approximate position of mean high water (from Galster, 1989).
Table 5. Initial construction of major structures and subsequent upkeep (from Galster, 1989).

<table>
<thead>
<tr>
<th>STRUCTURE LOCATION</th>
<th>INITIAL CONSTRUCTION</th>
<th>MAINTENANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRAYS HARBOR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Jetty</td>
<td>1907-1913</td>
<td>1941-42, 1973</td>
</tr>
<tr>
<td>South Jetty</td>
<td>1889-1902</td>
<td>1935, 1939, 1966</td>
</tr>
<tr>
<td>Westport Groins</td>
<td>1950’s to 1960’s</td>
<td>none noted</td>
</tr>
<tr>
<td>COLUMBIA RIVER</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Jetty</td>
<td>1913-1917</td>
<td>1939-40, 1965</td>
</tr>
<tr>
<td>South Jetty</td>
<td>1885-1889</td>
<td>1936, 1960’s, 1982</td>
</tr>
<tr>
<td>Jetty A</td>
<td>1932-1938</td>
<td>none noted</td>
</tr>
</tbody>
</table>
Harbor. In most cases, a significant accumulation of sediment had occurred on the uprift side in relation to the size of the structures. A corresponding amount of erosion was documented on the downdrift side. Groins were absent along the Columbia River shore.

Pieces of peat were found along two of the drift cells near the inlet of Grays Harbor (Figure 16). The presence of peat in these locations implies significant migration of the shore to override the former marsh area (Figure 36). This is consistent with Galster's (1989) description of the geomorphic changes that have occurred over the years as a result of jetty construction. Galster (1989) states that Damon Spit (Point) is a highly migratory feature. The peat outcrop in drift cell GH-1 is located in this general area.
Figure 36. Migration of a spit. The upper diagram shows three stages in the migration of a spit. Note the marshland that has formed on the sheltered side. The middle and lower diagrams are cross-sections from A to B at the first and third stages, showing how the main bank had been driven landward over the marshland until peat cropped out on the seaward side (from Bird, 1984).
SUMMARY

The shore is a dynamic system that is constantly changing in response to its environment. The coastal process of longshore transport moves sediment along the shore. The overall, net effect of this process is termed net shore-drift. This study documents the net shore-drift directions and limits within Willapa Bay, Grays Harbor, and mouth of the Columbia River through the use of drift cells, which are discrete compartments of sediment transport. Drift cells were identified through field investigations of geomorphologic and sedimentologic indicators. Previous investigations of net shore-drift had been carried out along the entire marine coast of the state except for these three segments.

Grays Harbor, Willapa Bay, and mouth of the Columbia River are all estuarine environments with many unique characteristics. Estuarine beaches are affected by many of the same processes, including longshore transport, as open ocean shores. However, estuaries tend to have lower wave energies than open ocean shores due in part to the prevalence of tidal flats. Near-shore vegetation is also common within estuarine environments. Much of the shore within the study areas lacks sand-sized or larger sediment for transport. Due to the lack of appropriate sediment and the low wave energy, the majority of shore within these areas is characterized by a lack of appreciable net shore-drift. Fetch appears to be the most important factor in determining the direction of net shore-drift as shown by the variable directions of the drift cells identified. This has been found to be the case in previous net shore-drift studies as well.

In addition to mapping net shore-drift, artificial structures along the shore have been documented. Artificial structures generally impact the processes occurring along
the shore. The entrances of Grays Harbor and the Columbia River have been greatly modified as a result of massive jetties. The type and location of other structures within the study areas varies widely.

Identification of drift cells and documentation of structures is imperative for a better understanding of the littoral regime which contributes to more informed decisions regarding these important coastal areas.
REFERENCES


Andrews, G., 1994, personal communication, resident of property that was formerly the Willapa Camp.


Hunter, R.E., Sallenger, A.H. and Dupre, W.R., 1979, Methods and descriptions of maps showing the direction of longshore sediment transport along the Alaskan Bering Seacoast: U.S. Geological Survey Miscellaneous Field Studies Map MF-1049, 5 sheets.


Pilkey, O.H. and Wright, H.L., 1988, Seawalls vs. beaches: Journal of Coastal Research, Special Issue n. 4, p. 41-64.


Terchunian, A.V., 1988, Permitting coastal armoring structures: can seawalls and beaches coexist: Journal of Coastal Research, Special Issue n. 4, p. 65-75.


