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HISTORICAL BATHYMETRIC CHANGES NEAR THE ENTRANCE TO GRAYS HARBOR, WASHINGTON

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SUMMARY

Large changes in the distribution of sediment near the entrance to Grays Harbor, Washington, have occurred since the long rock jetties were built to confine flow. Spits to the north and south of the entrance have grown, the entrance channel has deepened, and the outer bar has eroded and moved offshore. The shorelines of North Beach and South Beach have experienced significant amounts of both erosion and accretion since the jetties were constructed around the turn of the century. North Beach has mostly accreted since reconstruction of the North Jetty in 1975. South Beach has been generally erosional since 1967. Recently, the erosion rate at South Beach has increased and, because Half Moon Bay is growing at the expense of the shoreward side of Point Chehalis, the vegetated portion of the spit is now less than 350 ft wide at the narrowest section. As a result of these alarming trends, and under their authority to study and mitigate erosion and sedimentation resulting from federal projects, the U.S. Army Corps of Engineers, Seattle District, requested that Battelle/Marine Sciences Laboratory evaluate long-term trends in erosion near the entrance to Grays Harbor.

Bathymetric data from U.S. Army Corps of Engineers condition surveys were used to calculate the volume of sediment in four areas: the nearshore region off North Beach, the nearshore region off South Beach, the Entrance area, and the Bar area. These volume calculations supplemented data previously compiled and discussed in a comprehensive review by the U.S. Army Corps of Engineers Committee on Tidal Hydraulics (1967). Data were also obtained from aerial photographs and drawings of vegetation lines mapped from aerial photographs and supplied by the U.S. Army Corps of Engineers.

The data from aerial photographs confirm that recent shoreline erosion rates (now between -47 and -62 ft/yr) at South Beach are higher than the historical average of about -3 ft/yr since 1949. The volume calculations confirm that the recent loss rates have increased in the nearshore region as well. (In this study, the nearshore region is defined by the North Beach and South Beach study areas and is generally seaward of the surf zone and landward of the 60-ft depth contour). The volume calculations also reveal a long-term

loss of sediment in three of the four areas studied. Only North Beach has been relatively stable. Overall, more than 150 million yd^3 of sediment has been lost from the four areas around the entrance to Grays Harbor since 1900.

Available climate and wave data were examined to determine whether patterns of erosion and deposition at Grays Harbor could be correlated with long-term fluctuations in climate or wave energy. Although wave energy has varied and is related to climate fluctuations and although beach erosion is an episodic event that occurs during storms, no direct link was found between long-term storm activity and long-term trends in deposition or erosion at Grays Harbor.

ACKNOWLEDGMENTS

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1.0 INTRODUCTION

1.1 PROJECT BACKGROUND

Two large jetties were built at the entrance to Grays Harbor, Washington, nearly a century ago (Figure 1.1). The South Jetty was completed in 1902 and the North Jetty was finished early in 1916. Since then, the configuration of the entrance region has changed significantly: the entrance channel is deeper, the spits to the north and south of the entrance have grown, and the crest of the offshore bar has moved seaward into deeper water. Most of the changes that occurred were anticipated. In fact, they were planned when the U.S. Army Corps of Engineers (USACE) designed and built the jetties, which were successful in establishing a deep navigable channel into Grays Harbor. Recently, however, beaches near the South Jetty have been eroding at an alarming rate. Since 1986, the vegetation line on the seaward side of South Beach has retreated in some places by more than 300 ft (Figure 1.2). Erosion is occurring at apparently accelerated rates, and the retreat of South Beach and growth of Half Moon Bay threaten land owned by the city of Westport and Washington State Parks.

The Port of Grays Harbor requested that the USACE investigate the causes of erosion at Grays Harbor. Under provisions of §111 of the Rivers and Harbors Act of 1968 (Public Law 90-483) as amended by §940 of the Water Resources Development Act of 1986 (Public Law 99-662), the USACE is authorized to evaluate and mitigate adverse effects, including erosion and sedimentation, associated with federal projects. Toward that end, the Seattle District requested that Battelle/Marine Sciences Laboratory (MSL)[a] review historical data to determine trends in erosion and accretion since the construction of the jetties, and to determine, if possible, the cause(s). Specifically, the USACE requested that MSL:

1. analyze rates of erosion or accretion at South Beach and Half Moon Bay using data digitized from aerial photographs

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(a) The Battelle/Marine Sciences Laboratory is part of the Pacific Northwest Laboratory, which is operated for the U.S. Department of Energy by Battelle Memorial Institute.

2. quantify rates of sediment erosion or accretion (including dredging contributions) for specific areas near the entrance, including North Beach, South Beach, the outer Bar, and the Entrance

3. summarize historical oceanographic conditions and evaluate their contribution to long-term trends in erosion or accretion.

This report presents the results of that study and updates information provided in a report by the Committee on Tidal Hydraulics (1967) that analyzed changes up to 1960.

1.2 STRUCTURE OF THIS REPORT

The remainder of Section 1.0 provides background information, summarizing results from previous studies. Section 2.0 describes the techniques used to determine beach-erosion rates from aerial photographs of South Beach and Half Moon Bay, and presents results of those measurements. Section 3.0 presents methods for, and results of, measurements of deposition and erosion at four areas near the entrance to Grays Harbor. These areas, called North Beach, South Beach, Bar, and Entrance, were chosen to extend results from the USACE Committee on Tidal Hydraulics (1967) report, which are discussed later in this section. In Section 4.0, physical oceanographic characteristics of Grays Harbor are summarized, and available long-term wave data are presented and discussed. Contributions of large-scale, long-term variations are also discussed in Section 4.0. Section 5.0 discusses results of previous sections and presents conclusions.

1.3 RECENT EROSION AT SOUTH BEACH AND HALF MOON BAY

Estimates of erosion of South Beach, made by the USACE from aerial photographs, show that the ocean beach just south of the South Jetty eroded at an average rate of approximately -15 to -20 ft/yr between 1967 and 1986. The spit is eroding from both sides as Half Moon Bay grows westward and the ocean beach retreats eastward. Since 1986, the rate of erosion has apparently increased to about -60 ft/yr. The apparent recent increase in the rate of erosion has raised concerns about the possibility of a breach in Point Chehalis spit. Just south of the South Jetty, the spit (in 1992) was only about 300 ft wide at the narrowest vegetated section (Figure 1.2). A concern is that a breach might result in a significant loss of land area on the northern portion of Point Chehalis and would affect entrance-channel maintenance, local navigation, and stability of the South Jetty.

1.4 EROSION MITIGATION

The USACE is evaluating the use of dredged material to mitigate erosion at Grays Harbor. Suitable, clean material can be used to build underwater berms or as beach nourishment material. Berms are elongated mounds of sand oriented parallel to shore that resemble offshore bars. One berm was built in June 1992, and is located approximately 1500 ft north of Half Moon Bay. A second berm has been proposed, to be located seaward of South Beach, centered 6500 ft offshore and 5000 ft south of South Jetty. The berm at the Half Moon Bay site was emplaced just inshore of the 18-ft depth contour relative to mean lower low water (MLLW; to which all depths in this report are referred). The berm is approximately 1250 ft long by 600 ft wide at its base, rising to a crest about 7 ft below MLLW. The berm proposed for South Beach has not been constructed.

Berms are intended to ameliorate beach erosion by providing some protection from incident waves and by providing material to nourish the beaches and nearshore regions. The berms at Grays Harbor would be constructed of sand dredged from the entrance region. Berms are economically attractive for beach protection because they can be built by hopper dredges; thus they serve a dual function as disposal sites for clean dredged material and a source of sediment for the littoral system. It is not certain how effective berms are either for protection or as sources of beach nourishment, and it is likely that their effectiveness diminishes with increased water depth and distance offshore. At Grays Harbor, their effectiveness may be limited because the hopper dredges cannot build berms in depths less than about 28 ft. There are also drawbacks to berm construction: berms are essentially man-made shoals designed to affect local wave conditions, so they can be a hazard to navigation. At Grays Harbor, crab fishermen are concerned that berm construction off South Beach in a profitable fishing area will increase fishing costs, increase the risk to small boats using the area, and reduce available crab habitat. Some of these impacts might be reduced by dispersing dredged materials over a broad nearshore region off South Beach. The sand would still be available to nourish the beach, but would not increase the hazard to navigation, and might have a less acute effect on the crab fishery. Unfortunately, because the material would be spread over a wide area it would be more difficult to monitor and discern benefits or adverse impacts. An objective of this study is to provide data that can be used in making management decisions regarding berms or other erosion-control measures.

1.5 HISTORICAL BACKGROUND AND PREVIOUS STUDIES OF EROSION AND DEPOSITION

Patterns of sediment deposition and erosion near the entrance to Grays Harbor before 1960 were studied by the USACE Committee on Tidal Hydraulics (1967; hereafter referred to as the CTH report) and are reviewed here. Bathymetric charts of the entrance to Grays Harbor have been made regularly since the late 1800s. These charts document substantial changes in the volume and distribution of sediments.

Before construction of the South Jetty (1896 to 1902), there was a well-defined channel, approximately 2000 ft wide and 40 to 60 ft deep, separating the broad shoals of Point Hansen (now Point Chehalis) to the south and Point Brown to the north. The channel extended seaward 2.5 to 3 mi from its narrowest section between the shoals, but ended on the landward side of the outer bar, a large, fan-shaped shoal that extended around the entrance area. Water depths along the crest of the outer bar were nowhere deeper than 18 ft, and were often less than 10 ft. The outer bar was about 5000 ft wide (between the inner and outer 24-ft depth contours), and the crest of the bar was located about 3.75 mi west of the entrance-channel narrows.

The South Jetty was completed in 1902 and extended 13,734 ft west of Point Chehalis, or approximately 12,200 ft west from the high water line of that time. The entrance channel began to deepen and extend westward, forcing the outer bar seaward, in response to the changed pattern of tidal currents induced by the South Jetty. The North Jetty was constructed between 1907 and 1916, and extended 17,204 ft southwest across the (then) extensive tidal flats south of Point Brown. From there it angled westward for 6250 ft, along the shoals north of the entrance channel. The western terminus of the North Jetty was located approximately 6800 ft north of the South Jetty terminus.

The jetties acted as efficient training structures, fixing the alignment and increasing the velocity of tidal currents through the entrance, particularly during ebb tides, creating a westward jet. The result was significant deepening of the entrance channel and seaward movement of the outer bar. In addition, the portions of the bar located to the north and south of the entrance moved closer to shore under incident wave action and reduced ebb currents at these locations. Sand from these regions probably enhanced the supply of material trapped during alongshore sediment transport by the jetties. The beaches to the north of North Jetty (North Beach) and to the south of South Jetty (South Beach) both grew rapidly. The tidal flats between North Jetty and Point Brown, which had been more than 1.5 mi wide, began to fill and, by 1921, an unbroken supratidal spit (an accretional sand body extending above high water) more than 2000 ft wide extended to the bend in the North Jetty. The location of the MLLW line at the North Jetty had advanced to within 4000 ft of the outer terminus by 1925. In a similar fashion, the high-water line at South Beach advanced seaward more than 3000 ft between 1898 and 1910.

Deterioration of both jetties began soon after construction, probably caused by scouring of sand from beneath the jetties by wave and current action. According to the CTH report, the South Jetty had, by 1933, sunk to an average elevation of -5 ft MLLW over the outer 12,000 ft. The North Jetty sank to an average elevation of about -1.5 ft MLLW along the outer 7000 ft during this time. The South Jetty was completely reconstructed to +20 ft elevation between 1935 and 1940, and the North Jetty was rehabilitated to +20 ft along its outer 8000 ft between 1941 and 1942. Again, both jetties progressively degraded so that, by 1962, South Jetty was below MLLW along the outer 7000 ft. A rehabilitation effort during 1965-1966 restored the middle 4000-ft section of South Jetty to +20-ft elevation, but the outer 6000-ft section remained below MLLW. By 1992, this outer section of South Jetty averaged -10 to -20 ft in elevation. North Jetty, by 1960, had degraded to an average elevation of +14 ft along the outer 6500-ft section, with minimum elevations around +3 ft. In 1975, this section was reconstructed to +20 ft.

Previous studies, including the CTH report, note that accretion along North and South Beaches appears to occur soon after construction or restoration of the jetties, and erosion appears to correlate with periods of jetty deterioration. Sediment erosion and deposition patterns for the entrance area and outer bar are significantly influenced by the state of the jetties via tidal-current effects, sand-transport blockage, and wave sheltering.

Dredging of the channel through the outer bar was first performed in 1916 and 1917, and was performed annually from 1920 to 1942. After 1942, dredging was not required to maintain the authorized channel depths, which were increased from -18 ft to -26 ft in 1930, and to -30 ft in 1945. During this early period of dredging of the bar channel, approximately 22 million yd^3 of sand were removed, averaging 810,000 yd^3/yr. The dredge spoils were disposed in deep water at the end of the channel (CTH 1967).

