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# South Jetty Sediment Processes Study, Grays Harbor Washington: Evaluation of Engineering Structures and Maintenance Measures

Philip D. Osborne, Ty V. Wamsley, and Hiram T. Arden

With assistance by
(in alphabetical order)

Zeki Demirbilek, Nicholas C. Kraus, Robert M. Parry, William C. Seabergh, Vladimir Shepsis, and David P. Simpson

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Philip D. Osborne

*Pacific International Engineering
123 Second Avenue, South
Edmonds, WA 98020*

Ty V. Wamsley

*Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199*

Hiram T. Arden

*U.S. Army Engineer District, Seattle
P.O. Box 3755
Seattle, WA 98124-3755*

With assistance by

Zeki Demirbilek, Nicholas C. Kraus,
Robert M. Parry, William C. Seabergh,
Vladimir Shepsis, and David P. Simpson

Final report

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Prepared for U.S. Army Engineer District, Seattle
P.O. Box 3755
Seattle, WA 98124-3755

ABSTRACT: Grays Harbor is located on the southwest Washington coast at the mouth of the Chehalis River, about 45 miles north of the Columbia River mouth. The harbor is 13 miles wide at its broadest point and 15 miles long from Aberdeen, WA, on the east to the entrance o the west. Two convergent rock jetties, a north jetty and a south jetty, are part of the Grays Harbor navigation project, which is a federally constructed and maintained navigation channel. Development of the channels and facilities at Grays Harbor has been a continuing process since the Rivers and Harbors Act of June 1896 authorized the construction of the south jetty. Maintenance dredging has been required after the 1990 Grays Harbor navigation improvement project was completed.

The U.S. Army Engineer District, Seattle requested a study to evaluate the engineering features and maintenance measures in the vicinity of the south jetty. The south jetty sediment processes study was developed and keyed to elements of a plan of action. The purpose of the study is to evaluate the performance of engineering and maintenance measures that have been implemented to control breaching next to the south jetty, and to reduce shoreline erosion in Half Moon Bay and placement of dredged material to alleviate erosion. Another study in a series on the south jetty is in progress to document the analysis of a breached condition and assess the risk of future breaching.

This report documents the history of the south jetty and related engineering structures, and reviews previous studies relevant to the acting coastal processes. It includes reviews of dredging and disposal activities associated with maintenance and new work dredging, analysis of the wave diffraction mound performance, analysis of upland and intertidal topography and nearshore bathymetry surveys, analysis of shoreline position change, identification of sediment pathways, and a sediment budget. The performance of the engineering and maintenance measures is then evaluated based on these results. The role of continued periodic nourishment activities is also assessed.

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# Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| acres | 4,046.873 | square meters |
| cubic yards | 0.7645549 | cubic meters |
| feet | 0.3048 | meters |
| inches | 2.54 | centimeters |
| miles (U.S. statute) | 1.609347 | kilometers |
| pounds | $4.5359 \times 10^2$ | grams |
| tons | $1.016 \times 10^3$ | kilograms |
| square miles | 2,589,998 | square meters |

# Preface

This report describes an evaluation of the performance of engineering measures that have been implemented to control breaching of the south jetty and shoreline erosion in Half Moon Bay at Grays Harbor, WA. The study was conducted by the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), for the U.S. Army Engineer District, Seattle. Mr. Hiram T. Arden, Navigation Section, Operations Division, was the Seattle District point of contact for the study, with technical assistance and review of this report by Messrs. Arden; George A. Hart, Environmental Resources Section; and Robert M. Parry, Chief, Navigation Section.

The ERDC study team was under the technical direction of Dr. Nicholas C. Kraus, Senior Scientists Group, CHL, and task-area leaders were Mr. Ty V. Wamsley, Coastal Processes Branch, CHL, for review of engineering history and previous scientific studies; Mr. William C. Seabergh, Harbors and Entrances Branch, CHL, for physical modeling; Dr. Zeki Demirbilek, Harbors and Entrances Branch, for wave numerical modeling; Dr. Philip D. Osborne, Pacific International (PI) Engineering^PLLC^, for field data collection, morphological change, and sediment budget analysis; and Dr. Vladimir Shepsis, PI Engineering, for dredging and disposal analysis. Mr. Harry Hosey and Dr. Osborne were the study leaders for PI Engineering.

Technical assistance at PI Engineering in conducting the study was provided by Messrs. David Katzev and David P. Simpson, in support of morphologic change analysis; Messrs. David B. Hericks and Scott B. Hicks, in support of field data collection and data processing; and Mr. Charles Haynes for the aerial photograph analysis. The Washington State Department of Ecology and U.S. Geological Survey provided assistance with nearshore bathymetric surveying in Half Moon Bay and South Beach. Mr. Terry Larson, captain of the vessel *Tricia Rae*, provided support for the field data collection. Ms. Tiina Elken-Muld, PI Engineering, provided support in preparation of selected figures and graphics, and Ms. J. Holley Messing, Coastal Engineering Branch, CHL, formatted this report. Work at CHL was performed under the general administrative supervision of Mr. Thomas W. Richardson, Director, and Dr. William D. Martin, Deputy Director, respectively, CHL. Mr. Arden and Dr. Kraus provided technical review of this report.

COL John W. Morris III, EN, was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

# 1 Introduction

## Background

Grays Harbor is located on the southwest Washington coast at the mouth of the Chehalis River, about 45 miles[1] north of the Columbia River mouth. The harbor is 13 miles wide at its broadest point and 15 miles long from Aberdeen, WA, to the entrance. The water surface area is 91 square miles at mean higher high water (mhhw) and 38 square miles at mean lower low water (mllw). The estuary is enclosed on the ocean side by spits, Point Brown on the north and Point Chehalis on the south. The spits are separated by a 2-mile-wide opening, which forms the natural harbor entrance. Two convergent rock jetties, north jetty and south jetty, extend seaward from the spit points. The jetties are part of the Grays Harbor navigation project, which is a federally constructed and maintained navigation channel that allows deep-draft shipping through the outer bar, Grays Harbor estuary, and the Chehalis River to Cosmopolis (Figure 1).

The development of the channels and facilities at Grays Harbor has been a continuing process since the Rivers and Harbors Act of June 1896 authorized the construction of the south jetty. Maintenance dredging has been required after the 1990 Grays Harbor navigation improvement project was completed. Erosion on South Beach and Half Moon Bay prompted the disposal of a portion of this dredged material in these areas. In December 1993, persistent shoreline erosion near the south jetty culminated in the formation of a breach between the jetty and the adjacent South Beach. The U.S. Army Engineer District, Seattle, filled the breach in 1994 with 600,000 cu yd of sand dredged from the navigation channel as a temporary measure to protect the Grays Harbor navigation project and alleviate local concerns. During the seventh winter that the fill was in place (2001-2002), a series of storms damaged the South Beach and modified the Half Moon Bay shoreline, re-emphasizing the temporary nature of the sand fill. From November 1998 to March 1999, the Point Chehalis revetment extension and fill was constructed. In 1999, construction began on a wave diffraction mound, and about one-third of a recommended design for a transition gravel beach with cobble material was placed on a subsequent fill of the breach. This greatly reduced scope of a transition gravel beach with cobble was required to alleviate

[1] This study involves analysis of historic and recent engineering documents with values expressed in American customary (non-SI) units. To maintain continuity with the previous body of work, the original units are retained in their context. Measurements and calculations made as part of the present study are expressed in SI units. A table of factors for converting non-SI units of measurement to SI units is presented on page ix.

concerns about the environmental resources and access impacts of placing gravel on a sandy beach.

## Purpose of Study

A project technical meeting was held 15 January 2002 to develop this study. The U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL) coordinated with the Seattle District to develop a plan of action to evaluate the engineering features and maintenance measures in the vicinity of the south jetty. The south jetty sediment processes study was developed and keyed to elements of the plan of action. The purpose of the study is to evaluate the performance of engineering and maintenance measures that have been implemented to control breaching of the south jetty, and to reduce shoreline erosion in Half Moon Bay and placement of dredged materials to alleviate erosion. During the course of study, critical issues in the scope of work were identified and addressed in the present report.

Relevant engineering and maintenance measures in the area include the maintenance dredging and disposal program for the Grays Harbor and Chehalis River navigation project, the Point Chehalis revetment fill, the South Beach breach fill with gravel transition beach, and the south jetty wave diffraction mound. Each of these measures was designed to prolong the life of the breach fill and provide beach erosion protection. The purpose of the maintenance dredging is for continued deep draft navigation with a managed dredged materials disposal program that reduces the rate of beach erosion by periodically reintroducing sediment into the littoral system. The Point Chehalis revetment extension project is subject to the Point Chehalis Revetment Extension Project, Interagency Mitigation Agreement with a plan dated 7 October 1998. The agreement provides for periodic renourishment of the Half Moon Bay shoreline. The gravel with cobble transition beach was designed to slow erosion of the beach directly adjacent to the south side of the jetty and to eliminate the dangerous 8-ft-high scarp at that location. In 2000, a wave diffraction mound was constructed to terminate the inner end of the jetty and maximize wave refraction-diffraction, thereby reducing wave-induced erosion of the shore in the western portion of Half Moon Bay.

This report documents the history of the south jetty and related engineering structures, and reviews previous studies relevant to coastal processes. It includes a review of dredging and disposal activities associated with maintenance and new work dredging, analysis of the wave diffraction mound performance, analysis of upland and intertidal topography and nearshore bathymetry surveys, analysis of shoreline position change, identification of sediment pathways, and a sediment budget. The performance of the engineering and maintenance measures is then evaluated based on these results. The role of continued periodic nourishment activities is also assessed.

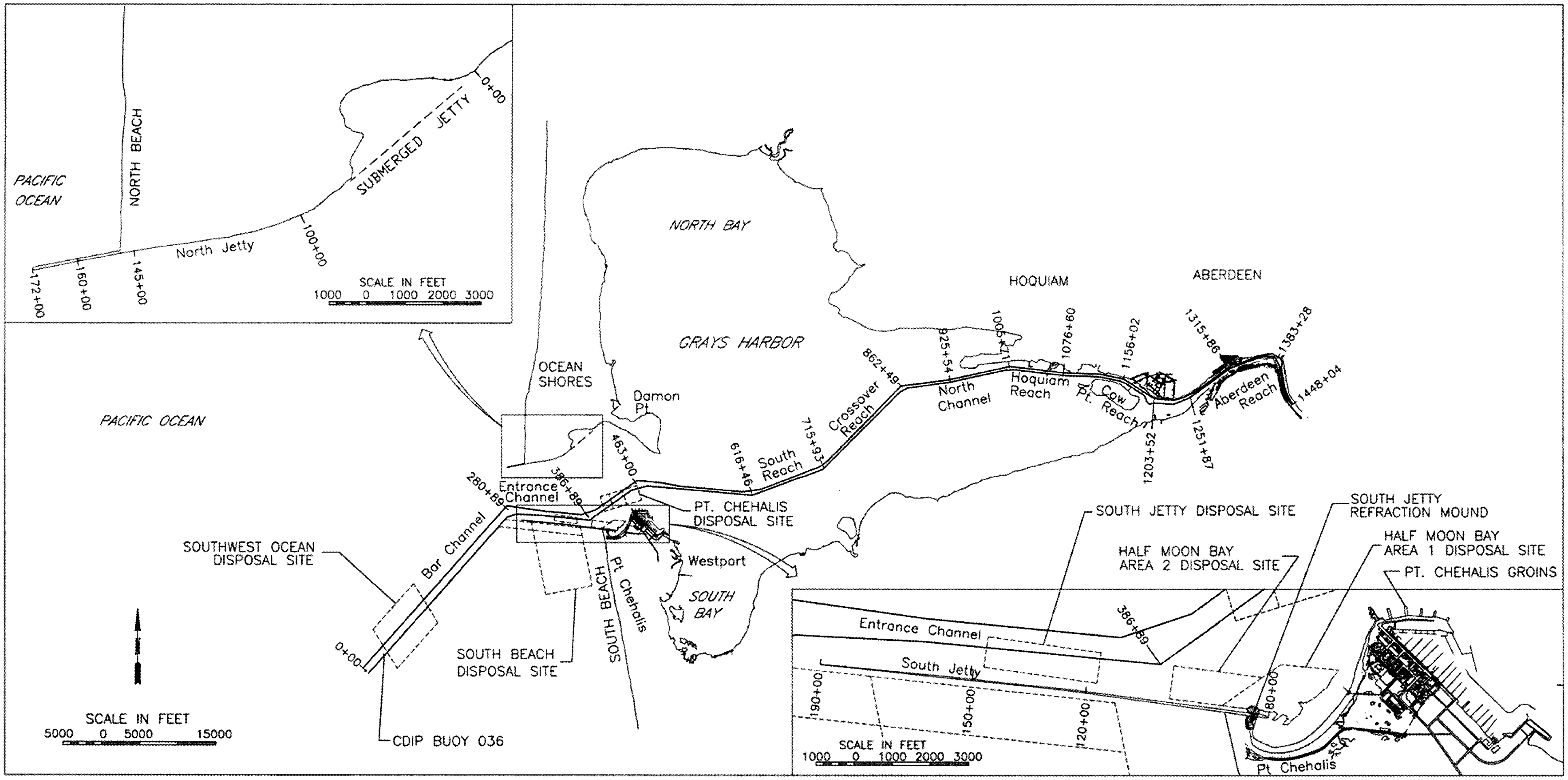


Figure 1. Grays Harbor navigation project

# 2 History of South Jetty and Related Engineering Structures

This chapter documents the history and reviews previous studies of the south jetty and related structures. The development of the channels and facilities at Grays Harbor has been a continuing process since the Rivers and Harbors Act of June 1896 authorized construction of the south jetty. In the past 50 years, considerable study effort has been expended to understand coastal processes at this site, including field measurements, physical model tests, and numerical model simulations. Table 1 chronologically lists the major engineering studies conducted on the south jetty, adjacent shorelines, and the navigation project. In addition to the reports listed in Table 1, other research by the U.S. Army Corps of Engineers (USACE), USACE contractors, and other consultants and agencies was included in the present review.

**Table 1**
**Major Studies of South Jetty and Related Structures**

| Date | Report |
|---|---|
| 1955 | U.S. Army Engineer Waterways Experiment Station (WES), "Plans for Improvement of Grays Harbor and Point Chehalis, Washington: Hydraulic Model Investigation" |
| 1965 | USAED, Seattle, General Design Memorandum "South Jetty Rehabilitation" |
| 1967 | U.S. Army Corps of Engineers, Committee on Tidal Hydraulics (CTH), "Report on Grays Harbor, Washington" |
| 1972 | WES, "Report 4, South Jetty Study" |
| 1992 | Battelle/Marine Sciences Laboratory, "Historical Bathymetric Changes Near the Entrance to Grays Harbor, Washington" |
| 1994 | Hartman Associates, Inc., "Technical Analyses of the Shoreline Breach at the South Jetty, Grays Harbor, Washington"* |
| 1995 | Special Subcommittee of the Committee on Tidal Hydraulics and Coastal Engineering Research Board, "Review of Long-Term Maintenance Plans for the South Jetty, Grays Harbor, Washington" |
| 1997 | USAED, Seattle, Evaluation Report, "Long-Term Maintenance of the South Jetty at Grays Harbor, Washington" |
| 1998 | Pacific International Engineering (PI Engineering), "Grays Harbor Navigation Project South Beach Stabilization Analysis"* |
| 1999 | USAED, Seattle, "Design Analysis (Revised) Grays Harbor, Washington, FY 1999 South Jetty Repair"* |

* NOTE: Although in draft form and/or not published, these reports have contributed to the development of engineering activities at the south jetty and are part of the history.

## Engineering History of South Jetty

The earliest mapping of Grays Harbor (1852) shows a relatively narrow channel between Point Chehalis and Point Brown with Eld Island just south of Point Brown. Maps from 1862 through 1891 show that Eld Island eroded completely and Point Brown receded in a northeasterly direction about 4,300 ft. During the same time period, Point Chehalis accreted about 4,300 ft in a northwesterly direction (Phipps and Smith 1978). The entrance migration indicated a predominant direction of littoral drift from south to north. The engineering history at Grays Harbor commenced with the construction of the south jetty to prevent shoaling of the navigation bar channel. Major events in the history of the harbor entrance are summarized in Table 2. Channel depths are referenced to mllw.

South jetty construction began in 1898 and was completed in 1902 to a height of +8 ft mllw and a total length of 13,734 ft, of which 11,950 ft extended seaward of the high water line at that time. The construction of a second jetty north of the harbor entrance began in 1907. The north jetty was completed in 1913 to a length of 17,000 ft and a height of +8 ft mllw. Storm damage during and after construction lowered the top elevation to +3 ft mllw. By 1916, it was reconstructed and the crest elevation was again +8 ft mllw. Once the north jetty was reconstructed, the existing channel adjacent to the south jetty shoaled and a new wider and deeper channel developed north of the older channel.

Westhaven Cove formed naturally at Point Chehalis after construction of the south jetty, and the Port of Grays Harbor constructed a harbor there in 1929. From 1904 to 1933, the south jetty subsided to elevations varying from +6 ft mllw at the shore end to –10 ft mllw at the seaward end. The outer 12,656 ft of south jetty was reconstructed to elevation +20 ft mllw between 1935 and 1939. The first shoreline trace of Half Moon Bay appeared after 1940, following the completion of the south jetty rehabilitation. The north jetty also deteriorated between 1916 and 1940 and was reconstructed to +20 ft mllw during 1941 and 1942.

Surveys show that Point Chehalis continued to build to the north, west, and east until reconstruction of the jetty in 1935. The material to build and nourish Point Chehalis apparently came from the south and passed over or through the south jetty prior to reconstruction (e.g., Figure A-1, Appendix A). The reconstructed jetty prevented the passage of material over and through the jetty, cutting off the longshore supply of sediment. The result was continued erosion of Point Chehalis until protective work concepts were created in the 1950s by the U.S. Army Engineer Waterways Experiment Station (USAEWES 1955). Considerable deterioration of the south jetty continued after its completion in 1937. By 1953, surveys showed that nearly 6,000 ft of the jetty had subsided nearly down to mllw.

In August 1950, a model study by researchers at WES, currently ERDC, was initiated with the primary purpose of developing a comprehensive plan for the protection of Point Chehalis, Westhaven Harbor, and the south jetty from wave and tidal current action. The model was constructed as a fixed-bed facility with a horizontal scale of 1 to 800 and a vertical scale of 1 to 80. The model test results