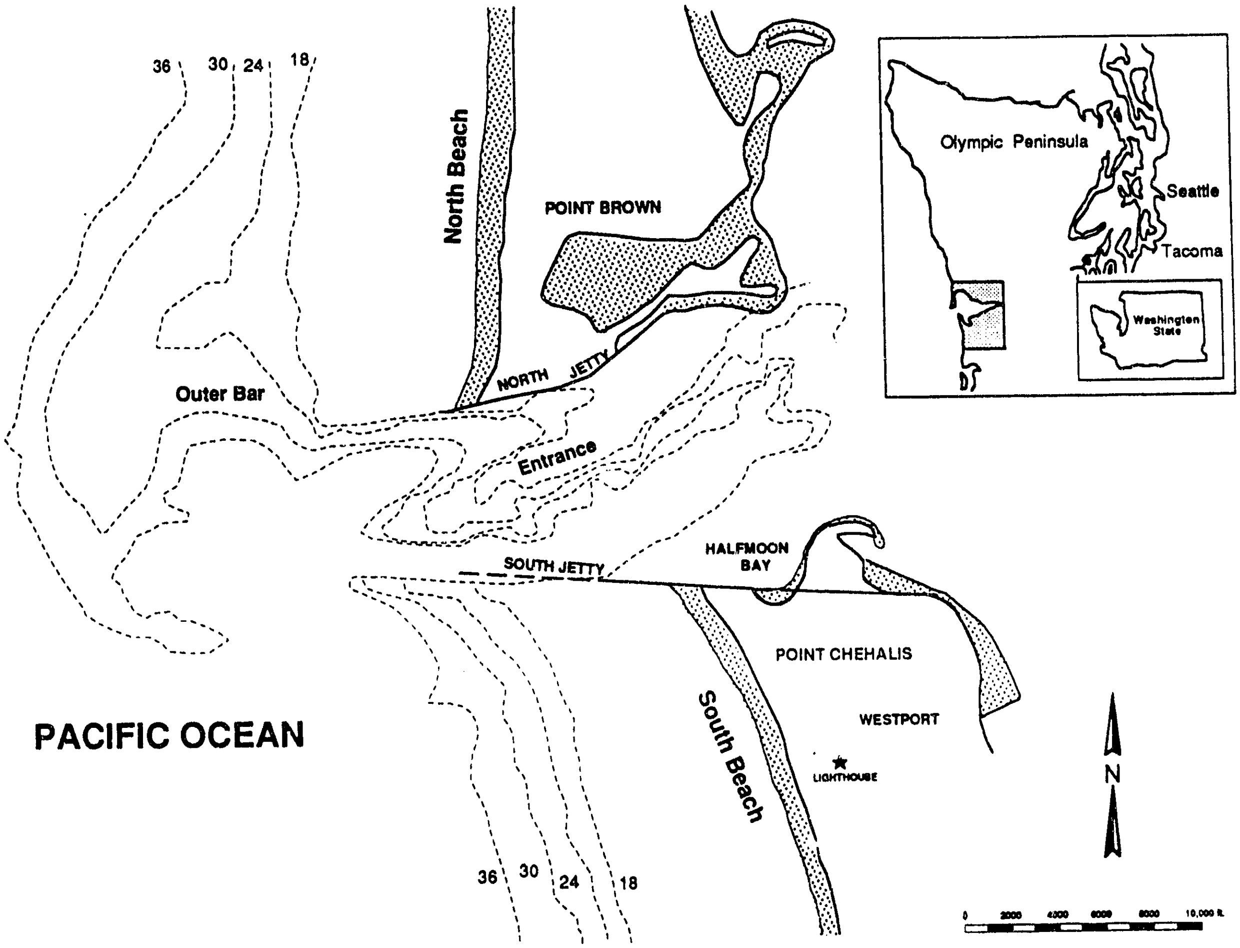


FIGURE 1.1. Study Area at the Entrance to Grays Harbor, Washington. Bathymetry contours are in feet relative to Mean Lower Low Water (MLLW). Intertidal areas are stippled.

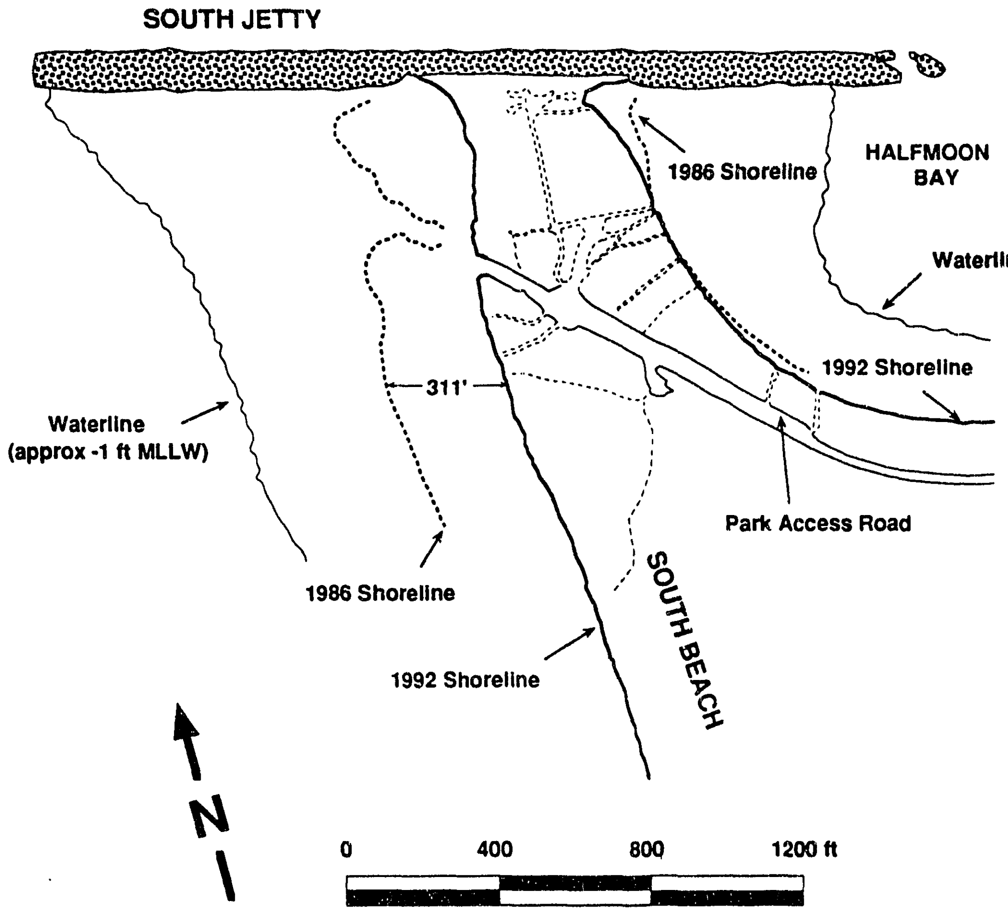


FIGURE 1.2. Erosion Between 1986 and 1992 at South Beach. Heavy solid line marks limit of vegetation interpreted from air photo taken May 6, 1992; short-dashed line marks vegetation limit in 1986 photo. Light solid line marks water line in 1992 photo, taken ½-h before predicted -1-ft low tide.

2.0 SHORELINE CHANGES AT SOUTH BEACH AND HALF MOON BAY

2.1 DATA SOURCES AND PERIOD OF ANALYSIS

Aerial photographs of the northern tip of Point Chehalis, encompassing the portion of South Beach within several thousand feet of the South Jetty and Half Moon Bay, were used to measure changes in shoreline position. Data from large-scale vertical aerial photographs taken in 1949, 1967, 1973, 1977, 1982, 1986, and 1988 were provided by the USACE as maps of the vegetation line bordering the beaches. These maps were produced by the USACE at a scale of 1 in. = 400 ft. Smaller-scale (approximately 1 in. = 2000 ft) aerial photographs from 1967, 1973, 1976, 1978, 1982, 1985, and 1987 were also examined during this study. Estimated high water (HW) lines on these photographs were digitized at MSL to calculate shoreline advance/retreat at South Beach, and to calculate surface areas of Half Moon Bay. Similar analysis of the HW lines present on condition-survey charts, available for the years 1949, 1970, 1973, 1976, 1979, 1982, 1985, 1987, and 1990 was also performed. A photograph from 1992 did not cover enough area to be included in this analysis, but qualitative comparisons have been made using this photograph (see Figure 1.2).

2.2 ANALYSIS PROCEDURES

The vegetation-line maps were retraced on a digitizing table to estimate changes in beach area at Half Moon Bay and South Beach (Figure 2.1). The beach line at Half Moon Bay was defined as the vegetation line between the South Jetty and an east-west line located approximately 400 ft north of the Westport sewer line. These features were chosen because they appeared on each of the USACE maps. The change in beach area between photo years was calculated as the area enclosed by the two beach lines, the South Jetty, and the east-west line. Beach length was measured around the perimeter of the bay, midway between the plotted beach lines for each pair of photo years. Perimeter-average change in beach width between years was computed by dividing the area change by the beach length, and the average rate of advance or retreat (ft/yr) was calculated by dividing the change in average width by the number of years in the interval between photos. Similar calculations of changes in beach area, beach length, change in average beach width, and advance/retreat rates were made for South Beach. The measurements were made for the section of beach extending from the South Jetty to an east-west line approximately 1600 ft south of the jetty (Figure 2.1). The changes in beach width and rates of advance/retreat are average values over the defined areas, and differ from the maximum rates determined by USACE via analysis of the plotted lines of beach vegetation.

For comparison, calculations were performed for Half Moon Bay using as data 1) HW lines from USACE condition survey charts, and 2) estimated HW lines determined from the small-scale aerial photos. These calculations actually compared water area in the bay, defined by the eastward extension of the South Jetty. Also for comparison, estimates were made of South Beach advance/ retreat along a line orthogonal to the beach, located approximately 1000 ft south of the jetty. These estimates were made on the digitizing table from small-scale aerial photographs and from large-scale condition-survey charts (1 in. = 2000 ft).

2.3 ERROR ANALYSIS

There are several potential sources for errors in these procedures. Errors in the digitizing procedures can be estimated by repetitive digitization of areas with known size; these errors tend to be random (i.e., do not systematically bias the data) and small (less than 1% for areas of the size considered here). Digitization of the small-scale photos are subject to higher error because of the coarser scale of measurement. Larger errors probably arise in identification of the vegetation line or HW line on the photos and charts. In particular, the HW line mapped on the condition-survey charts is not intended to be used in this manner, and may provide misleading results. Although these errors may be systematic, they are somewhat mitigated because the data are only used for comparison with similar data. Therefore, it is difficult to assign error estimates to the changes and rates presented here, and the numbers should be treated as indicators and examined primarily for trends, while keeping in mind the very local nature of the processes and measurements.

2.4 RESULTS

The results of shoreline-change analysis for Half Moon Bay are presented in Tables 2.1 and 2.2. These tables list the change in beach area between photo years, along with average beach length used to convert area to width, the resulting average beach width, and the average rate of beach advance/retreat. Table 2.1 and others that follow indicate beach advance (accretion) with a plus (+) sign and retreat (erosion) with a minus (-) sign. Table 2.3 summarizes changes in beach width and rates of advance/retreat, comparing results determined from the various data sources.

Results for South Beach are presented in Table 2.4, which lists beach-area changes from analysis of vegetation-line maps, along with changes in average width, and average rate of advance/retreat. Table 2.5 summarizes changes in beach width and rates of advance/retreat determined from changes in beach area given in Table 2.4, along with estimates measured from aerial photographs and condition-survey charts along the beach-orthogonal line located approximately 1000 ft south of the Jetty. Also presented in Table 2.5 are historical values taken from Phipps and Smith (1978, Figure 9).

2.5 DISCUSSION OF SHORELINE CHANGES

2.5.1 Half Moon Bay

Half Moon Bay began to form after reconstruction of the South Jetty in 1940. The first indication of a small shoreline indentation at the eastern end of the South Jetty appears on the condition-survey charts from 1946. Material from the eastern end of South Jetty was cannibalized and used for the construction of the revetment and groins at Pt. Chehalis circa 1952. Apparently, removal of this end of the jetty permitted wave- and current-induced erosion of material to accelerate, and Half Moon Bay grew rapidly afterward.

Analysis of vegetation lines shows that from 1949 to 1967, Half Moon Bay grew from a small area to approximately 1,836,000 ft^2, corresponding to an average total shoreline retreat of -482 ft (see Table 2.1). For this 18-yr period, the average rate of retreat was -27 ft/yr. From 1967 to 1973, an additional increase in the size of Half Moon Bay amounts to an estimated loss of another 102,800 ft^2 of beach area. During the period from 1973 to 1977, the trend reversed, with Half Moon Bay decreasing in size, amounting to a growth in beach area totaling 234,000 ft^2, an increase in average beach width of +51 ft, and an average rate of advance of about +13 ft/yr. After 1977, the vegetation line retreated at a slow average rate (-4 ft/yr to -2 ft/yr), but this has apparently accelerated to an average retreat rate of -18 ft/yr during the period 1986 through 1988.

The analysis of changes in the areas defined by HW lines from condition survey charts and small-scale aerial photographs corroborate the accelerated growth rates for Half Moon Bay after about 1985, indicating increases in the rate of average retreat to more than -10 ft/yr.

2.5.2 South Beach

Changes in the shoreline at South Beach are summarized in Tables 2.4 and 2.5. Historical data summarized by Phipps and Smith (1978) show that South Beach accreted rapidly until 1910 following construction of the South Jetty (Table 2.5). Much of that initial accumulation was lost during a long period of erosion (1910 to 1935). Between 1935 and 1959, a period that included reconstruction of the South Jetty, South Beach again grew rapidly.

Results of the vegetation-line analysis performed in this study indicate that South Beach generally accreted between 1949 and 1967 at the relatively slow rate of +7 ft/yr (Table 2.4). Results reported by Phipps and Smith (1978) and analysis of the aerial photographs show that the 1949 to 1967 period included shorter episodes of both erosion and deposition (Table 2.5). The vegetation-line analysis indicates that South Beach has been erosional since 1967, at rates ranging from -2 to -62 ft/yr. The data of Phipps and Smith (1978) and aerial photographs confirm the long-term erosional trend, but also indicate that brief periods of accretion occurred during this period. In particular, the aerial photographs indicate that South Beach accreted between 1967 and 1972, and again between 1974 and 1977. Since then, the aerial photos indicate erosion at rates of -5 to -250 ft/yr.

South Beach has historically fluctuated more than North Beach, but the trend has been mostly erosional since 1967. More rapid erosion has occurred during the mid- to late-1980s, with vegetation-line retreat rates ranging from

-26 to -62 ft/yr through 1988. Although this is the last year for which quantitative vegetation-line data have been compiled, comparison of aerial photos (Figure 2.1) indicates that South Beach continued to retreat at a rate of -47 to -52 ft/yr through May 1992.

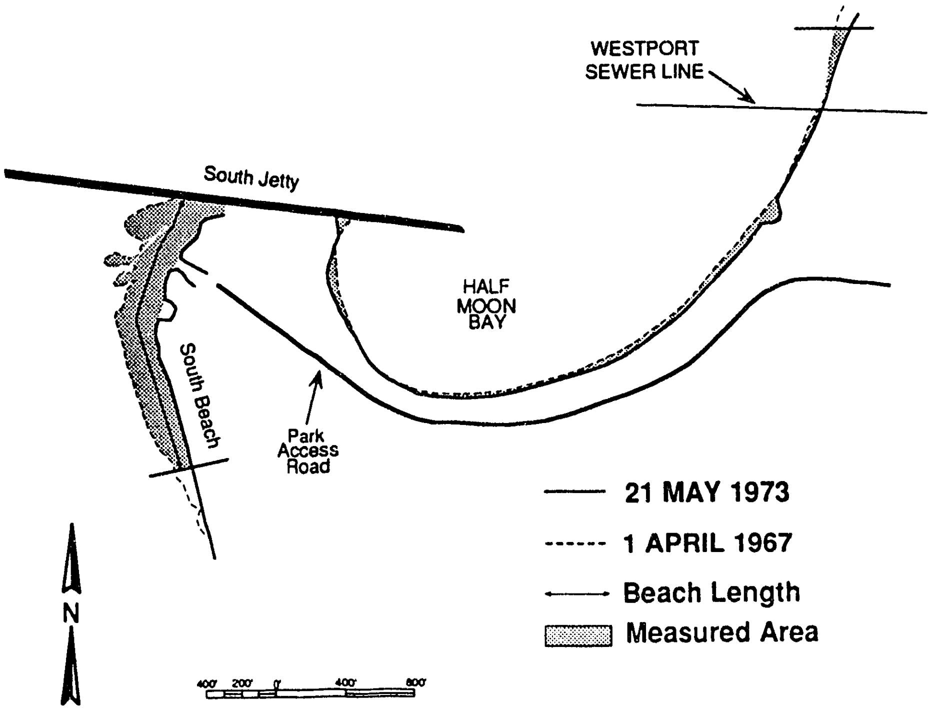


FIGURE 2.1. Vegetation-Line Map Showing Method for Measuring Erosion and Deposition Rates for South Beach and Half Moon Bay. Heavy solid and dashed lines denote shoreline positions on photos taken May 1973 and April 1967. Shaded area indicates areas measured. Light solid line indicates beach length used to calculate average width of beach erosion from measured area.

TABLE 2.1. Shoreline Changes at Half Moon Bay from Analysis of Vegetation-Line Maps

Period (years)	Beach Area (ft^2)	Beach Length (ft)	Beach Width (ft)	Advance Rate (ft/yr)
1949-67	-1,836,140	3,810	-482	-27
1967-73	-102,812	4,675	-22	-4
1973-77	+234,210	4,625	+51	+13
1977-82	-99,468	4,635	-21	-4
1982-86	-34,948	4,630	-8	-2
1986-88	-168,941	4,680	-36	-18

TABLE 2.2. Shoreline Changes at Half Moon Bay from High-Water Line on Condition-Survey Charts

Period (years)	Beach Area (ft^2)	Beach Length (ft)	Beach Width (ft)	Advance Rate (ft/yr)
1949-67	-1,190,000	2,500	-476	-26
1970-73	+309,032	3,575	+86	+29
1973-76	+34,442	3,402	+10	+3
1976-79	-351,099	3,500	-100	-33
1979-82	+827,853	3,120	+265	+88
1982-85	+35,668	2,525	+14	+5
1985-87	-44,108	2,580	-17	-9
1987-90	-88,081	2,625	-34	-11

TABLE 2.3. Estimates for Half Moon Bay Vegetation Line Advance/Retreat (Negative Values Indicate Increase of Bay Area and Retreat of Beach)

From Condition-Survey Charts			From Aerial Photographs			From Analysis of Vegetation Line		
Period (years)	Amount (ft)	Rate (ft/yr)	Period (years)	Amount (ft)	Rate (ft/yr)	Period (years)	Amount (ft)	Rate (ft/yr)
1949-67	-476	-26				1949-67	-482	-27
1970-73	+86	+29	1970-73	-15	-5	1967-73	-22	-4
1973-76	+10	+3	1973-76	-17	-6	1973-77	+51	+13
1976-79	-100	-33	1976-78	-37	-19	1977-82	-21	-4
1979-82	+265	+88	1978-82	+27	+7	1982-86	-8	-2
1982-85	+14	+5	1982-85	0	0	1986-88	-36	-18
1985-87	-17	-8	1985-87	-21	-11			
1987-90	-34	-11						

TABLE 2.4. Shoreline Changes at South Beach Estimated from Vegetation Lines

Period (years)	Change in Beach Area[a] (ft^2)	Change in Width (ft)	Advance or Retreat Rate (ft/yr)[b]
1949-67	+241,259	+121	+7
1967-73	-350,834	-175	-29
1973-77	-93,006	-47	-12
1977-82	-19,240	-10	-2
1982-86	-63,642	-32	-8
1986-88	-247,327	-124	-62
1986-92[c]	---	-280 to -310	-47 to -52

(a) Sampled area extends approximately 200 ft south of jetty.
(b) Positive (+) is accretion (beach growth), negative (-) is erosion (beach loss).
(c) Estimated from comparison of 1986 and 1992 aerial photos (see Figure 1.1). Limited coverage in 1992 photo prevented exact comparison with other years.

TABLE 2.5. Estimates for South Beach Advance (+)/Retreat (-) Along Onshore-Offshore Line Approximately 1000 ft from South Jetty

Period (years)	Phipps and Smith 1978 (Fig. 9) Amt (ft)	Phipps and Smith 1978 (Fig. 9) Rate (ft/yr)
1898-1910	+3,850	+320
1910-39	-3,000	-103
1939-46	+1,100	+157
1946-59	+500	+38
1959-64	-500	-100
1964-68	+500	+125

Period (years)	Analysis of Aerial Photographs Amt (ft)	Analysis of Aerial Photographs Rate (ft/yr)
1962-67	-500	-100
1967-70	+186	+62
1970-72	+83	+42
1972-73	-68	-68
1973-74	-203	-203
1974-76	+170	+85
1976-77	+160	+160
1977-78	-250	-250
1978-82	-18	-5
1982-85	-38	-13
1985-87	-52	-26

Period (years)	Condition-Survey Charts (HW Line) Amt (ft)	Condition-Survey Charts (HW Line) Rate (ft/yr)
1970-76	-90	-15
1976-79	+500	+167
1979-82	-438	-146
1982-85	-38	-13
1985-87	-21	-11
1987-90	-19	-6

Period (years)	Analysis of Beach Vegetated Line Plots Amt (ft)	Analysis of Beach Vegetated Line Plots Rate (ft/yr)
1949-67	+121	+7
1967-73	-175	-29
1973-77	-47	-12
1977-82	-10	-2
1982-86	-32	-8
1986-88	-124	-62

3.0 SEDIMENT-VOLUME CHANGES

3.1 DATA SOURCES AND ANALYSIS PROCEDURES

Bathymetric charts for the entrance to Grays Harbor have been made annually from condition surveys conducted by the USACE. These charts were used to estimate volumes of sediment deposition and erosion within four areas near the entrance (Figure 3.1). The area denoted South Beach corresponds to Zones A+B+C of Plate 2 in the CTH report. The Bar corresponds to Zone G in the CTH report, and the Entrance corresponds to Zones I+II+III in the CTH report. The results of this study, therefore, update the earlier estimates of erosion and deposition through 1960, provided in the CTH report.

Condition-survey charts at a scale of 1 in. = 5000 ft were used for years prior to 1970. From 1970 on, larger-scale (1 in. = 2000 ft) condition-survey charts were used. Condition surveys were performed annually, but comparisons were made on a subset of surveys that provided good spatial coverage at intervals of 3 to 4 yr. The years examined were 1900, 1942, 1948, 1953, 1956, 1959, 1962, 1965, 1968, 1970, 1973, 1976, 1979, 1982, 1985, 1987, and 1990. Several of these years predate 1960 to allow comparison with results presented in the CTH report. Nearly all of the survey data analyzed were collected in late summer or fall, so bias from seasonal variations in erosion and deposition should be minimized.

Bathymetric contours were digitized and subareas within contour intervals for each study area were measured using planimetry software. The subareas were multiplied by their average water depth to compute the overlying water volumes in units of cubic yards (yd^3). The computed subvolumes were then summed within each study area to estimate a total water volume in each of the four study areas for the year. Changes in the water volume between survey years were interpreted as changes in sediment volume, with an increase in water volume corresponding to decreased sediment volume (erosion) and a decrease in water volume indicating increased sediment volume (deposition). Plus (+) signs indicate sediment deposition, and minus (-) signs indicate erosion. Sediment volumes have been uniformly equated with water volumes, with no adjustments made for consolidation in the sediments.

3.2 ERROR ANALYSIS

Digitizing errors on the small-scale charts were measured at approximately 0.71% of the calculated area, but because volume estimates are based on area differences that are also small percentages of the total area, the error bars around the volume estimates are wide. Error estimates, based on the average areas and average depths of the study areas, are as follows: North Beach, ±0.21 million yd^3; South Beach, ±0.89 million yd^3; Bar, ±0.94 million yd^3; Entrance, ±0.71 million yd^3. On the larger-scale charts, digitized errors were only 0.11% of the measured area, and error bars around the volume estimates are reduced by a factor of 6.5 after 1970.

Changes in survey datum and adjustment of horizontal control have occurred from time to time, and may introduce errors in some time intervals. No attempt has been made to correct such errors. The method for calculating changes in sediment volume is an expedient approximation used because the bathymetric data were not available in digital form. It is possible that this method produces systematic biases by either overestimating or underestimating sediment volumes in each survey, but biases are likely to be reduced in the differencing process. Nonetheless, the volumes reported here should be used as indicators, rather than precise measurements of the sediment budget.

3.3 RESULTS

Water-volume estimates are listed (Table 3.1) in units of millions of cubic yards, and represent the volume of water (relative to MLLW) overlying the respective study areas. Table 3.2 presents the deposition and erosion estimates (changes in sediment volumes) derived from the differences in water volumes between selected surveys. Units are listed in millions of cubic yards, and positive values represent an increase in sediment volume (fill or deposition) during the interval, while negative values indicate a decrease (scour or erosion). The results are plotted in Figure 3.2.

3.4 COMPARISON WITH COMMITTEE ON TIDAL HYDRAULICS REPORT

Changes in sediment volume from 1900 to 1960 were taken from Plate 2 of the CTH report for zones corresponding to the present study areas. The values are plotted in Figure 3.3. Table 3.3 compares the deposition and erosion estimates of the CTH report with those of the present study for the overlap period. There is good correspondence, with only a slight offset and change in slope. A linear regression for five time intervals and the four study areas had a correlation coefficient (r^2) of 0.85 and provided the following relationship between the two data sets:

$$(\text{CTH volumes}) = 1.17 \times (\text{present study volumes}) + 1.6 \times 10^6 \text{ yd}^3$$

Because the difference in these estimates is within the error bars provided above, no adjustment has been made to the volume changes calculated in the present study. The results of both studies have been combined by appending volume changes from the present study to the CTH report data. This was accomplished by setting estimates for 1959 from the present study equal to the corresponding 1959 estimates from the CTH Report and making no adjustments to the slopes. Figure 3.4 shows the combined data for the period 1900 to 1990.

3.5 SUMMARY OF SEDIMENT-VOLUME CHANGES

The combined results of this study and the earlier CTH report are summarized in Figures 3.4 and 3.5 and Tables 3.1 through 3.3. Results for each of the four areas are discussed below. Deposition rates have been calculated by dividing volume changes by the size of the area and the length of the period; these rates have units of ft/yr but should not be confused with the shoreline advance/retreat rates discussed in Section 2.0. Note that the areas discussed are nearshore regions (defined by the study areas shown in Figure 3.1), and do not include the beach or shoreline.