**Table 2**
**Engineering History at Grays Harbor Entrance (Adapted from USAED, Seattle 1997)**

| Period | Event |
|---|---|
| 1898-1902 | Initial construction of south jetty. Constructed to 13,734 ft with initial appropriation. Top el +8 ft mllw. Authorized to 18,154 ft. |
| 1907-1916 | Initial construction of north jetty, 17,204 ft, top el +8 ft mllw. |
| 1935-1939 | South jetty reconstruction, sta 80+00 to 210+00, top el +20 ft mllw. |
| 1935-1940 | North jetty reconstruction, outer 7,000 ft, top el +20 ft mllw. |
| 1942 | Maintenance dredging of bar and entrance channels no longer required due to scouring effect of jetty system. |
| 1950-1956 | Construction of Point Chehalis shore protection (revetment and groins). |
| 1966 | South jetty reconstruction, sta 110+00 to 150+00, top el +20 ft mllw. |
| 1970-1973 | Extensive groin replacement and revetment repair along Point Chehalis, including timber pile closure of entrance between breakwaters A and B at Westport Marina. |
| 1975 | North jetty reconstruction, outer 6,000 ft, to top el +20 ft mllw. |
| 1990 | Construction of outer harbor navigation channel improvements including deepening of bar and outer entrance channel to 46 ft, widening of bar channel to 1,000 ft, and entrance to 600 ft. |
| 1991 | Re-institute maintenance dredging of bar and entrance channels. |
| 1992-1996 | Nearshore placement of maintenance dredged material by the Seattle District in Half Moon Bay (1992,1994, 1996) and off South Beach south of south jetty (1993,1994), to reduce offshore erosion. |
| Fall 1993 | Rehabilitate southern portion (800 ft) of the Point Chehalis revetment. |
| Dec. 1993 | Breach occurs between south jetty and adjacent shore. |
| Fall 1994 | Placement of 600,000 cu yd of dredged material to close south jetty beach. |
| 1995 | Placement of 82,000 cu yd of sand by city of Westport to protect sewer outfall line, and placement of 300,000 cu yd of dredged material by Corps to nourish Half Moon Bay shoreline (Section 111 project). |
| Feb. 1997 | Placement of 5,000 cu yd of sand by the Seattle District to raise low area of Half Moon Bay shoreline berm adjacent to western terminus of the Point Chehalis revetment. |
| Nov. 1998 – Mar. 1999 | Point Chehalis revetment extended 1,900 ft. |
| Dec. 1999 – Feb. 2000 | South jetty rehabilitation with modifications. Wave diffraction mound constructed at landward end of south jetty, including placement of 17,358 tons of 12-in. minus transition gravel and cobble materials. |
| 2000-2003 | North jetty rehabilitation. |
| 2001-2002 | South jetty rehabilitation, including a modification for rehandling of 135,000 cu yd of sandy dredged material from Seattle District's existing Half Moon Bay direct beach nourishment disposal site (upland stockpile) to eroding breach fill over approximately 8 acres. Fill was constructed in form of a dune with top el of +36 ft. Modification includes placement of 24,146 tons of additional 12-in. minus rock to extend transition gravel and cobble berm protection. |
| May 2002 | Contract hopper barge placed 102,672 cu yd of sand in nearshore Half Moon Bay and Government hopper dredge Yaquina placed 275,769 cu yd of sand in nearshore of Half Moon Bay. |
| June 2002 | Contract hopper with pumpoff booster restores upland revetment stockpile with 136,706 cu yd from South Reach |

indicated that the removal of the outer 6,000 ft of the south jetty above mllw (which was rapidly being accomplished by nature) would reduce current velocities in the southern portion of the entrance channel and benefit Point Chehalis. The researchers concluded that "the erosion rate along the northern and western shores of Point Chehalis will undoubtedly be reduced when deterioration of the south jetty has progressed eastward a sufficient distance to permit material to pass over the jetty and replenish erosion losses along those beaches; however, local protection must be provided for the northern and western shores of Point Chehalis while this additional destruction is taking place" (USAEWES 1955). Four groins were under construction at Point Chehalis prior to the initiation of the model study. The study recommended that three additional groins also be constructed, which was done in 1951 and 1952. The groins were constructed with rock from the inner 1,000 ft of the south jetty. In 1952, unrelated to the model study, the westernmost groin was intentionally breached to permit the passage of sand to the west. Between 1953 and 1956 a 2,880-ft-long rock revetment was constructed along the north and west shores.

By 1962, the outer 7,000 ft of the south jetty had an average top elevation of -1.5 ft mllw. The north jetty had also deteriorated to an average elevation of less than +14 ft mllw over a distance of 6,500 ft with minimum elevations less than +3 ft mllw. In 1966, 4,000 ft of the south jetty was rehabilitated to +20 ft mllw. The outer 6,000 ft was left in its degraded condition (USAED, Seattle, 1965). The channel was self-maintaining at its location directly adjacent to the south jetty. However, swift currents at ebb tide in the entrance channel had eroded the foundation materials near the jetty toe to depths up to 65 ft mllw. Also, because of the close proximity of the channel to the jetty, large vessels and small sport-fishing craft experienced navigation problems. In 1967, the Seattle District Engineer requested the U.S. Army Corps of Engineers, Committee on Tidal Hydraulics (CTH) make recommendations as to additional investigations that should be undertaken at Grays Harbor to correct these and other problems. The CTH recommended the construction of a second physical hydraulic model (USACE, CTH, 1967).

The second Grays Harbor model was constructed at WES in 1968. The model reproduced 230 square miles of the prototype from the Chehalis River at South Montesano to beyond the 60-ft depth contour in the Pacific Ocean. Seven south jetty plans were subjected to model testing. The study concluded that rehabilitation or reduction in length of the of the jetty as it existed in 1967 would result in a potential for increased scour adjacent to the south jetty. The high portion of the south jetty in 1967 was deemed to be located at or near the optimum position, and no further maintenance was done (Brogdon 1972).

The ocean beach just south of the south jetty receded at an average rate of 15 to 20 ft/year between 1967 and 1986. In 1986, the rate of shoreline recession increased to about 60 ft/year. Erosion was occurring not only on the beach, but also on the landward side of the spit at Half Moon Bay, and concerns emerged over the possibility of a breach. In May 1992, a submerged berm was constructed in Half Moon Bay to evaluate the use of dredged material to mitigate the erosion. Approximately 200,000 cu yd of sediment was placed in the form of a submerged berm just inshore of the -18-ft mllw contour. Plans to place material at South Beach were opposed by local crabbers, and 435,000 cu yd of maintenance material dredged from the Bar Channel was placed in deep water at the southwest disposal site.[1]

About the time the Half Moon Bay berm was constructed, the Seattle District requested that Battelle/Marine Sciences Laboratory review historical data to determine trends in erosion and accretion that occurred since the construction of the jetties. The report (Burch and Sherwood 1992) found that South Beach erosion was part of a much more significant, long-term loss of sediment from the entire inlet system. The report concluded, "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" (Burch and Sherwood 1992). In the fall of 1993, 373,000 cu yd were placed at South Beach along the –40-ft mllw contour.[1]

Two months later, during a storm on 10 December 1993, a breach formed between the jetty and the adjacent South Beach. The storm lasted from 8 December until 15 December. The maximum significant offshore wave height was 25 ft, and the period was 13 sec. The direction of the offshore waves varied from south-southwest to west. In terms of peak significant wave height, the storm had a 2-year return period. The breach widened rapidly, exposing the landward end of the jetty and eroding portions of the adjacent Westhaven State Park. Much of the material that was washed out of the breach was deposited in Half Moon Bay.

The city of Westport contracted consultants Hartman Associates, Inc., to prepare a technical analysis of the barrier breach. The purpose of the analysis was to identify the consequences created by the breach for the deep-draft navigation project and for the city infrastructure. The Hartman report concluded that the breach would aggravate the beach erosion and jetty deterioration processes, adversely impacting the Grays Harbor navigation project. The report recommended immediate filling of the breach.[2]

The Seattle District made a request to the CTH and the USACE Coastal Engineering Research Board (CERB) to review the Hartman report and assist in the planning and design of protection measures. A special subcommittee of CTH and CERB (Special Subcommittee) members was formed to respond to the request. The subcommittee concluded that erosion would continue and concurred with the Hartman report that without intervention, the breach would be a threat to the jetty and the entrance channel (Special Subcommittee 1995). The breach was filled in the fall of 1994 with 600,000 cu yd of sand dredged from the bar channel. The breach was filled to temporarily protect the navigation project while plans for long-term management were developed.

In May 1994, the Seattle District placed an additional 146,000 cu yd of dredged sand in the Half Moon Bay berm at approximately –20 ft mllw. In January 1995, the city of Westport placed 82,000 cu yd of sand along the eroded

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[1] Nelson, E. (1996). "Effectiveness of the Halfmoon Bay and South Beach nearshore berms," Memorandum For Record, U.S. Army Engineer District, Seattle, Seattle, WA.

[2] Hartman Associates, Inc. (1994). "Technical analyses of the shoreline breach at south jetty Grays Harbor, Washington," Report submitted to Department of Public Works, City of Westport Washington. Hartman Associates, Inc., Seattle, WA.

area of Half Moon Bay to further protect their sewer line and to prevent additional damage. Nearly all of this material was eroded by the end of the 1995 winter storm season. In the fall of 1995, under the authority of Section 111 of the River and Harbor Act of 1968, the Seattle District placed 300,000 cu yd of dredged material directly along the Point Chehalis beach. The 300,000 cu yd quickly eroded causing termination of the Section III project by February 1996. Observations of nearshore placement confirms that seasonal placement in May results in onshore transport compared to the erosion offshore that occurred in the fall of 1995.

In 1997, the Seattle District completed a comprehensive study to determine the most appropriate long-term solution and presented the results in an evaluation report. The results and plan developed from this study were similar to that of the Special Subcommittee (1995). The study concluded that extending the south jetty to meet the existing Point Chehalis revetment, combined with beach nourishment was a long-term solution to the erosion attributable to wave interaction with the south jetty (USAED, Seattle, 1997). Implementing the solution was to be accomplished in phases. The Point Chehalis revetment extension and fill was constructed as the first phase from November 1998 to March 1999.

The city of Westport contracted PI Engineering to analyze the shore erosion problem and identify possible engineering solutions. In a draft report dated November 1998, PI Engineering proposed a design that included a wave diffraction mound added to the inshore end of the south jetty, sand tightening of a section of the south jetty, construction of a buried revetment extending through the former breach area from the flank of the south jetty, and a beach fill placed along the first 1,000 ft of beach south of the jetty.[1]

The Seattle District designed the jetty repair and breach fill protection, which incorporated elements of the PI Engineering design. The innovative soft solution design included a wave diffraction mound at the east end of the jetty, a gravel transition beach in Half Moon Bay adjacent to the wave diffraction mound, and armor and filter rock added to the jetty where it abuts the existing breach fill.[2]

In November 1998, the Seattle District requested ERDC to conduct physical model tests of the proposed modifications to the south jetty and Half Moon Bay. The model tests were conducted in the idealized inlet physical model operated by the Coastal Inlets Research Program (CIRP) (Seabergh 1999b). Various plans were tested including the existing condition, and the Seattle District modified design with a wave diffraction mound. Test results indicated that the modified Seattle District design with the wave diffraction mound was the most effective for protecting the breach fill directly adjacent to the jetty. The diffraction mound was constructed from December 1999 to February 2000.

In 1999, PI Engineering was contracted by Evans-Hamilton, Inc. and ERDC to analyze aerial photographs to determine the permeability of the south jetty. The objective of the study was to determine under what conditions, if any, the

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[1] Pacific International Engineering PLLC. (1998). "Grays Harbor Navigation Project South Beach stabilization analyses," Draft report submitted to the city of Westport, Pacific International Engineering PLLC, Edmonds, WA.

[2] U.S. Army Engineer District, Seattle. (1999). "Design analysis (revised) Grays Harbor, Washington FY 1999 south jetty repair," U.S. Army Engineer District, Seattle, Seattle, WA.

south jetty was permeable to longshore sediment transport. The study concluded that the jetty was not permeable to transmission of a significant amount of sand from the south to the north side of the jetty[1]. In 2001, the emergent portion of the south jetty was rehabilitated.

During the seventh winter that the original south jetty breach fill was in place (2001-2002), an unusually severe series of storms damaged South Beach, modified the Half Moon Bay shoreline, and resulted in losses of sand fill from both the breach fill and revetment fill areas. In May 2002, approximately 135,000 cu yd of sandy dredged material was excavated from the existing upland stockpile disposal site and placed over approximately 8 acres in the breach-fill area. The fill was placed to a maximum elevation of +36 ft and minimally graded to approximate the form of a natural dune. The fill was planted with Native American dune grass sprigs in November 2002 to reduce wind erosion of the dune.

## Shoreline Change

The construction of the south jetty has induced changes to the shorelines at Point Chehalis. Persistent erosion of South Beach and Half Moon Bay has threatened the Federal navigation channel and south jetty, as well as the adjacent public facilities. In this section, historical shoreline change at both South Beach and Half Moon Bay that has occurred since the construction of the south jetty is analyzed. The changes in the bathymetry offshore of South Beach and Half Moon Bay are also reviewed.

### South Beach

Between 1862 and 1891, Point Chehalis prograded about 4,300 ft in a northwesterly direction. In 1898, construction began on the south jetty and was completed in 1902. The jetty was a barrier to the northerly longshore drift, and by 1904 the shoreline adjacent to the jetty advanced 3,000 ft to the west. The jetty deteriorated from 1904 to 1933 and the shoreline receded about 2,700 ft by 1939. The jetty was rehabilitated between 1933 and 1939, and by 1946 the shoreline advanced 1,100 ft from its 1939 position. Continued jetty deterioration led to shoreline recession after 1959, but following the jetty rehabilitation in 1965 the beach regained what was previously lost, where it stabilized until the early 1970s (USAED, Seattle, 1965).

Results of a vegetation-line analysis performed by Burch and Sherwood (1992) indicate that, although there were episodes of both erosion and accretion, South Beach advanced between 1949 and 1967 at the relatively low (for this area) rate of 7 ft/year. Since 1967, South Beach has been recessional at rates ranging from 2 to 62 ft/year. Recession rates increased during the mid- to late-1980s, with vegetation line retreat rates ranging from 26 to 62 ft/year (Burch and Sherwood 1992).

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[1] Pacific International Engineering $^{PLLC}$. (1999). "Analysis and interpretation of aerial photographs to determine permeability of south jetty," Technical Memorandum draft, Edmonds, WA.

USAED, Seattle (1997) documented shoreline position and rates of change for the period 1973 to 1996 by determining the location of the beach scarp on aerial surveillance photographs taken in 1973, 1986, and 1990, and on detailed surveys made in 1992, 1993, 1994, and 1996. The recession rates vary widely in time and space, but it is clear that within at least 5,000 ft of the south jetty, the beach underwent a sustained period of erosion. USAED, Seattle (1997) estimated an average recession rate that varied from a low of 4 ft/year between 1973 and 1986, to a high of 54 ft/year between 1990 and 1992. These results are similar to that found by Burch and Sherwood (1992). For the period 1990 to 1996, USAED, Seattle (1997) computed an average recession rate of 36 ft/year.

As part of the southwest Washington coastal erosion study, the Washington Department of Ecology (WDOE) collected data from 1997-2000, including cross-shore beach profiles, three-dimensional (3-D) topographic surface maps, and nearshore bathymetry along the entire Columbia River littoral cell. Data collected near the south jetty at Grays Harbor showed that from August 1997 to August 1998 the 2-m contour of South Beach advanced approximately 30 m. Ruggiero and Voigt (2000) suggest "this advance was most likely due to the El Niño of the previous winter and the associated high rates of northerly sediment transport." Shoreline recession returned the following year as the 2-m contour receded 20 m from August 1998 to August 1999.

Volume losses in the nearshore region off South Beach are occurring as well. Burch and Sherwood (1992) analyzed bathymetric charts to compute sediment volume changes in the nearshore off of South Beach through 1990, updating the earlier estimates of the erosion and deposition through 1960 that were provided in USACE, CTH (1967). The areas analyzed within the entrance are identified in Figure 2. The deposition and erosion estimates made from the Burch and Sherwood (1992) volumetric analysis are listed in Table 3. The long-term trend is clearly erosional for the entrance as a whole. The nearshore region off North Beach is the only study area that did not experience extensive erosion from 1900 to 1990. The pattern of erosion at the nearshore area off South Beach was rapid during the first third of the 90-year period, remained unchanged for the second third, and eroded slowly during the last 30 years. Following jetty construction, approximately 36 million cu yd was lost from the area off South Beach until 1928. Between 1928 and 1943, net accretion occurred and then the area remained relatively unchanged until about 1949. Beginning in 1949, the area off South Beach has eroded almost continuously. The net loss from 1900 to 1990 was about 61 million cu yd (Burch and Sherwood 1992).

The South Beach shoreline change data exhibit a long-term erosional trend over the last 30 years. Bathymetric analysis shows that there has been a consistent, long-term loss of sediment from the nearshore since the early 1900s. As Burch and Sherwood (1992) conclude, "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." Shoreline recession at South Beach is part of a more significant long-term loss of sediment from the system as a whole (Burch and Sherwood 1992). Nearshore changes off of South Beach for the period 1993 to 2001 are examined by Byrnes, Baker, and Kraus (2003).

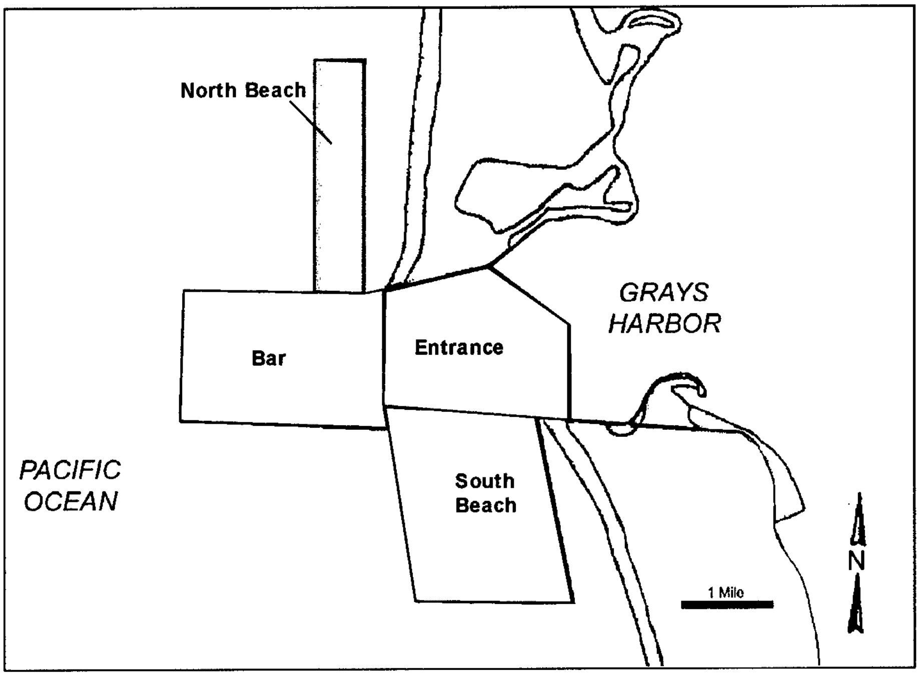



Figure 2. Areas for sediment volume calculations

**Table 3**
**Deposition (+) and Erosion (-) Estimates in $10^6$ cu yd Between Indicated Years (from Burch and Sherwood 1992)**

| Years | North Beach | South Beach | Bar | Entrance | Total |
|---|---|---|---|---|---|
| 1900-1942 | -8.0 | -27.7 | -21.7 | -21.0 | -78.4 |
| 1942-1948 | +4.6 | +1.6 | -9.8 | +8.4 | +4.8 |
| 1948-1953 | -3.0 | -2.8 | -8.9 | -4.4 | -19.1 |
| 1953-1956 | +2.5 | -4.0 | -2.7 | -3.8 | -8.0 |
| 1956-1959 | +2.2 | -3.7 | -3.1 | -2.2 | -6.8 |
| 1959-1962 | -0.2 | -3.2 | -4.9 | +1.7 | -6.6 |
| 1962-1965 | +1.1 | -2.3 | +0.2 | -2.4 | -3.4 |
| 1965-1968 | 0.0 | +1.4 | +1.1 | +1.5 | +4.0 |
| 1968-1970 | +1.6 | -8.6 | -4.8 | -2.5 | -14.3 |
| 1970-1973 | +0.9 | -4.4 | +5.7 | +3.7 | +5.9 |
| 1973-1976 | -0.8 | -1.9 | -5.3 | -3.5 | -11.5 |
| 1976-1979 | -0.6 | -2.9 | -1.6 | +1.0 | -4.1 |
| 1979-1982 | -0.2 | +8.9 | -2.9 | -4.4 | +1.4 |
| 1982-1985 | -0.9 | -3.0 | -3.2 | +0.2 | -6.9 |
| 1985-1987 | -0.7 | -4.6 | +3.8 | -1.5 | -3.0 |
| 1987-1990 | -1.8 | -4.3 | -12.9 | -3.3 | -22.3 |
| Total | -3.3 | -61.5 | -71.0 | -32.5 | -168.3 |

## Half Moon Bay

The shoreline at Point Chehalis just east of the south jetty receded during the construction and after completion of the jetty. The shoreline recovered during the period that the jetty was in a deteriorated condition. After repairs to the south jetty were completed in 1939, erosion again occurred, initiating the formation of Half Moon Bay in 1946 and necessitating construction of the Point Chehalis revetment and groins in the 1950s. The revetment stabilized Point Chehalis, but the shoreline between the revetment and the south jetty has continued to recede. The receding shoreline at Half Moon Bay destroyed several U.S. Coast Guard structures and continues to endanger city infrastructure (USAED, Seattle, 1997).