3.5.1 North Beach

The nearshore area off North Beach is the only study area that has not experienced significant erosion in the last 90 yr. As of 1960, the area off North Beach had accreted approximately +24 million yd^3. Half of that deposition occurred between 1944 and 1948 at deposition rates greater than +2 ft/yr soon after the reconstruction of the North Jetty in 1942. Since then, there has been very little change at North Beach. The nearshore area off North Beach has been eroding at slow rates (-0.04 to -0.43 ft/yr) since 1973.

3.5.2 Entrance

The Entrance was erosional for about the first third of the 90-yr period, remained unchanged for the second third, and eroded slowly during the last 30 yr. Following construction of the South Jetty in 1902, the Entrance area eroded at rates of up to -1 ft/yr until about 1928, losing about -34 million yd^3. Between 1928 and 1936, the Entrance accreted slightly, initially at rates as great at +1.1 ft/yr, but then more slowly, at rates of about +0.3 ft/yr, and regained about +14 million yd^3. Erosion occurred in the Entrance area between 1936 and 1939 at rates exceeding -2.2 ft/yr, followed by about 10 yr of deposition at slow rates (+0.24 to +0.58 ft/yr). By 1960, the net loss since 1900 at the Entrance was about -33 million yd^3, virtually the same as in 1928. However, since then, the Entrance has mostly eroded and, in 1990, had lost a total of -40 million yd^3. A substantial volume of dredged material has been disposed in the entrance region, as will be discussed in Section 3.7.

3.5.3 South Beach

The pattern of erosion at the nearshore area off South Beach is very similar to the pattern in the Entrance. Following jetty construction, the area off South Beach eroded until 1928, losing -36 million yd^3. Net accretion occurred until 1943, and the area remained relatively unchange' until about 1949, when it had lost a total of -30 million yd^3 since 1900. After that, the area off South Beach eroded almost continuously until 1979, at rates between -0.2 and -1.2 ft/yr. Between 1979 and 1982, the area off South Beach briefly accreted about +7 million yd^3, but since then it has eroded at rates of -0.3 to -0.6 ft/yr. The net loss since 1900 is about -61 million yd^3.

3.5.4 Bar

The Bar area has been erosional for virtually the entire 90-yr period, and has lost the largest amount of sediment. Erosion rates have been relatively slow, typically -0.3 to -0.8 ft/yr, but continuous, except during brief depositional periods from 1928 to 1936, 1962 to 1968, 1970 to 1973, and 1985 to 1987. Overall loss in the Bar region since 1900 has amounted to -75 million yd^3.

3.5.5 Total for Four Areas

The long-term trend for the combined areas is unmistakable. More than half of the total loss (-97 million yd^3) occurred between 1900 and 1928. Substantial accretion occurred between 1928 and 1933, followed by about 5 yr with little change. Rapid erosion at rates up to -0.8 ft/yr occurred between 1937 and 1939, then the combined areas remained fairly stable until 1944. Beginning in 1944, deposition at rates up to +0.4 ft/yr occurred for 3 yr and, in 1948, the net loss in combined area was -64 million yd^3. Since then, the combined areas have been almost continuously erosional, at rates as high as -0.7 ft/yr. The overall net loss since 1900 amounts to -153 million yd^3, an average loss of -13 ft over the entire study area, at a rate of -0.15 ft/yr.

3.6 SEDIMENT VOLUMES FOR OUTER BAR

Examination of the annual condition surveys suggests that the crest of Outer Bar first moved seaward into deep water then landward as erosion continued to decrease the size of the bar. To quantify this apparent trend, estimates of changes in the total sediment volume were calculated for a new area called the Outer Bar. The -42-ft contour was chosen to delineate the Outer Bar because it appears on all of the condition surveys and clearly defines this feature. The volume of sediment between -42 ft and MLLW was calculated by digitizing the contours and multiplying the area by the average depth. Figure 3.6 shows the location of the -42-ft contour in 1972 and 1990, and shows the boundary considered in estimates of sediment volume in the Outer Bar. Note that the Outer Bar area includes substantial portions of the Bar and North Beach areas discussed above. Figure 3.6 indicates a significant landward shift of the -42-ft contour associated with loss of material from the Outer Bar. Sediment volumes for the Outer Bar area are tabulated in Table 3.5, along with the deposition rate. For comparison, the corresponding combined volumes and deposition rates for the North Beach and Bar areas are also listed. The estimates indicate that more than -50 million yd^3 of sediment has been lost from the Outer Bar area between 1973 and 1990. Approximately one-half of this came from the Bar area, and most of this loss occurred between 1987 and 1990 (-12.9 million yd^3; Table 3.2). This recent loss of sediment follows a nearly continuous loss of sediment from the Outer Bar since initial jetty construction, which is documented in Plate 5 of the South Jetty Rehabilitation General Design Memorandum (USACE 1965) and in Plate 2 of the CTH report.

3.7 DREDGING AND DISPOSAL ACTIVITIES

Dredging and disposal records for 1977 through 1991 were provided by USACE. The quantities of material removed by dredging or added by disposal in the study areas are summarized in Table 3.4. Note that several Point Chehalis disposal sites and the South Jetty disposal site are all in the Entrance area defined by this study. No dredging or disposal has occurred in the North Beach or South Beach area. It is uncertain whether any of the dredging in the bar channel occurred within the Bar area but, in any case, the only significant dredging since 1942 in the bar channel occurred in 1990, too late to affect the volumes tabulated in the previous sections. Similarly, there was no significant dredging in the entrance channel until 1990. The volumes of material placed at the Point Chehalis disposal sites range between +1 and +2 million yd^3/yr, with greater exceptions. A total of +25.9 million yd^3 was deposited there between 1977 and 1991, an average of +1.85 million yd^3/yr for the 14-yr period. Similar disposal amounts probably apply for preceding years. The cumulative sediment loss in the Entrance area between 1976 and 1990 was -8.0 million yd^3. The relatively large volume of material placed in the Entrance area indicates that dredged materials may be an important contribution to the sediment budget there, and may help to explain why long-term sediment loss is occurring more slowly at the Entrance than at the Bar or South Beach areas. On the other hand, most of the dredged materials placed at Point Chehalis are fine-grained sediments from upriver dredging, and only the sand fraction (possibly 10%) is expected to remain in the high-energy Entrance region. The contribution of dredged materials to changes in sediment volumes is further discussed in Section 5.0.

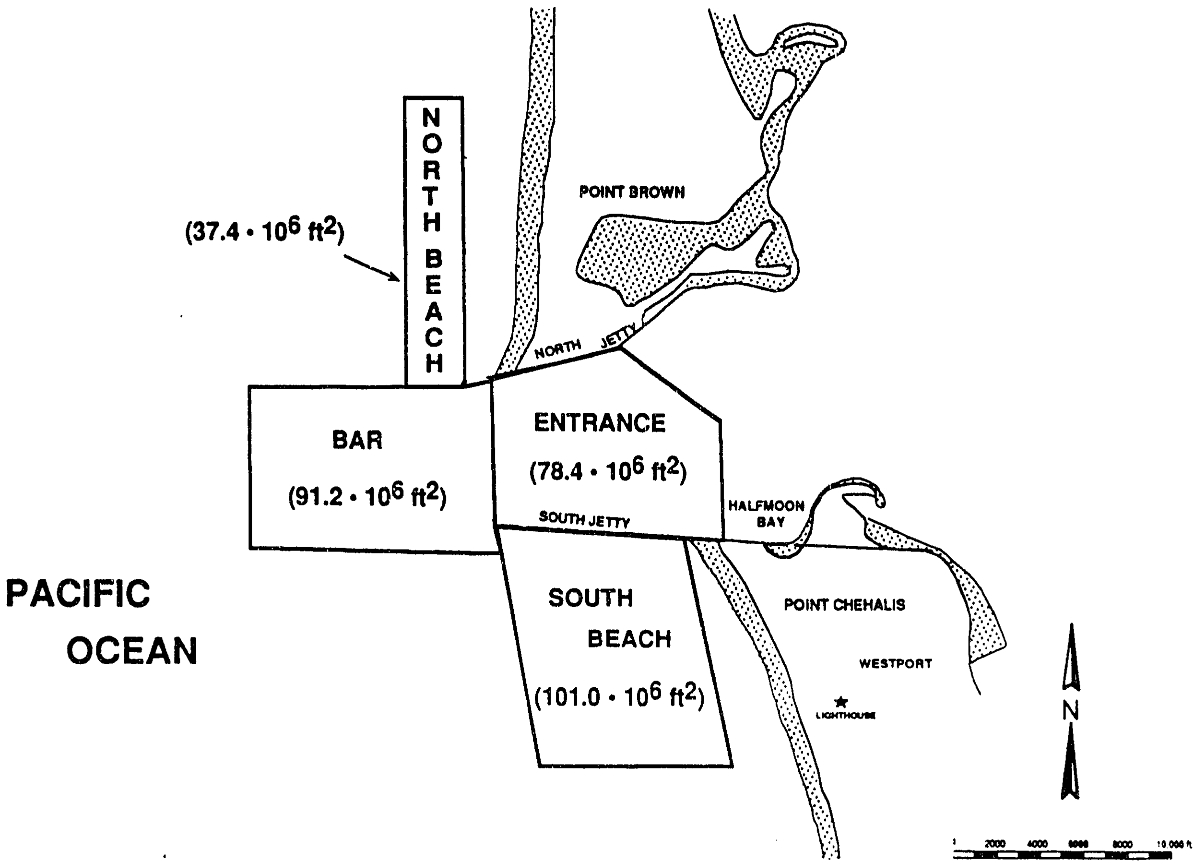


FIGURE 3.1. Areas for Sediment-Volume Calculations. Numbers in parentheses indicate size of each area.

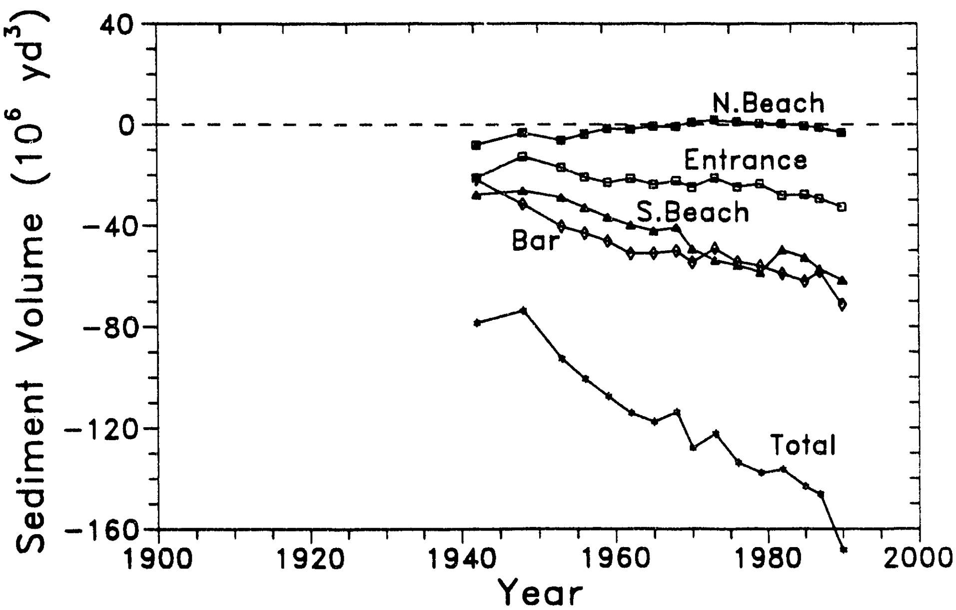


FIGURE 3.2. Sediment-Volume Changes Calculated from Digitized Condition-Survey Charts. Cumulative sediment volume calculated in this study for each of the four study areas, and total for all four, are plotted relative to 1900 values.

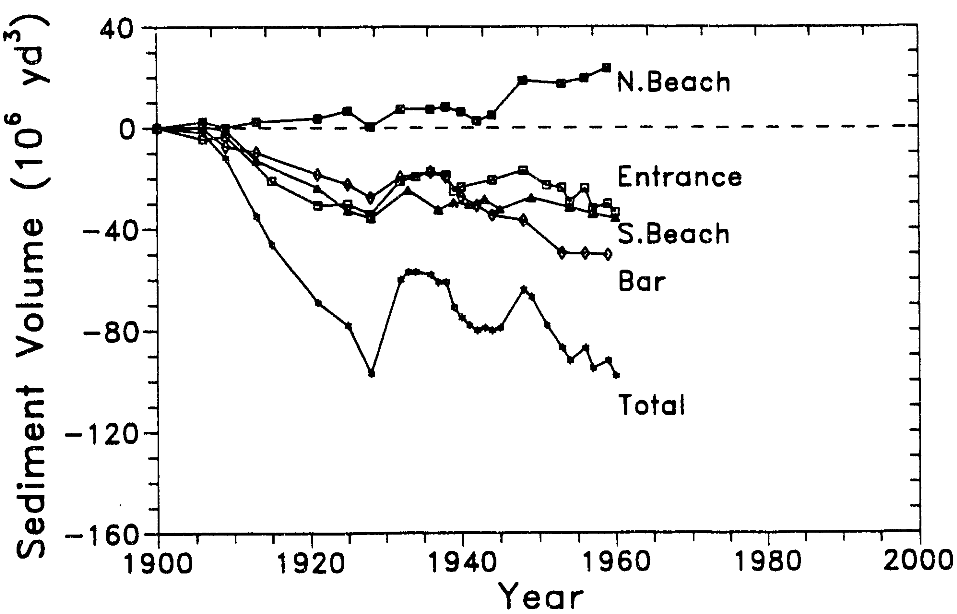


FIGURE 3.3. Sediment-Volume Changes Calculated by Committee on Tidal Hydraulics. These data were taken from Plate 2 of the CTH report.