The formation of crenulate shaped bays at artificial headlands on the open coast is a commonly observed phenomenon. Several researchers (e.g., Silvester 1960; Yasso 1965; Silvester and Ho 1972; Hsu, Silvester, and Xia 1987) have studied this shape and established relationships between the shoreline shape and wave direction. Hsu, Silvester, and Xia (1987) developed parabolic-equation curves for predicting the equilibrium shoreline by analyzing physical model data together with field data from bays known to be in equilibrium. Seabergh (1999a) examined this phenomenon at the channel side of a jetty where it terminates in a sandy shore. Dean (1977) observed such erosion at Shinnecock Inlet, NY. The Hsu, Silvester, and Xia (1987) method was applied at Half Moon Bay to estimate the equilibrium shoreline shape (see Figure 3). The computed equilibrium shoreline fits well with the existing bay shoreline. Note that the additional volume of sand at the jetty in Figure 3 is nourishment material that has been placed there. Although the shoreline is near the computed equilibrium position, the shoreline is dynamic and will respond to changes in water level and incident wave conditions. Storms characterized by prolonged elevated water levels will result in increased erosion. The dynamic character of the bay shoreline is evident from the variability observed in the field data that have been collected there and analyzed from the 1960s to the present.

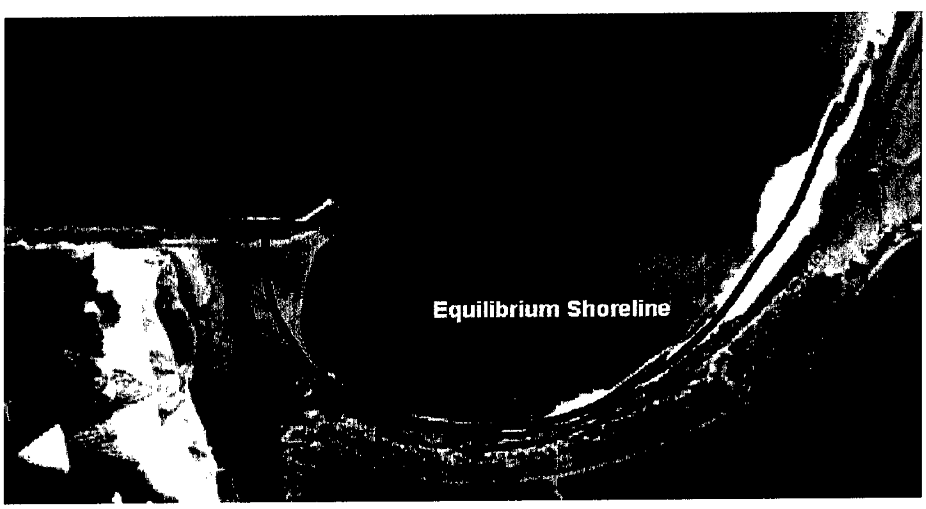



Figure 3. Equilibrium shoreline for Half Moon Bay based on Hsu, Silvester, and Xia (1987)

Burch and Sherwood (1992) examined shoreline changes at Half Moon Bay by analyzing vegetation lines. From 1949 to 1967, Half Moon Bay grew with an average shoreline recession rate of 27 ft/year. The trend then reversed, and the shoreline advanced at a rate of about 13 ft/year from 1973 to 1977. During the period from 1977 to about 1985, the vegetation line movement again reversed and receded at a slow average rate of about 3 ft/year. After 1985, analysis of high water lines indicates that recession rates have increased to an average rate of more than 10 ft/year. USAED, Seattle (1997) estimated the long-term recession rate by measuring the change in position of shoreline contours between 1957 and 1967, and 1993 to 1996. The Half Moon Bay shoreline was found to have a long-term recession rate of between 5 and 10 ft/year.

The beach directly south and west of the west end of the Point Chehalis revetment eroded extensively between May 1993 and December 1994. The shoreline receded landward an average of 70 ft and up to 150 ft in localized areas. This erosion prompted dredged material placements in excess of 350,000 cu yd during 1995. Much of this material eroded as it was placed on the beach. A comparison of pre- and post-construction surveys in January 1996 revealed that most of the beach-fill material had eroded from the fill site and deposited in a layer up to 6 ft thick in the area directly offshore. Based on these data and volume comparisons further offshore in Half Moon Bay, USAED, Seattle (1997) estimates that the total annual loss from the Half Moon Bay shoreline (to a depth of 20 ft mllw) is about 63,000 cu yd/year.

Similar to the behavior of South Beach, the Half Moon Bay shoreline data to 1996 clearly demonstrate a long-term erosional trend, although at a slower rate. Shoreline recession rates have increased in recent years despite continued nourishment. However, bathymetric analysis suggests that relatively little material is being lost offshore; if the entire bay is considered, the long-term rate of erosion may not have increased as significantly as shoreline change data alone indicate (USAED, Seattle, 1997). Shoreline changes in Half Moon Bay since 1997 are further analyzed in Chapter 3. Supplemental photograph documentation of the Half Moon Bay area is provided in Appendix A.

## Regional Sediment Transport

The major source of sediment to the Washington shelf and the beaches of the southwest Washington coast is the Columbia River. Studies by Ballard (1964) showed that sand is moved northward from the Columbia by seasonally reversing longshore currents. The regional regime of longshore movement is locally altered by wave refraction, which may produce deviations from the general trend of movement. The historical northward flow of sand is evidenced by diagnostic mineralogy studies that have traced Columbia River sands as far north as Ocean Shores and by the northward movement of the mouth of Willapa Bay and the mouth of Grays Harbor prior to jetty construction.

## Sediment supply

The Columbia River is the primary sediment source for the continental shelf and littoral zones of the southwest Washington coast. Sternberg (1986) suggests that 84 percent of the annual Columbia River sediment discharge has accumulated on the shelf or in the deep sea. The remainder accumulates in the estuaries and on the beaches. Gelfenbaum et al. (1999) estimated the accumulation rate available for beach nourishment since 1878 is about 400,000 cu yd/year.

It has been hypothesized that the construction of dams during the past 75 years in the Columbia River drainage basin has decreased the sediment discharge of the system and reduced the sediment budget of Washington's beaches. Gelfenbaum et al. (1999) estimated that the dams have reduced the sand supply to the estuary by 67 percent. In 1978, concern over the possibility of a diminished sand supply to the southwest Washington beaches was a major factor in initiating a coastal accretion and erosion study. One of the conclusions of the study was that any reduced discharge by the Columbia River had not yet affected the sand supply to the beaches (see also Phipps and Smith 1978).

Subsequent study indicated that a probable source of sand for Washington beach accretion was Peacock Spit, created by sand jetted out of the Columbia after construction of the jetties. The shoal injected sand into the longshore system over the years but by the 1990s was essentially no longer a source (Phipps 1990). More recently, sediment has slowly been removed from the outer bar of the Columbia and, as the system approaches equilibrium, changes are occurring more slowly. Therefore, perhaps more important than the reduction in sediment supply from the river is the erosion of the sand sources at the mouth of the Columbia. Burch and Sherwood (1992) conclude, "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 . . . ." The Grays Harbor entrance area has itself also seen a decrease in sediment supply with the deflation of the ebb shoal following the structuring of that inlet.

The shoreline progradation rates from the early part of the 1900s are much greater than rates from before this time and, in general, also greater than recent accretion rates. Gelfenbaum et al. (1999) conclude that the timing of the rapid accretion and the longshore variation in the accretion suggest the changes in the ebb-tidal deltas after jetty construction are the primary cause for much of the beach accretion. The current deflated state of the Columbia River and Grays Harbor deltas signals an end of this once vast source of sediment, eventually reducing the sediment supply at Grays Harbor. The area around Grays Harbor is likely evolving because of a reduction in sediment supply from both internal (ebb-tidal deltas) and external (Columbia River) sources (Kaminsky, Buijsman, and Ruggiero 2001). The reduction of internal sources appears to be the dominant factor in the recent reversal of historical shoreline advance.

## Longshore transport

The longshore transport regime on the beaches adjacent to Grays Harbor has been a subject of confusion over the years. The earliest mappings of Grays Harbor showed migration of the entrance to the north, indicating northerly transport. When construction was begun on the south jetty in 1896, the predominant direction of transport was believed to be in this direction. After the south jetty was constructed, the channel continued to shoal, and the north jetty was built in 1907 to constrict the entrance and block the south-directed transport from shoaling the channel. The north jetty quickly impounded large volumes of sand. After reconstruction of the north jetty in 1916, the existing channel adjacent to the south jetty shoaled, and a new channel, wider and deeper, developed to the north of the older channel. This observation, along with evidence produced in studies from the early 1950s, led USAED, Seattle (1965) to conclude that littoral drift was predominantly from north to south with seasonal changes, a reversal of previous thought.