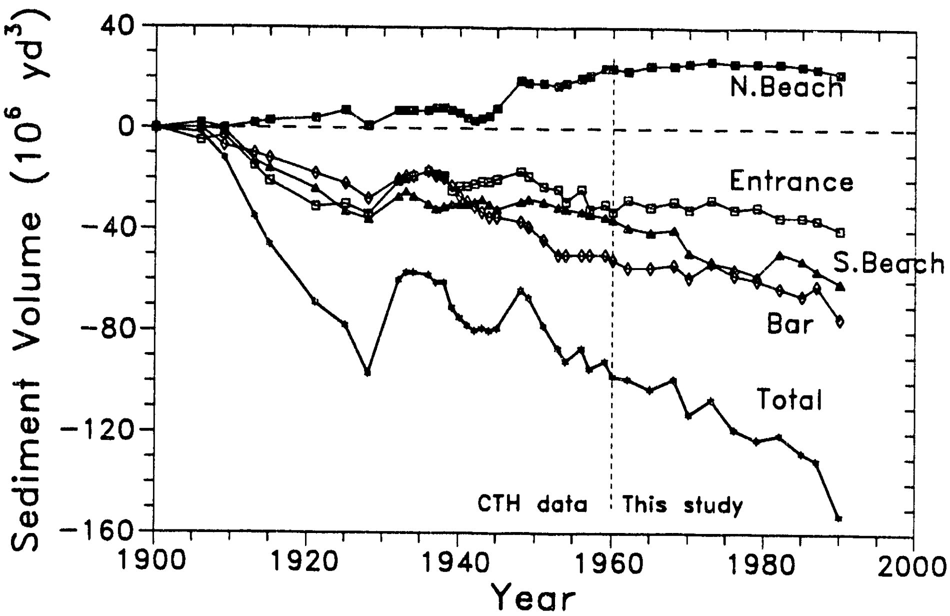


FIGURE 3.4. Sediment-Volume Changes for the Period 1900 Through 1990 from Combined Data of the Committee on Tidal Hydraulics Report and This Study.

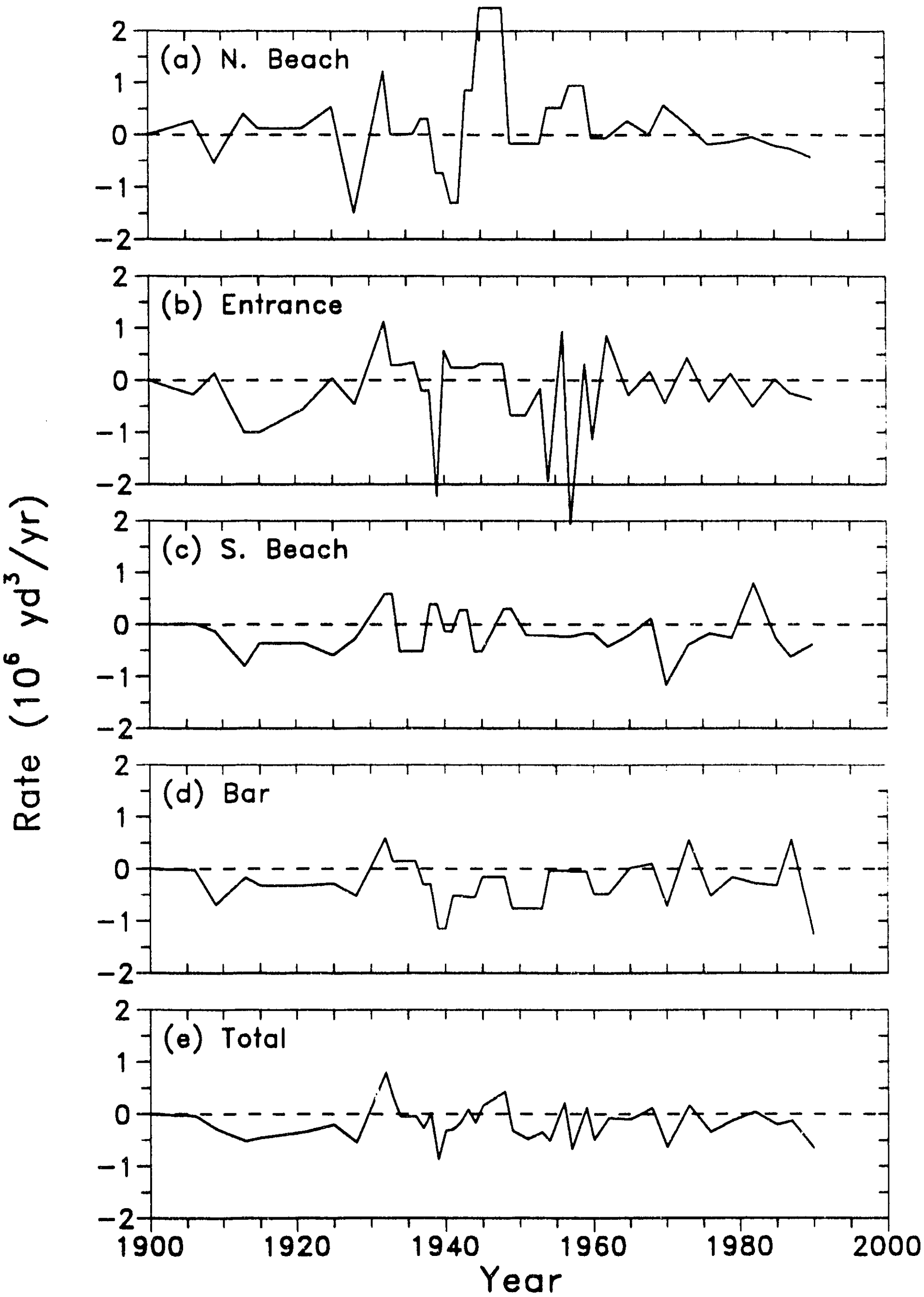


FIGURE 3.5. Rates of Deposition (+) or Erosion (-) for 1900 Through 1990 from Combined Data of the Committee on Tidal Hydraulics Report and This Study.

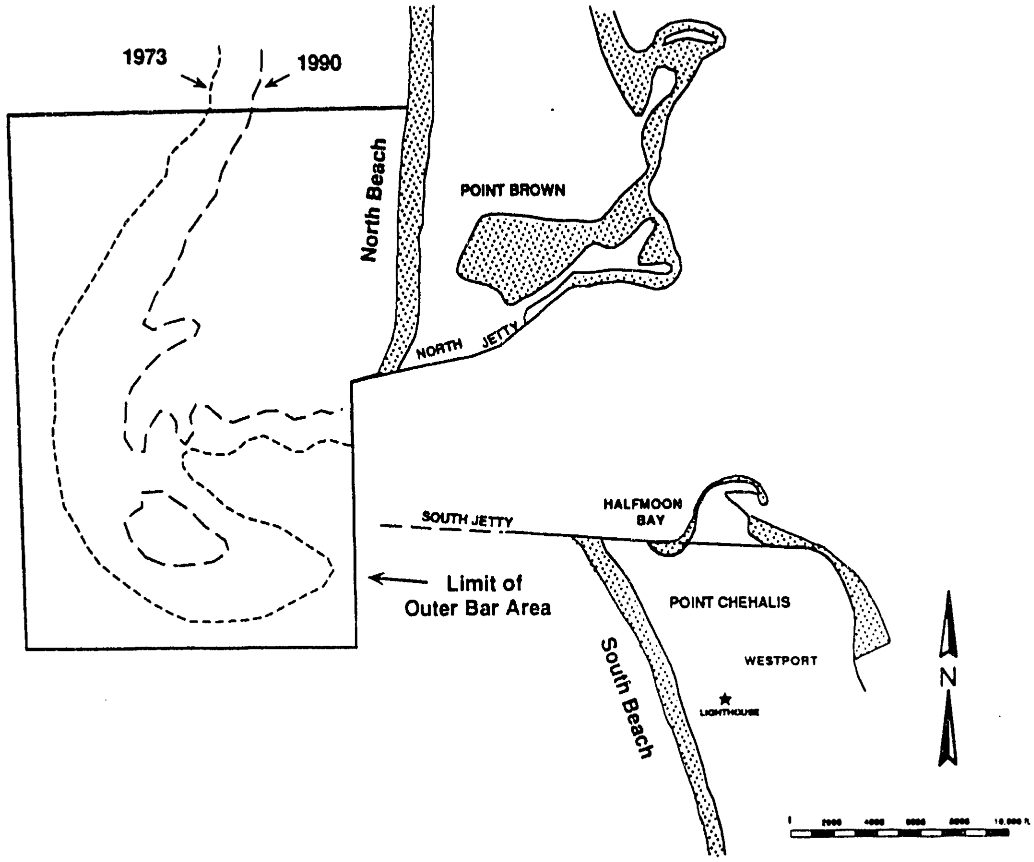


FIGURE 3.6. Erosion of Outer Bar Between 1973 and 1990. Dashed (1973) and long-dashed (1990) lines mark location of -42-ft contour on U.S. Army Corps of Engineers - Seattle District condition-survey charts. Box encloses limits of outer bar area used to calculate sediment-volume changes.

TABLE 3.1. Digitized Water Volumes for Study Areas (10^6 yd^3)

Year	North Beach	South Beach	Bar	Entrance
1900	27.571[a]	78.572	81.134	78.177
1942	35.534	106.318	102.882	99.218
1948	30.896	104.751	112.635	90.857
1953	30.859	107.532	121.533	95.210
1956	31.403	111.542	124.225	99.043
1959	29.183	115.274	127.365	101.218
1962	29.423	118.443	132.261	99.538
1965	28.279	120.709	132.069	101.982
1968	28.255	119.337	131.013	100.475
1970	26.667	127.976	135.822	103.002
1973	25.785	132.380	130.160	99.285
1976	26.537	134.277	135.508	102.829
1979	27.111	137.174	137.139	101.788
1982	27.279	128.231	140.037	106.194
1985	28.135	131.216	143.284	106.012
1987	28.858	135.841	139.453	107.492
1990	30.657	140.116	152.346	110.744

(a) Increase in water volumes indicate loss of sediment.

TABLE 3.2. Deposition (+) and Erosion (-) Estimates Between Indicated Years (10^6 yd^3)

Period (years)	North Beach	South Beach	Bar	Entrance
1900-42	-8.0	-27.7	-21.7	-21.0
1942-48	+4.6	+1.6	-9.8	+8.4
1948-53	-3.0	-2.8	-8.9	-4.4
1953-56	+2.5	-4.0	-2.7	-3.8
1956-59	+2.2	-3.7	-3.1	-2.2
1959-62	-0.2	-3.2	-4.9	+1.7
1962-65	+1.1	-2.3	+0.2	-2.4
1965-68	0.0	+1.4	+1.1	+1.5
1968-70	+1.6	-8.6	-4.8	-2.5
1970-73	+0.9	-4.4	+5.7	+3.7
1973-76	-0.8	-1.9	-5.3	-3.5
1976-79	-0.6	-2.9	-1.6	+1.0
1979-82	-0.2	+8.9	-2.9	-4.4
1982-85	-0.9	-3.0	-3.2	+0.2
1985-87	-0.7	-4.6	+3.8	-1.5
1987-90	-1.8	-4.3	-12.9	-3.3

TABLE 3.3. Comparison of Deposition (+) and Erosion (-) Estimates (10^6 yd^3)

Period	North Beach[a]		South Beach[b]		Bar[c]		Entrance[d]	
(years)	CTH Report	This Study	CTH Report	This Study	CTH Report	This Study	CTH Report	This Study
1900-42	+2.6	-8.0	-28.3	-27.7	-30.9	-21.7	-23.4	-21.0
1942-48	+16.0	+4.6	+2.7	+1.6	-5.8	-9.8	+5.1	+8.4
1948-53	-1.1	-3.0	-5.8	-2.8	-12.9	-8.9	-6.8	-4.4
1953-56	+2.2	+2.5	-2.6	-4.0	-0.3	-2.7	-0.2	-3.8
1956-59	+4.0	+2.2	-1.7	-3.7	-0.4	-3.1	-6.1	-2.2

(a) North Beach corresponds to CTH Report Zone E.
(b) South Beach corresponds to CTH Report Zones A+B+C.
(c) Bar Area corresponds to CTH Report Zone G.
(d) Entrance Area corresponds to CTH Report Zones I+II+III.