Because of the seasonality of the longshore drift, the beaches display accretion patterns that are characteristic of drift in both directions. Large volumes of sand are transported in both directions. However, because the northward drift is forced by winter storms, the sand moving in this direction tends to be removed from the beach. Conversely, the summer south-directed drift tends to move sand onto the beach under the action of constructive waves. Therefore, examination of shoreline change only may lead to the perception that the southerly component is dominant, whereas, in fact the northerly component of transport is dominant.

Kaminsky, Buijsman, and Ruggiero (2000) performed numerical model simulations of shoreline change along the southwest Washington coast. They concluded "The wave climate combines with coastal currents to result in a net regional sediment transport to the north along the Washington shelf. However, shoreline changes and net sediment transport along the subcell beaches are driven locally by wave refraction and shoreline orientation, causing some reversals of net sediment transport within the subcells." The direction of net littoral drift at North Beach was northward, and along the Grayland beaches it was reported to be to the south. The Special Subcommittee (1995) and a year 2000 study of potential longshore transport conducted by ERDC for the Seattle District also documented the potential for south-directed transport along the beaches south of Grays Harbor. An estimation of the potential transport due to waves was made using SEDTRAN (Gravens and Kraus 1991). SEDTRAN computes potential longshore sand transport rates based upon calculation of the longshore energy flux with input wave conditions from a time series. SEDTRAN calculations were idealized in that nearshore wave transformation was not included. Where bathymetry data were available, transport estimates were made by NSTRAN (Gravens and Kraus 1991). NSTRAN computes potential longshore sand transport rate based upon the longshore energy flux with nearshore wave output from a wave model. Wave parameters computed by the nearshore wave transformation model Steady-State Spectral Wave Model (STWAVE) (Smith, Resio, and Zundel 1999) were input to NSTRAN to compute sediment transport. The nearshore wave simulation was driven by incident waves based on data from the Grays Harbor wave buoy (Coastal Data Information Program (CDIP) sta 036) supported by the Seattle District. The resulting longshore transport regime was similar to that found by Kaminsky, Buijsman, and Ruggiero (2000), with north-directed transport along North Beach and south-directed transport at South Beach.

Wamsley and Hanson (2002) applied the numerical model GENESIS (Hanson and Kraus 1989) to predict the longshore transport and shoreline change just north of the Grays Harbor entrance. The calibrated model results confirm the regional trend of north-directed transport for North Beach. The model predicts a net southbound transport within approximately 500 m of the north jetty that transitions to northbound transport through the remainder of the model domain (which extends about 2.5 miles north of the north jetty). Calibration of the model required feeding from the Grays Harbor ebb-tidal delta, suggesting that sediments bypass the Grays Harbor ebb delta from the south.

In developing an integrated sediment budget for the entire Columbia River littoral cell, Kaminsky, Buijsman, and Ruggiero (2001) concluded that from a mass balance perspective it was "evident that sand (at Grays Harbor) is supplied from the south by longshore transport across the Willapa Bay ebb-tidal delta. However, the erosion of the upper shoreface along Grayland Plains indicates that this region does not accumulate sand, rather it is bypassed to the Grays Harbor ebb-tidal delta, and potentially northward to the North Beach shelf and coast." This northward bypassing of sand to North Beach is congruous with the findings of Wamsley and Hanson (2002). The implication is a bidirectional net transport regime just south of the entrance where the net directions of sediment flow is to the north in deeper water and across the ebb shoal and to the south along the nearshore.

It appears that the ocean circulation and severe winter storms that create intense waves from the southwest combine to produce northerly transport of sediments along the Washington Shelf. Recent modeling studies have suggested that shoreline reorientation caused by structures at the Grays Harbor entrance has caused localized reversal of net sediment transport along the northern Grayland beaches adjacent to the entrance. Despite these localized reversals, the balance of evidence suggests that the regional trend for sediment transport is from the south to the north. Sediment bypasses the Grays Harbor entrance and feeds North Beach. A possible localized reversal of net transport and the rip current that forms adjacent to the south jetty contribute to the persistent erosion at South Beach adjacent to the jetty.

# 3 Performance Evaluation

## Introduction

This chapter reviews dredging and disposal activities associated with maintenance and new work dredging of the navigation channel, and morphologic change analysis of the shore and nearshore areas near the south jetty as a means of evaluating the effectiveness of engineering activities. Performance evaluation is based on numerical model simulations of the wave diffraction mound, upland and intertidal topography and nearshore bathymetry surveys, shoreline position changes in the South Beach nourishment and dune restoration area near the south jetty, and the evolution of gravel transition in the lee of the diffraction mound. Maintenance dredging and disposal volumes are included in the sediment budget analysis presented in Chapter 4.

## Maintenance Dredging and Disposal

Sediment that shoals the Grays Harbor navigation channel is derived from marine and fluvial sources. Marine sediment is delivered to Grays Harbor and the navigation channel mainly through longshore sediment drift, transported to the bay by waves, nearshore currents, and tidal currents through the entrance. Fluvial or river-borne sediment in the channel is primarily from the Chehalis River, which discharges at the head of the estuary. Small rivers and creeks discharge sediments in the upper and middle estuary. Previous studies (e.g., Beverage and Swecker 1969; WDOE 1977) indicate that river-borne sediment is mostly deposited in the upper estuary and does not exit Grays Harbor as a significant amount. Sediments removed from the inner harbor by clamshell and hopper dredges have been placed into the south jetty disposal site (Figure 1), and some of that material is transported out of Grays Harbor by the ebb-tidal current. The same studies determined that marine sediment that enters the estuary disperses as far as 10 to 14 miles upstream, resulting in deposition in all lower channel reaches up to the north channel. Dredging data presented and discussed in this chapter relate only to the outer reaches of the channel, including the outer bar, entrance channel, Point Chehalis, South Reach, Crossover Reach, and the north channel. Figure 1 shows locations of these reaches.

Prior to the construction of the jetties, the deepest part of the entrance channel was 40 to 60 ft mllw. The controlling (minimum) depth over the outer bar was about 15 ft. The jetties, as they were originally constructed, were inadequate in providing the required navigation depth in the bar channel, particularly with the jetties in a deteriorated condition. Supplemental bar channel dredging began in 1916 and continued at regular intervals until 1926. Almost continuous dredging of the bar channel was required from 1926 until the jetties were reconstructed in the late 1930s. The total volume dredged from the bar and entrance channels from 1916 to 1942 was approximately 22,000,000 cu yd, all of which was disposed of in deep water (-60 ft mllw) outside the harbor. Between 1916 and 1927, the bar channel was dredged to a depth of 24 ft mllw, and from 1928 the dredging continued to a depth of 36 ft mllw. Following rehabilitation of the north jetty in 1942, the scouring of current as constrained by the jetties was sufficient to maintain the authorized channel depth of 36 ft mllw. As a result, neither the bar nor the entrance channel required maintenance dredging from 1942 to 1990.

No data on maintenance dredging at Crossover Reach or South Reach prior to 1961 have been found. Between 1961 and 1974, an average of 1,040,000 cu yd/year was dredged from Crossover Reach and Sand Island Reach. In 1978, the Sand Island Reach realignment construction (to become South Reach) was completed. Between 1980 and 1989, following north jetty rehabilitation in the late 1970s, the annual volumes dredged from Crossover Reach and South Reach were 460,000 and 650,000 cu yd/year, respectively.

The Grays Harbor navigation improvement project of 1990 was completed by 1991. Channel dimensions were achieved as specified in Table 4. To maintain the new authorized depths, maintenance dredging has been required since 1990 in both the outer bar and entrance channels.[1] The entrance and bar channels were dredged below existing bottom elevations, creating dredge cuts that capture sediment in transport. Advance maintenance dredging has been accomplished as part of the channel maintenance since 1991 to provide navigable depths of the channels for the duration of the maintenance cycle.

Data from maintenance dredging reports and dredging contract documentation for the period 1991 to 2001 were analyzed to identify trends in sediment distribution along channel reaches. Average annual maintenance dredging volumes and associated 95 percent confidence limits were estimated from dredging records maintained by the Seattle District. The 95 percent confidence limits on the mean annual dredging volume ($\bar{x}$) is calculated as:

$$\bar{x} \pm z_{\alpha/2} \frac{\sigma}{\sqrt{n}} \qquad (1)$$

where $\sigma$ is the sample standard deviation, $n$ is the number of samples, and $z_{\alpha/2}$ has a value of 1.96. Assuming the annual dredging volumes for a reach are normally distributed, the 95 percent confidence limits of the annual maintenance dredging volume is interpreted as follows: 95 percent of all estimates of channel dredging volume will fall within the confidence limits, and 5 percent will not.

[1] U.S. Army Engineer District, Seattle. (2001). "Analysis of future dredging requirements; Entrance Channel, Point Chehalis Reach, South Reach, and Crossover Channel," U.S. Army Engineer District, Seattle, Seattle, WA.

**Table 4**
**Grays Harbor Navigation Channel Dimensions**

| Channel Reach | Stations (see Figure 4) | Length (ft) | Channel Depth (ft) | Channel Width (ft) |
|---|---|---|---|---|
| Bar Channel | From 0+00 to 280+89 | 28,089 | 46 | 1,000 |
| Entrance Channel | 280+89 to 292+89 | 1,200 | 46 | Varies |
| Entrance Channel | 292+89 to 342+89 | 5,000 | 44 | 600 |
| Entrance Channel | 342+89 to 377+89 | 3,500 | 42 | 600 |
| Entrance Channel | 377+89 to 386+89 | 900 | 40 | 600 |
| Point Chehalis Reach | 386+89 to 463+00 | 7,611 | 40 | 600 |
| South Reach | 463+00 to 715+93 | 25,293 | 36 | 400 |
| Crossover Channel | 715+93 to 862+49 | 14,656 | 36 | 350 |
| North Channel | 862+49 to 1005+71 | 14,322 | 36 | 350 |
| Hoquiam Reach | 1005+71 to 1156+02 | 15,031 | 36 | 350 |
| Cow Point Reach | 1156+02 to 1231+50 | 7,548 | 36 | 350 |
| Cow Point Reach | 1231+50 to 1251+87 | 2,837 | 32 | Varies |
| Aberdeen Reach | 1251 + 87 to 1315 + 86 | 6,399 | 32 | 200 |
| Upper S. Aberdeen Reach | 1315 + 86 to 1439 + 65 | 12,379 | 32 | 300 |

The calculated average annual volumes of dredged sediment for each of the channel reaches distributed along the channel length are presented in Figure 4. In the lower part of the figure, the solid line shows average volumes of maintenance dredging along channel reaches. The plot was developed by averaging over the period of record (11 years) the volumes reported for each dredging distance (station limits). Average annual maintenance dredging volumes and associated 95 percent confidence intervals for each channel reach are summarized in Table 5 and in Figure 5. Dredging volumes of a particular year reflect not only the channel infill, but also dredge availability, weather, funding, scheduling, and other factors. The long-term average, however, should indicate the mean shoaling rate in the channel.

The estimated volume of sand material dredged from the channel between 1991 and 2001 is approximately 1.1 million cu yd/year (Table 5). This estimate assumes that 50 percent of the dredged material from Crossover Channel is sand and that only silt material (no sand) is dredged in the North Channel. These assumptions are based on practical experience of the Seattle District[2] and analysis of limited sediment grain size data for dredged sediment.

Dredged material from the channels was disposed at six different disposal sites in the bay and in the open ocean. The locations of the disposal sites are depicted in Figure 6. The volume of dredged material placed at each site is summarized in Table 6. The table also lists the source of dredged material. Currently, the Seattle District uses disposal sites at Point Chehalis, Half Moon Bay, South Beach, the south jetty, and the southwest site. Other disposal sites shown in Figure 6 are permitted. Selection of specific disposal sites for the

[2] Personal Communication, August 2002, Robert M. Parry, Chief, Navigation Section, U.S. Army Engineer District, Seattle, Seattle, WA.

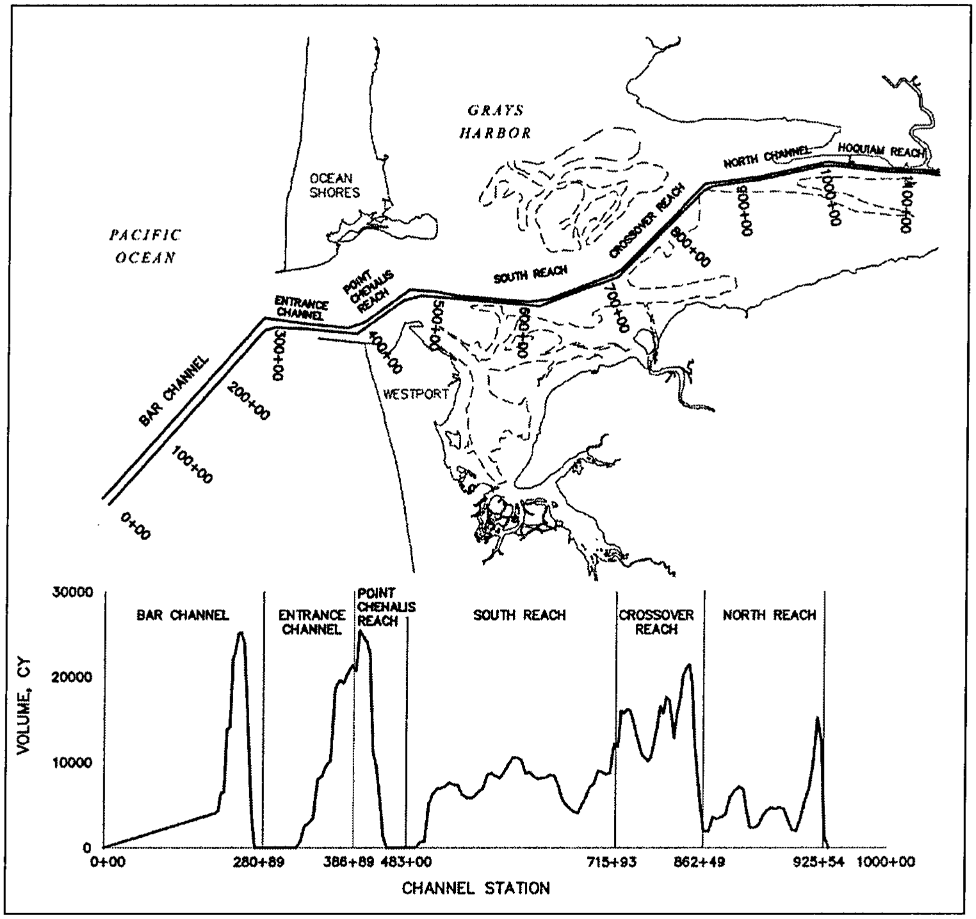



Figure 4. Calculated distribution of dredging volumes, 1991 to present

**Table 5**
**1991-2001 Annual Maintenance Dredging Volumes and Decadal Statistics by Reach**

| Year | Bar Channel (cu yd) | Entrance and Point Chehalis Reach (cu yd) | South Reach (cu yd) | Crossover Reach (cu yd) |
|---|---|---|---|---|
| 1991 | 452,000 | 453,000 | 477,000 | 88,000 |
| 1992 | 636,000 | 361,000 | 683,000 | 521,000 |
| 1993 | 373,000 | 324,000 | 158,000 | 639,000 |
| 1994 | 277,000 | 163,000 | 903,600 | 364,000 |
| 1995 | 0 | 0 | 332,000 | 469,000 |
| 1996 | 0 | 308,000 | 103,600 | 425,000 |
| 1997 | 0 | 136,000 | 226,400 | 456,000 |
| 1998 | 103,000 | 266,000 | 293,000 | 840,000 |
| 1999 | 76,000 | 382,000 | 229,000 | 390,000 |
| 2000 | 209,000 | 537,000 | 231,000 | 463,000 |
| 2001 | 227,000 | 358,870 | 169,000 | 190,000 |
| | | | | |
| Average annual volume, cu yd/year | 214,000 | 299,000 | 346,000 | 440,000 |
| Upper 95 percent confidence limit, cu yd/year | 91,000 | 209,183 | 200,000 | 322,000 |
| Lower 95 percent confidence limit, cu yd/year | 337,000 | 389,000 | 492,000 | 559,000 |
| | | | | |
| FY 2002 Actual volumes for comparison, cu yd | 144,031 | 605,459 | 135,706 | 180,967 |