TABLE 3.4. Summary of Net Dredging (-) and Disposal (+) Sediment Volumes by Study Area

Year	Bar (10^6 yd^3)	Entrance (10^6 yd^3)	Point Chehalis (10^6 yd^3)	South Jetty (10^6 yd^3)
1977	---[a]	---	+0.71	---
1978	---	---	+1.87	---
1979	---	---	+2.62	---
1980	---	---	+1.43	---
1981	---	---	+1.41	---
1982	---	---	+1.69	---
1983	---	---	+1.45	---
1984	---	---	+1.85	---
1985	---	---	+1.76	---
1986	---	---	+1.99	---
1987	---	---	+1.48	---
1988	-0.03	-0.06	+1.56	+0.09
1989	---	---	+1.23	---
1990	+1.21	+0.40	+4.16	+0.97
1991	+0.45	+0.45	+0.71	+1.11

(a) Missing values are zero.

TABLE 3.5. Deposition (+) and Erosion (-) Estimates for Outer Bar Area and Sum of North Beach and Bar Study Areas

Period (years)	Outer Bar Area (10^6 ft^2)	Outer Bar Volume (10^6 yd^3)	Outer Bar Deposition (ft)	North Beach plus Bar Volume (10^6 yd^3)	North Beach plus Bar Deposition (ft)
1970-73	280.3	+11.3	+1.08	+6.6	+1.38
1973-76	281.4	-10.6	-1.03	-6.1	-1.27
1976-79	265.8	-16.4	-1.67	-2.2	-0.46
1979-82	255.9	+2.4	+0.24	-3.1	-0.65
1982-85	251.9	-7.6	-0.81	-4.1	-0.86
1985-87	248.8	-3.1	-0.32	+3.1	+0.65
1987-90	223.3	-16.2	-1.94	-14.7	-3.08

4.0 PHYSICAL OCEANOGRAPHIC ENVIRONMENT

This section summarizes the prevailing physical oceanographic conditions at the entrance to Grays Harbor and discusses long-term variability.

4.1 WINDS, CURRENTS, AND TIDES

The seasonal winds and coastal currents for the coast of Washington are described in Barnes et al. (1972) and Hickey (1989). A brief summary is provided below.

4.1.1 Winds and Coastal Currents

During winter (November through March), winds on the Washington coast are typically southerly or southwesterly, and frequently strong. Gale- or storm-force winds occur 5% to 8% of the time. Summer winds (May through September) have generally lower speeds, and blow from northerly or northwesterly directions. October and April are usually transition months between winter and summer conditions.

Coastal currents respond fairly rapidly to local winds, and thus tend to follow the prevailing seasonal wind patterns, but there is considerable variability over short-term intervals. Mean surface currents flow northward in the winter and southward in the summer. Typical current speeds measured by various methods indicate average flows of 10 to 20 cm/s to the north during winter. Flow velocities during summer are weaker, averaging about 5 cm/s to the south.

Direct measurements of bottom currents are very limited, but releases of bottom drifters off the mouth of the Columbia River indicate a northward drift over the bottom during the winter. It has also been noted that bottom drifters released on the inner continental shelf in this region (depths less than 100 ft) tend to move onshore. Bottom drifters released in deeper waters (100 to 500 ft) tend to move north.

4.1.2 Tide Height and Tidal Currents

Tides on the Washington coast near Grays Harbor are mixed semidiurnal with two high tides of unequal heights each day. The mean diurnal range between the higher high water and lower low water each day is 9.0 ft at Point Chehalis. The tidal range undergoes a fortnightly (14-day) spring-neap cycle, with a 12.0-ft spring-tide range.

Tidal currents through the entrance to Grays Harbor are stronger near the surface than at the bottom. Typical current speeds during maximum flood and ebb for mean tidal range are listed in Table 4.1. The maximum ebb currents exceed flood currents flows by 20% to 50%. This ratio changes with the seasonal cycle of river discharge; the difference between ebb and flood is greater during periods of high river flow, which typically occur in winter and spring.

Model studies of currents near the entrance to Grays Harbor, performed in a large physical model of the estuary (USACE 1972), indicate that currents flowing along North Beach are directed to the south (toward the North Jetty) during both flood and ebb tidal stages, apparently because of the formation of a clockwise circulating eddy. The eddy forms during ebb tide, centered northwest of the North Jetty terminus. A similar eddy forms off the South Jetty. but this eddy rotates counterclockwise, is less well-defined, and is centered farther offshore, southwest of the South Jetty terminus. During ebb tide, the main axis of the current flows westward out the entrance, directing a jet-like feature against the outer bar and into the offshore coastal waters. The North and South Jetties serve as effective training structures in confining and aligning this ebb current. During flood tide, water flows toward the entrance from all directions (north, south, and west) in a radial pattern, with currents flowing past the tips of the Jetties and over the submerged portions of degraded sections.

4.2 WAVES

Ocean waves are the dominant source of energy for resuspension and transport of sediments along the coast. Wave-orbital motions near the bottom resuspend sediments and make them available for transport by prevailing coastal, tidal, or wave-induced currents. When waves approach the coast at an angle, a longshore drift is established that transports sediments in the nearshore region along the coast, usually away from the direction of wave approach. Longshore-drift patterns can be very complex, because they are strongly affected by local topography, offshore bathymetry, and the interaction of wave phenomenon that arise as the incident waves interact with each other and with the bathymetry and nearshore currents. However, on relatively straight sections of the coast, like the beaches north and south of Grays Harbor, the longshore drift of sediment is strongly controlled by incident wave angles, and the rate of transport depends strongly on wave energy. In this section, wave data are examined to determine whether changes in incident waves correlate with episodes of erosion or deposition at the entrance to Grays Harbor.

4.2.1 Sources of Wave Data and Periods of Coverage

Wave data were obtained from several sources for various periods since 1956. The longest continuous time series of wave information was obtained from the Wave Information Studies (WIS), prepared by the USACE Coastal Engineering Research Center (Jensen et al. 1986). The WIS data are products of numerical wave-model hindcasts performed in three phases. In Phase I, large-area synoptic atmospheric pressure fields are used as input. From these, the model produces 20-yr time histories (1956 through 1976) of surface winds and deepwater wave conditions for grid points along the U.S. coasts. In Phases II and III, the calculated deepwater waves are numerically propagated across the continental shelves to provide 20-yr histories of wave conditions at 10-m depths every 10 nmi along the coast. The WIS data for Station 16 (47°N, 124.18°W) were used here to represent conditions near the entrance to Grays Harbor. The WIS data provide estimates of significant wave height, dominant wave period, and average direction of the dominant waves at 3-h intervals for the 20-yr period. Also reported in the WIS calculations, but not considered in this study, are the significant heights of the swell and sea components, their periods, and the wind speed and direction.

Measurements of waves offshore Grays Harbor and Long Beach, Washington, provided additional information for the period 1982 through 1992. These data were collected as part of the Coastal Data Information Program (CDIP), sponsored by the USACE and California Department of Boating and Waterways, and operated by the Ocean Engineering Research Group of the Marine Research Division at Scripps Institution of Oceanography. The CDIP data have been acquired from accelerometer buoys and pressure-gauge arrays at various west-coast locations for up to 16 yr. The Grays Harbor wave data were measured by an accelerometer buoy, and provide 3-h measurements of significant wave height and dominant wave period (no wave direction information). Data are available from the Grays Harbor buoy intermittently for the period 1982 through 1992, with some long gaps between 1983 and 1985, and many shorter gaps. The Long Beach wave data were acquired by a bottom-mounted pressure-gauge array that provides wave-direction estimates as well as significant wave heights and dominant periods. The Long Beach data set provides coverage for 1984 through 1987, with partial coverage for 1988 and 1991 through 1992.

4.2.2 Wave Heights, Period, and Direction

Time series of WIS hindcast wave data are illustrated in Figures 4.1a, b, and c. Figure 4.1a shows the significant wave height at Station 16 for the entire 20-yr interval (1956 through 1976); Figure 4.1b dominant period, and Figure 4.1c shows the average direction. Significant-wave-height data from the Grays Harbor Buoy and the Long Beach array are shown in Figures 4.2a and 4.2b. As these plots demonstrate, there are only limited wave data available, and only the WIS hindcasts provide time series long enough for comparison with historical changes in deposition and erosion.

4.2.3 Wave Power

Sediments are more easily moved by large waves. Wave power, which is the rate at which wave energy moves in the direction of wave propagation, is a measure of wave size that incorporates both height and period and is particularly relevant to sediment transport (Komar 1976). The rate at which energy is transmitted in the direction of wave propagation, i.e., wave power P, is

$$P = \frac{1}{8}\rho g H^2 C n \qquad (1)$$

where ρ is water density, g is gravitational acceleration, H is wave height, C is celerity (phase speed), and

$$n = \frac{1}{2}\left[1 + \frac{2kh}{\sinh(2kh)}\right] \quad (2)$$

where k is $2\pi/\lambda$ (the wavenumber), in which λ is wavelength, and h is water depth. The term n has a value of ½ in deep water and gradually increases to 1 in shallow water. In deep water, phase speed depends on period T:

$$C = \frac{gT}{2\pi} \quad (3)$$

so Equation (1) can be simplified to

$$P = cH^2T \quad (4)$$

where c is a constant. Thus H^2T is proportional to wave power, and provides, for deep water, a consistent relative measure of the ability of waves to move sediment. Plots of H^2T (hereafter referred to as wave power; the constant c will be ignored) were made for the available data. Longshore drift is sensitive to the angle of wave incidence, and long-term changes in the alongshore component of wave power would directly affect nearshore sediment-transport rates and possibly directions.

Time series of monthly average wave-power at WIS Station 16 are shown in Figure 4.2a, b, and c. In the top panel (Figure 4.2a.), vectors pointing straight up denote waves from due west; vectors tilting to the right indicate a northerly component of wave approach, and vectors tilting to the left indicate a southerly component. Time series of the component of wave power perpendicular to shore is plotted Figure 4.2b., and the alongshore component (positive values indicate northerly wave approach) is plotted in Figure 4.2c. (on an expanded scale). The seasonal variation in magnitude and direction of wave power is apparent in Figure 4.2. Largest waves occur in winter, usually with a significant southerly component. Three of the four months with the most wave energy show a southerly approach; however, northerly wave approaches occur more frequently.

Monthly average wave power at the CDIP instruments is plotted in Figure 4.3. Only months with more than 10 days of data are included on the plots. In the upper panel, data from the Grays Harbor Buoy are shown. No directional information is acquired by this instrument. In the bottom panel, data from the Long Beach pressure-gauge array are shown, and the direction information has been omitted to allow more direct comparison with the Grays Harbor Buoy.

Wave data from WIS and CDIP are also summarized in Figure 4.5, with a time scale suitable for comparison with the sediment-volume data. Strict comparison of wave-model hindcasts with measured wave data is not possible because of the different time intervals, but qualitative observations suggest that the mean monthly values hindcast by the WIS model are higher than observed values. On the other hand, the hindcast values do not contain the high maximum values observed with the CDIP instruments. Because the WIS model uses large-scale atmospheric pressure fields, it produces smooth results, whereas the measurements display greater range and variability in wave conditions.

Not shown in the wave data are large-wave events that occurred in November 1988 and January and March 1990, and probably caused much of the recent erosion at South Beach. Significant wave heights at the Grays Harbor Buoy peaked above 8 m on these occasions.

4.3 LONG-TERM OCEAN CLIMATE

Long-term changes in climate are likely to affect physical processes on the Washington coast. The best-documented examples include decade-scale variations in sea-surface temperature and river flow. To the extent that winds and storm tracks are affected by these climate variations, wave energy will also vary. To search for correlations among long-term climate changes and erosion at Grays Harbor, several climatic indices were investigated.

4.3.1 Pacific Northwest Index

Ebbesmeyer et al. (1989) developed the Pacific Northwest (PNW) Index, which is an annual index based on sea-surface temperatures (SST) on the Washington coast and in Puget Sound, and snow-pack depths in the Cascades. The PNW Index calculated by Ebbesmeyer et al. (1989) for 1915 to 1988, and the 5-yr running average of this series, are shown in Figure 4.6a. The PNW Index correlates well with atmospheric and oceanographic parameters, including sea-level atmospheric pressure over the north Pacific and circulation in Puget Sound. In particular, a significant correlation was found among the frequency of occurrence of higher wind speeds and southerly winds and negative values of the PNW Index. This implies a correlation between negative values of the PNW index and higher frequency of occurrence of winter storms. Thus the PNW Index was chosen as a candidate indicator, potentially important to wave-driven sediment transport along the Washington coast.

4.3.2 Central North Pacific Index

Another climate index is the Central North Pacific (CNP) Index, calculated by Cayan and Peterson (1989), and found to correlate well with river flow around the northeast Pacific. The CNP Index is an average of the sea-level atmospheric pressure anomalies at two locations, one south of the Aleutian Islands and the other in the western Gulf of Alaska. Positive values tend to correspond to stormier years. The smoothed CNP Index is plotted in Figure 4.6b. It is well correlated with the PNW Index when the sign of one of the indices is reversed. Some correlation among the CNP Index and the WIS wave data is evident. Specifically, the low wave-power winters of 1964-1965 and 1968-1969 correspond to minima in the CNP Index, or maxima in the PNW Index. Longer time series of actual wave data would be needed to confirm a correlation among either index and wave regime.

4.3.3 El Niño

El Niño is an oceanographic phenomenon defined by the appearance of unusually warm surface water off the coast of Peru. The warm water indicates decreased upwelling, and is symptomatic of an episodic shift in atmospheric pressure across the equatorial Pacific called the Southern Oscillation. Large-scale changes in the weather around the Pacific are associated with the occurrence of El Niño and the Southern Oscillation, and recent studies indicate that, during strong El Niño years, measurable changes in the weather and ocean occur in the Pacific Northwest. Phipps (1990) summarizes the significant El Niños since 1900 and discusses the potential significance for the Washington coastal environment. The list of El Niños, categorized as strong or medium in intensity by Komar 1986 (cited in Phipps 1990), are listed in Table 4.2.

Anomolously higher sea levels, warmer sea-surface temperatures, and stronger northward currents across the Oregon and Washington shelves have been observed during El Niño years (Huyer and Smith 1985). No clear association with El Niño and wave energy has been established, but the strong El Niño of 1982-1983 appeared to have a significant effect on the Oregon and Washington coasts (Komar 1986). Coastal sea levels were elevated over the usual winter levels by approximately 1 ft. Winter storms, waves, and storm surges were also more severe than normal during this period, resulting in significantly more coastal erosion than normally occurs. Seymour (1983) reports that January, February, and March 1983 was a particularly stormy period, during which extraordinary waves were measured at the CDIP gauges and buoys in California. Phipps (1990) notes that, during that winter, about two-thirds of the foredune was eroded along a section of beach in the southern Grayland coastal area (15 mi south of Grays Harbor).

4.3.4 Long-Term Sea-Level Changes

Long-term trends of average sea level around the U.S. coast indicate an average rate of rise of about 0.06 in./yr since 1940 (Hicks 1978). However, tectonic uplift along the Washington coast is believed to exceed this amount, resulting in a slow sea-level fall of about 0.02 to 0.004 in./yr (Ando and Balazas 1979; Chelton and Davis 1982; Lyles et al. 1988). These estimated rates are small and unlikely to have a measurable effect on sedimentation near the entrance to Grays Harbor, even on an historical time scale.

4.3.5 Sediment Supply

The rate at which sediment is supplied to the study area is likely to have a significant effect on rates of erosion or deposition. Sources of sediment include the rivers draining into Grays Harbor, erosion of the coastline within Grays Harbor, and longshore transport along the Washington coast beaches. Although studies indicate that logging practices have increased the sediment supplied by local rivers (Kehoe 1982), most of this is fine-grained material unlikely to accumulate near the entrance. No measurements of shoreline erosion within Grays Harbor have been reported, but shoreline erosion is unlikely to provide large quantities of sediment. The largest term in the sediment budget at the Entrance to Grays Harbor is likely to be the rate of alongshore transport from adjacent coastal regions.

Much of the sediment found on beaches, in nearshore regions, and on the continental shelf of Washington has, as its origin, the Columbia River system (Nittrouer 1978). There has been speculation as to whether decreases in Columbia River sediment discharge have occurred as a result of dam construction, and whether that decrease has affected the sediment budget of Washington beaches (e.g., Phipps 1990). Sherwood et al. (1990) reviewed the sediment budget of the river and concluded that the dams have probably reduced the sand supply to the estuary by 30%. More important, changes near the entrance to the Columbia River occurred that are similar to those described here for Grays Harbor. Large volumes of sediments moved soon after initial construction of the jetties, injecting a pulse of sediment into the longshore system. More recently, sediment has been slowly removed from the outer bar and, as the system approached equilibrium, changes are occurring more slowly. A reasonable hypothesis is that sediment supply from the Columbia River entrance region has decreased, and that decrease in supply has affected the Grays Harbor entrance sediment budget, but data that could confirm that hypothesis are not available.

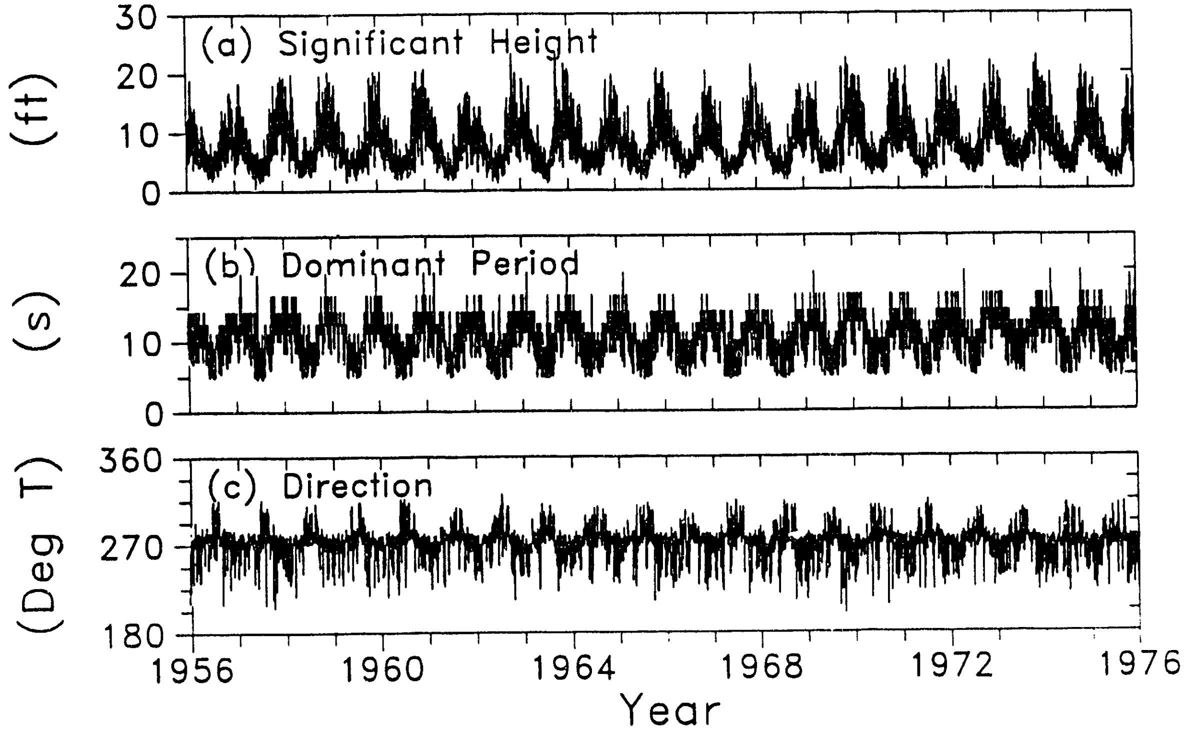


FIGURE 4.1. Time Series of Wave Information Studies Wave Model Hindcasts for Station 16 at 3-h Intervals from 1956 to 1976. (a) Significant wave height, (b) dominant wave period, (c) average wave direction.

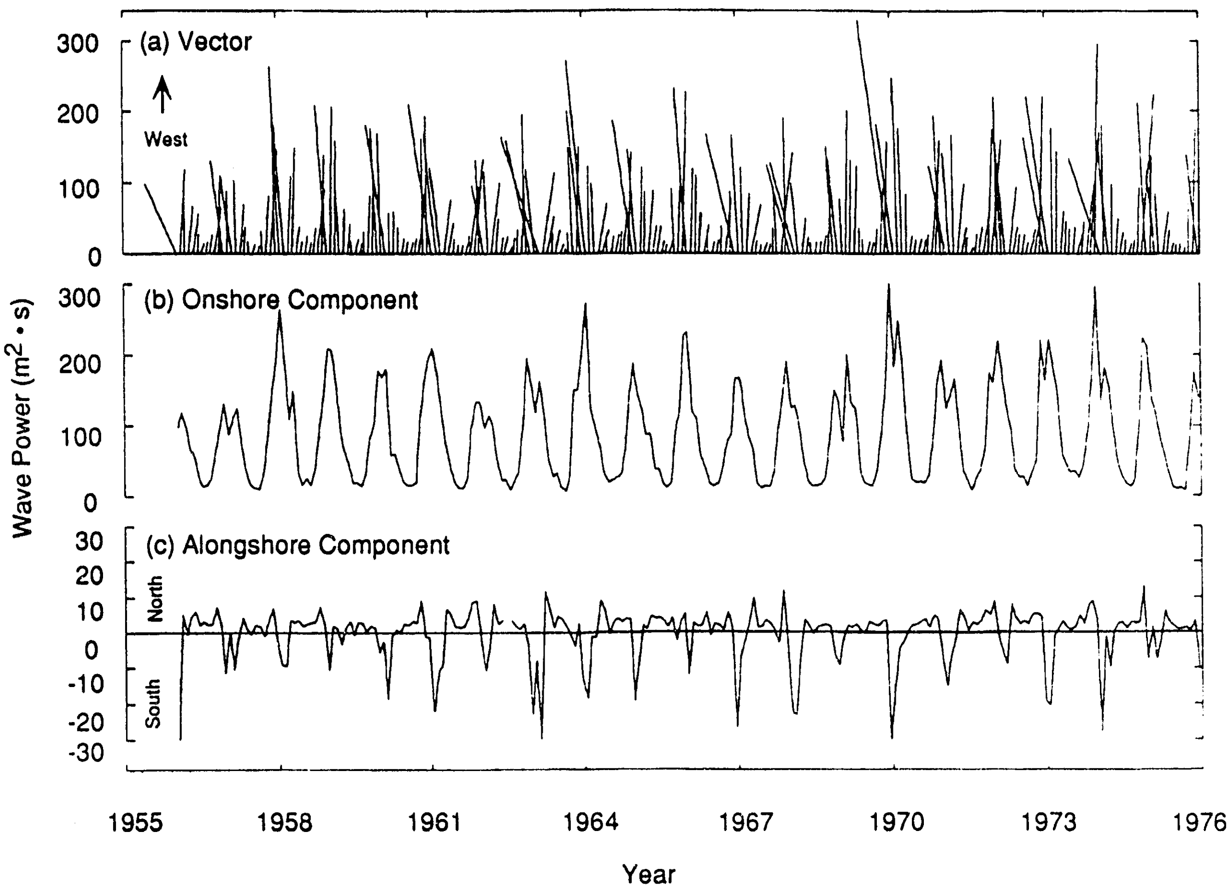


FIGURE 4.2. Time Series of Monthly Average Wave Power Calculated from Wave Information Studies Hindcast of Station 16 from 1955 to 1975. (a) Vector Plot of wave power, (b) onshore component of wave power, (c) alongshore component of wave power.

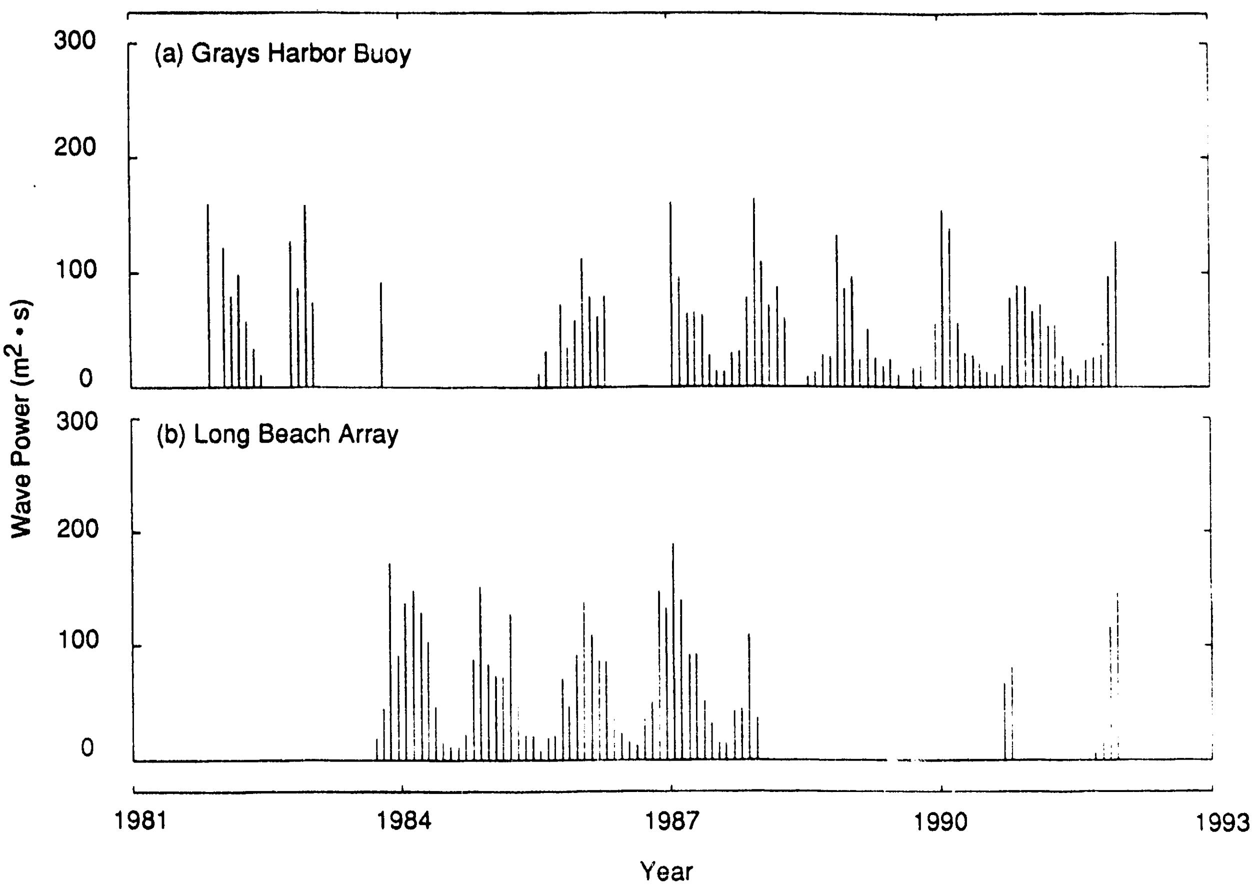
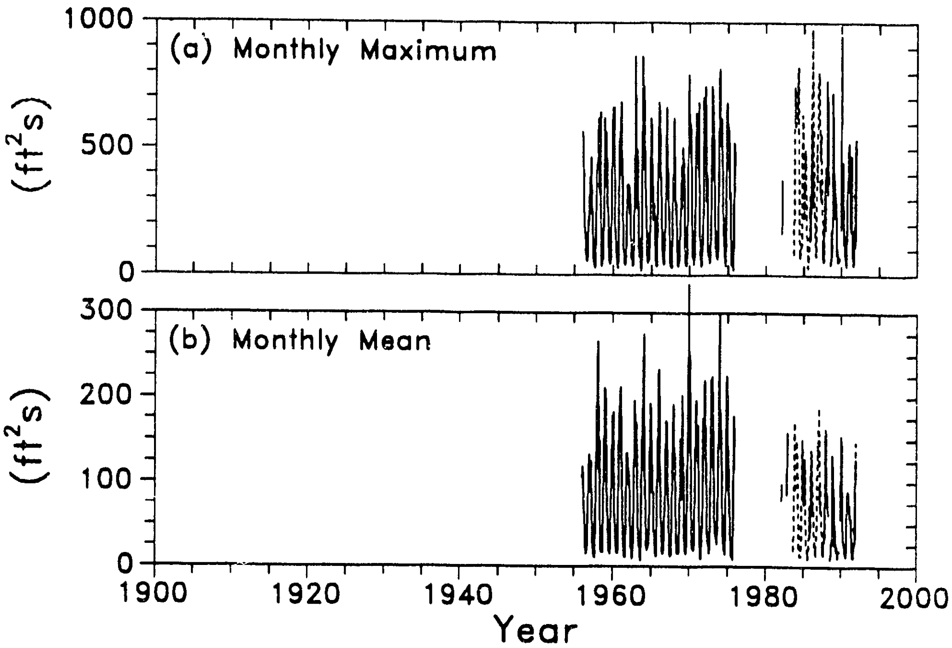
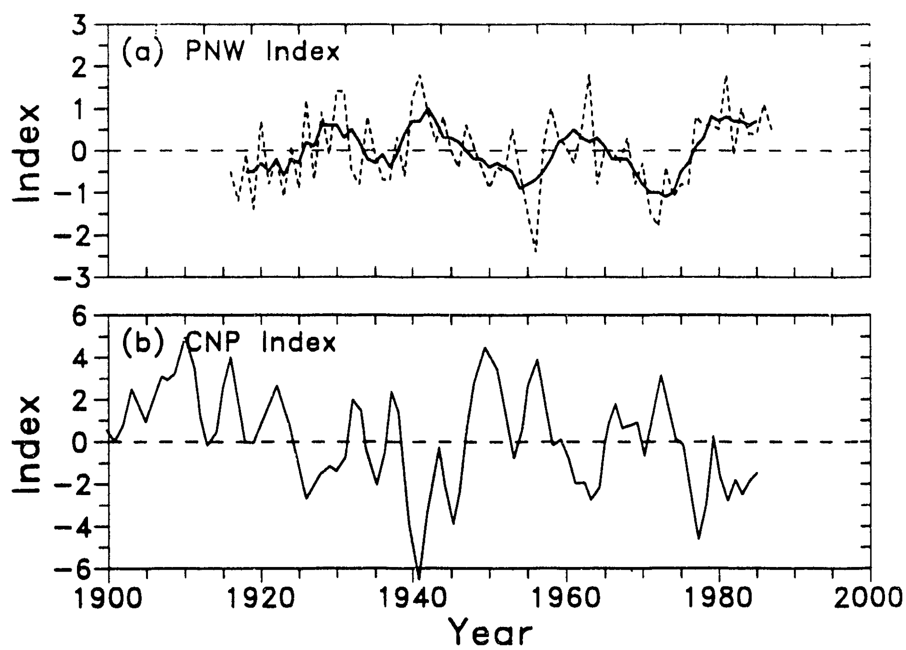


FIGURE 4.3. Time Series of Monthly Average Wave Power Calculated from Coastal Data Information Program Data. (a) Grays Harbor buoy, (b) Long Beach array.



<u>FIGURE 4.4</u>. Time Series of (a) Maximum Monthly Wave Power and (b) Monthly Average Wave Power for Wave Information Studies and Coastal Data Information Program Data. Dashed line represents Long Beach array data.



<u>FIGURE 4.5</u>. Time Series of Climate Indices. (a) Pacific Northwest Index of Ebbesmeyer et al. (1989). Dashed line is unsmoothed, solid line is smoothed with 5-yr running average, (b) central North Pacific Index smoothed with 3-yr weighted average filter, from Figure 10,

TABLE 4.1. Current Speeds in the Entrance to Grays Harbor[a]

Tide	Surface	Bottom
Flood	3.0 ft/s (0.91 m/s)	2.5 ft/a (0.76 m/s)
Ebb	4.5 ft/s (1.40 m/s)	3.0 ft/s (0.91 m/s)

(a) From CTH (1967)

TABLE 4.2. El Niño Episodes[a]

Period	Category
1902	Medium
1905	Medium
1911-12	Strong
1914	Medium
1918-19	Strong
1925-26	Strong
1929-30	Medium
1939	Medium
1941	Strong
1953	Medium
1957-58	Strong
1965	Medium
1972-73	Strong
1976	Medium
1982-83	Strong
1987	Medium

(a) From Komar (1986)

5.0 CONCLUSION

Data gathered in this study show that the recent (last 6 yr) rate of shoreline retreat on the seaward side of South Beach (between -47 and -62 ft/yr) exceeds the long-term average rate of retreat, which has been about -3 ft/yr since 1949 (Table 2.3). The shoreward side of South Beach has also retreated at rates as high as -18 ft/yr (Table 2.2), much higher than the average rate of -13 ft/yr since 1949. Erosion of Half Moon Bay is clearly associated with removal of the inner portion of South Jetty. The combined attacks on South Beach have left it less than 350 ft wide at its narrowest section (Figure 1.2).

Because beaches are dynamic features, short-term changes in shoreline position are normal. Analysis of the nearshore area off South Beach, however, demonstrates that there has been a consistent, long-term loss of sediment (Table 3.2, Figures 3.4 and 3.5) amounting to -60 million yd^3. The long-term loss of this sediment from the region off South Beach reduces the likelihood that the observed shoreline retreat is a short-term phenomenon that may soon reverse. The CTH (1967) argues that accretion tends to occur at South Beach following construction or rehabilitation of the South Jetty. As Figure 5.1 shows, the accretion episodes do not exactly correspond to construction periods and, in any case, they are short-lived, compared to the long-term trends. It seems likely that erosion of the South Beach will continue.

Sediment loss also occurred in most of the other offshore study areas. A combined loss of about -150 million yd^3 since 1900 was measured for the four offshore study areas. Only North Beach has accumulated sediment, but the trend in the area off North Beach has been flat or erosional since 1975. The morphology changes associated with the measured sediment losses are dominated by erosion of the outer bar, a remnant of the ebb-tidal delta. The outer bar was initially forced seaward as the entrance channel deepened, but has since eroded even more, resulting in a landward migration of the bar crest (Figure 3.6).

The underlying cause(s) for long-term loss of sediment from the Grays Harbor system cannot be established with certainty from this study. Figure 5.1 summarizes the available evidence. While wave energy has varied and is correlated with long-term fluctuations in the regional climate of the North Pacific, no direct link between storm activity and long-term trends in deposition or erosion was found in this study. Long-term variations in wave direction do not appear in the WIS hindcasts (Figure 4.2c.). The storms of 1983 were associated with a large El Niño episode, but the storms of early 1990 that caused significant erosion on the Washington coast preceded the present El Niño episode of 1991-1992. The construction of the jetties caused major changes to the natural system, including initial accretion of North and South Beaches, the deepening of the entrance channel. Changes in the outer bar are also the result of jetty construction. Long-term loss of sediment from the entrance region and outer bar are therefore related to jetty construction. The system is apparently still equilibrating 80 yr after construction of the South Jetty.

The erosional trends observed at the entrance to Grays Harbor may also be coupled to a large-scale littoral sediment budget for the entire Washington coast. Although the data from this study cannot address such large-scale, long-term events, one hypothesis is that fluctuations and long-term trends in the supply of sediment from the Columbia River system travel northward as pulse-like phenomena. It will be very difficult to prove this hypothesis, because the intermittent nature of storm erosion and fair-weather deposition complicate the time-varying sediment supplies from the longshore system, and these two sources of variation combine with man-made shifts in the system to completely hide systematic changes in the sediment supply. Interestingly, Phipps (1990) shows that the beaches north of Grays Harbor have accreted rapidly since 1978, growing more than 500 ft in places. New beaches have grown out from seacliffs in areas north of Copalis Rocks, and it is plausible that some of this sand has come from the Grays Harbor region.

The important results of this study are that the alarming erosion rates at South Beach are part of a much more significant, long-term loss of sediment for the system as a whole. The erosion is not clearly related to any long-term changes in sea level or wave energy. Although the long-term erosion may be related to long-term changes in sediment supply, it is most likely part of the slow adjustment to construction of the entrance jetties.

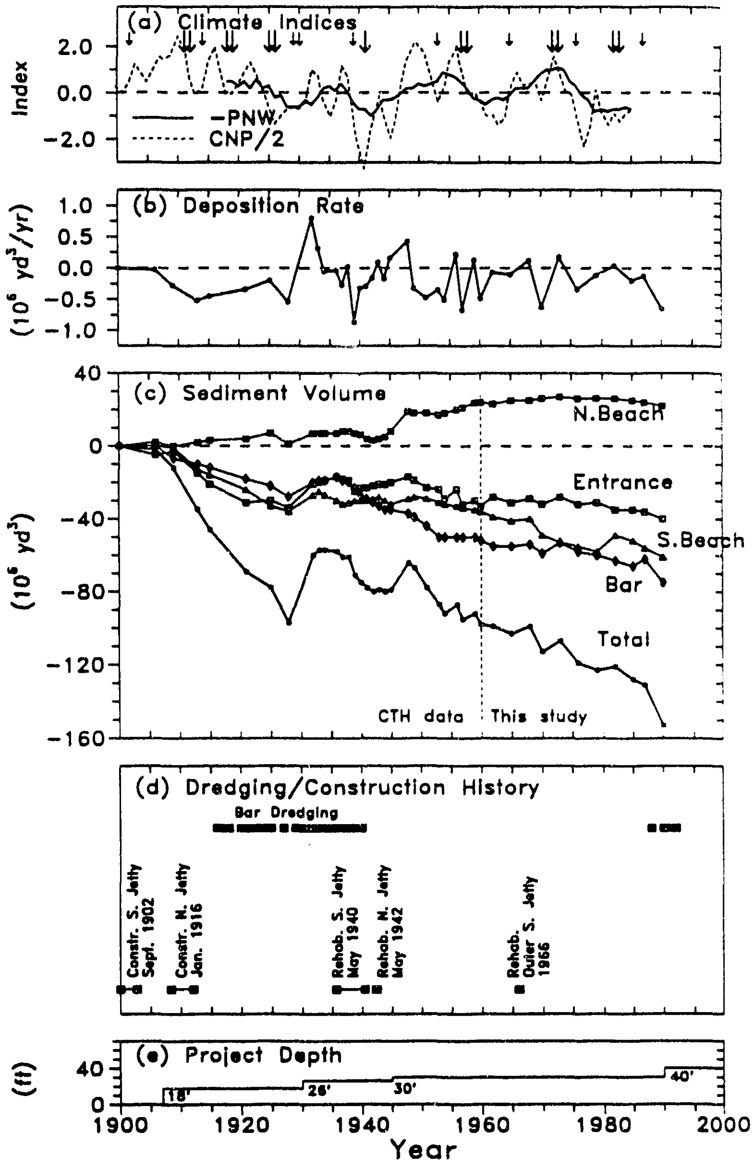


FIGURE 5.1. Summary of Climate Indices, Deposition and Erosion, and Dredging and Construction at the Entrance to Grays Harbor. (a) Climate indices: solid line is negative PNW Index of Figure 4.5a.; dashed line is 1/2 CNP Index of Figure 4.5b.; arrows indicate medium and large El Niño episodes (Table 4.1.); (b) deposition rate for 4 areas at entrance, from Figure 3.5e; (c) sediment volumes from Figure 3.4.; (d) summary of dredging and construction history; (e) authorized project depth.

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