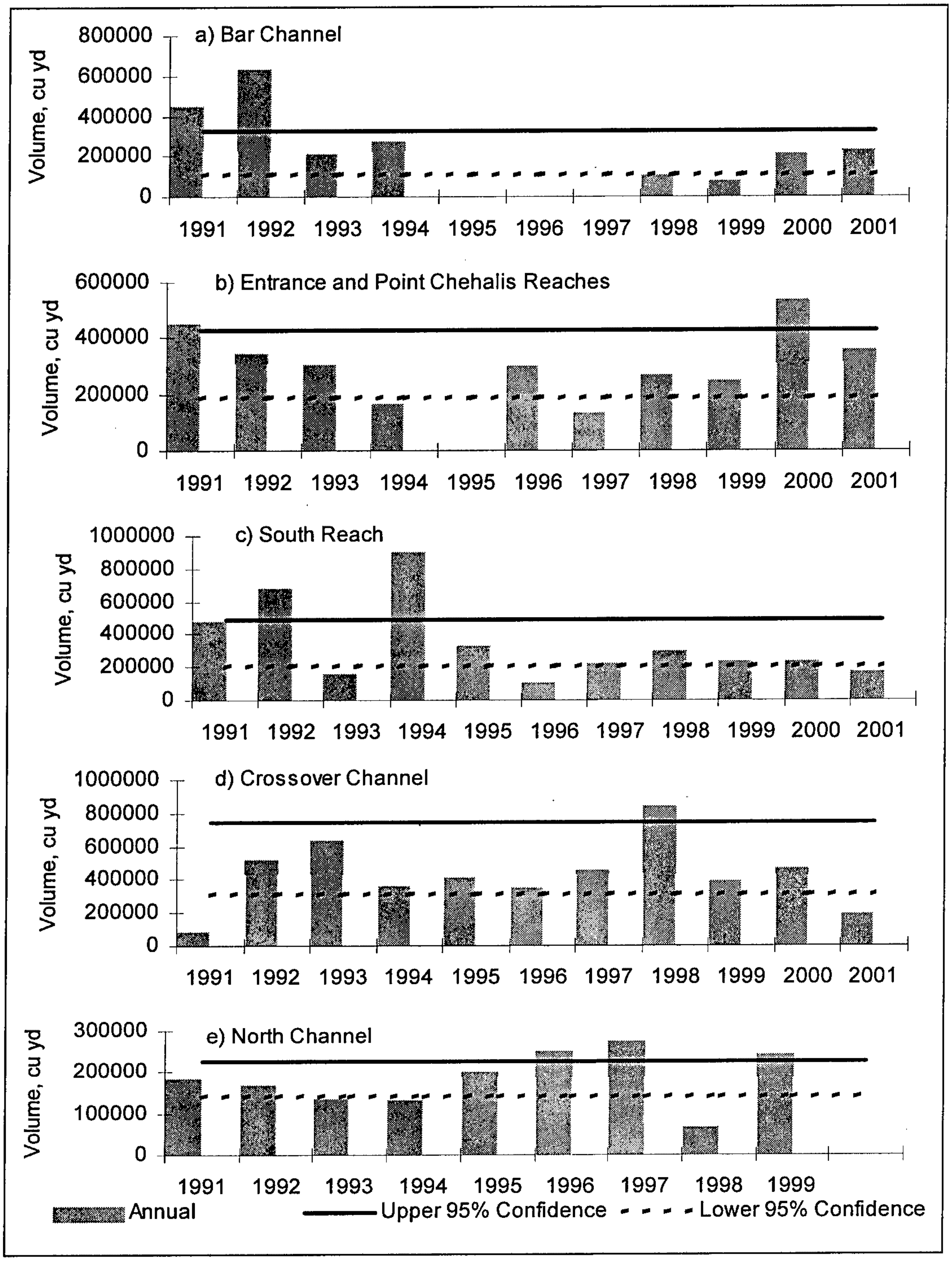



Figure 5. Annual maintenance dredging volumes between 1991 and 2001

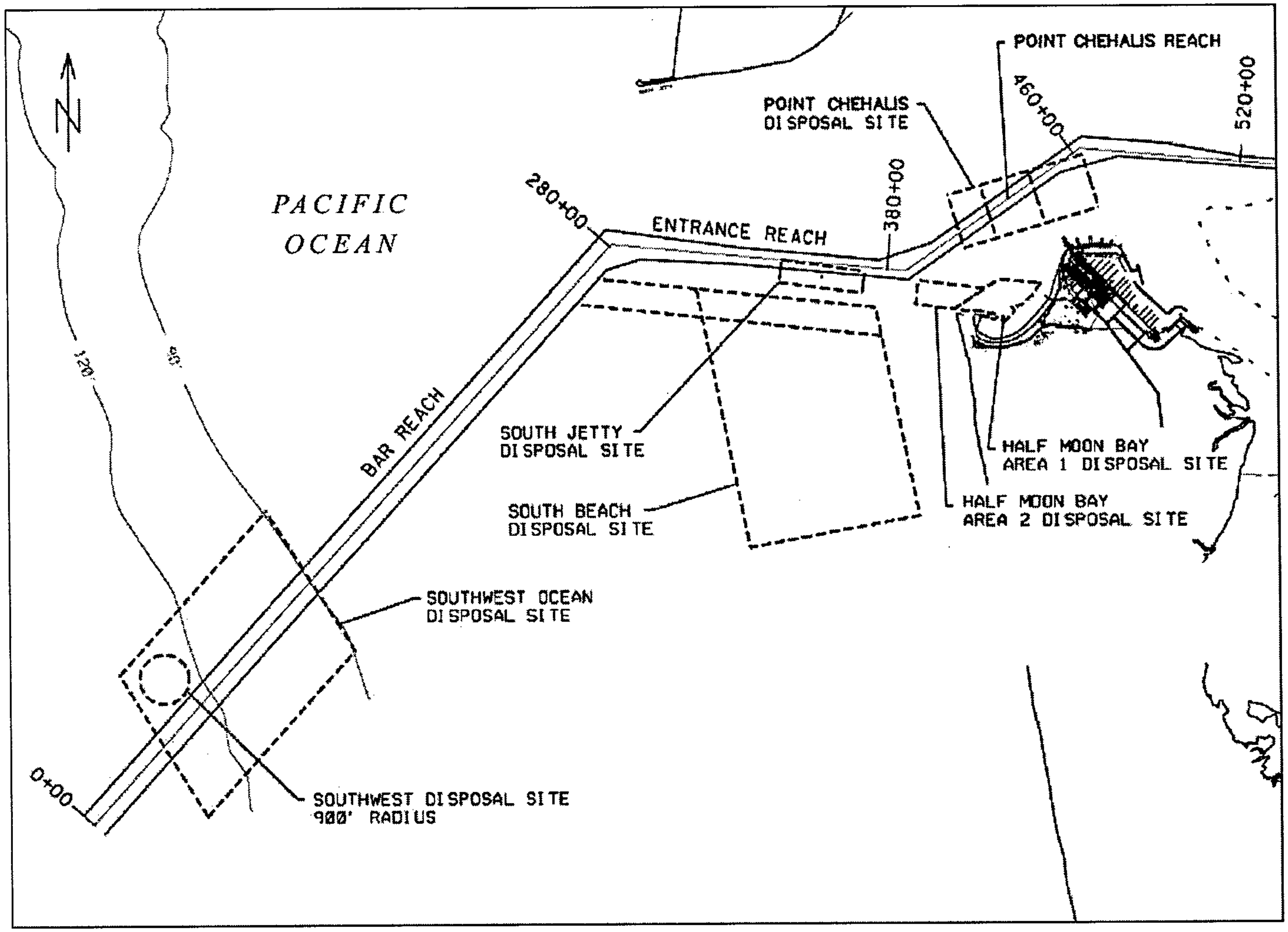



Figure 6. Location of dredged material disposal areas in and near Grays Harbor entrance

**Table 6**
**Disposal Site Volumes and Sources 1991-2002**

| | Disposal Sites, Annual Volumes (cu yd) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Year** | **Point Chehalis** | **South Jetty** | **Half Moon Bay Nearshore** | **Half Moon Bay Direct** | **Westport Fill** | **Breach Fill** | **South Beach** | **SW Ocean** | **Total** |
| 1991 | 710,000 | 1,109,000 | 0 | 0 | 0 | 0 | 0 | 452,000 | 2,271,000 |
| 1992 | 990,000 | 1,621,000 | 200,000 | 0 | 0 | 0 | 0 | 637,000 | 3,448,000 |
| 1993 | 683,000 | 1,120,000 | 0 | 0 | 0 | 0 | 373,000 | 0 | 2,176,000 |
| 1994 | 704,000 | 889,000 | 0 | 0 | 0 | 600,000 | 265,000 | 12,000 | 2,470,000 |
| 1995 | 1,181,373 | 392,185 | 0 | 0 | 300,295 | 0 | 0 | 0 | 1,873,853 |
| 1996 | 295,719 | 1,674,267 | 274,780 | 0 | 0 | 0 | 0 | 0 | 2,244,766 |
| 1997 | 598,735 | 959,249 | 308,508 | 0 | 0 | 0 | 0 | 0 | 1,866,492 |
| 1998 | 713,585 | 1,197,809 | 441,474 | 0 | 0 | 0 | 0 | 0 | 2,352,868 |
| 1999 | 1,156,375 | 593,036 | 228,470 | 228,963 | 0 | 0 | 76,187 | 0 | 2,283,031 |
| 2000 | 956,700 | 1,200,248 | 0 | 0 | 0 | 0 | 0 | 0 | 2,156,948 |
| 2001 | 667,969 | 358,873 | 0 | 0 | 0 | 0 | 0 | 227,297 | 1,254,139 |
| 2002 | 942,316 | 475,199 | 378,441 | 135,706 | 0 | 135,000 | 75,219 | 68,812 | 2,210,693 |
| | | | | | | | | | |
| **Total volume (cu yd)** | 9,599,772 | 11,589,866 | 1,831,673 | 364,669 | 300,295 | 735,000 | 789,406 | 1,397,109 | 26,472,790 |
| | | | | | | | | | |
| **Reaches Dredged** | Aberdeen, Cow Point, Cow Point Notch, Inner Crossover, Lower Crossover, Elliot Slough, Hoquiam, Inner Crossover, North Channel, South Reach, Turning Basin, Westport Marina | Aberdeen, Bar, Cow Point, Crossover, Elliot Slough, Entrance, Point Chehalis, Hoquiam, Inner Crossover, North Channel, South Reach | Entrance, South | Entrance, South | South | Entrance, South | Bar | Bar | |

dredged material disposal is controlled by economic and environmental considerations and attempt to maximize a beneficial use of dredged material for habitat enhancement and beach restoration projects. For example, sites in Half Moon Bay and Point Chehalis are designated for the disposal of dredged material that benefits beach nourishment and shore protection at Point Chehalis and Half Moon Bay. The amount of dredged material placed at the site is controlled by water depth that allows a hopper dredge safe maneuvering during disposal operations. Sites in Half Moon Bay receive dredged material predominately from South Reach, Point Chehalis, and the entrance channel, characterized by sand material typical of Half Moon Bay beach material.

## South Beach Dune Restoration and Transition Gravel

This section of the report documents the analysis of the beach nourishment and dune restoration at the south jetty and the transition gravel placed in the lee of the wave diffraction mound. The performances of the nourishment, restoration, and transition gravel are evaluated in terms of life span of the fill relative to expectations and contribution to reduction of shoreline recession in Half Moon Bay.

In December 1993, persistent shoreline erosion near the south jetty culminated in the formation of a breach between the jetty and the adjacent South Beach. The Seattle District filled the breach in 1994 with 600,000 cu yd of sand dredged from the navigation channel as a temporary measure to protect the Grays Harbor navigation project and alleviate local concerns regarding facilities located south and east of the breach area. The fill was originally expected to be effective in protecting the project for 5 to 10 years. During the seventh winter that the fill was in place (2001-2002), a series of severe storms damaged the fill placed at South Beach and modified the Half Moon Bay shoreline. In May 2002, the breach-fill dune was restored.

Gravel (1- to 2-in. size) was placed as a transition material between the diffraction mound and the sandy shore of Half Moon Bay at the time of construction of the mound in 1999. The purpose of the gravel transition material was to protect the breach fill from erosion in the lee of the diffraction mound.

The analysis includes comparison of repetitive beach profiles and shoreline position time series derived from aerial photographs for the South Beach and Half Moon Bay shorelines. Processes responsible for sediment transport and profile change have been altered nearly continuously for decades in the study area. A photographic record is available, and some profile surveys were made in the mid-1990s, but only recently have transects been established for repeat surveys that encompass the upland, foreshore, and nearshore bottom.

Figure 7 shows the location of the survey transects. Transects HD-1, Worm, and Spice were established as part of the southwest Washington coastal erosion study by the WDOE, and cross-shore profile data have been collected since 1997 (Ruggiero and Voigt 2000). Transects HMB1 to HMB10 and SB1 to SB8 were established in December 2001 following the series of storms that led to damage of the breach fill, revetment fill, and shoreline erosion. The WDOE was contracted through CHL to establish and survey upland portions of transects HMB1 to HMB10 and SB1 to SB8 (Figure 8). The U.S. Geological Survey (USGS) was subcontracted through WDOE to perform in-water surveys at transects HMB1 to HMB10 in April 2001. Transects SB1 to SB8 approximately coincide with the location of eight transects that were surveyed 17 times from April 1995 to August 1998 by Grays Harbor Community College under contract to the city of Westport.

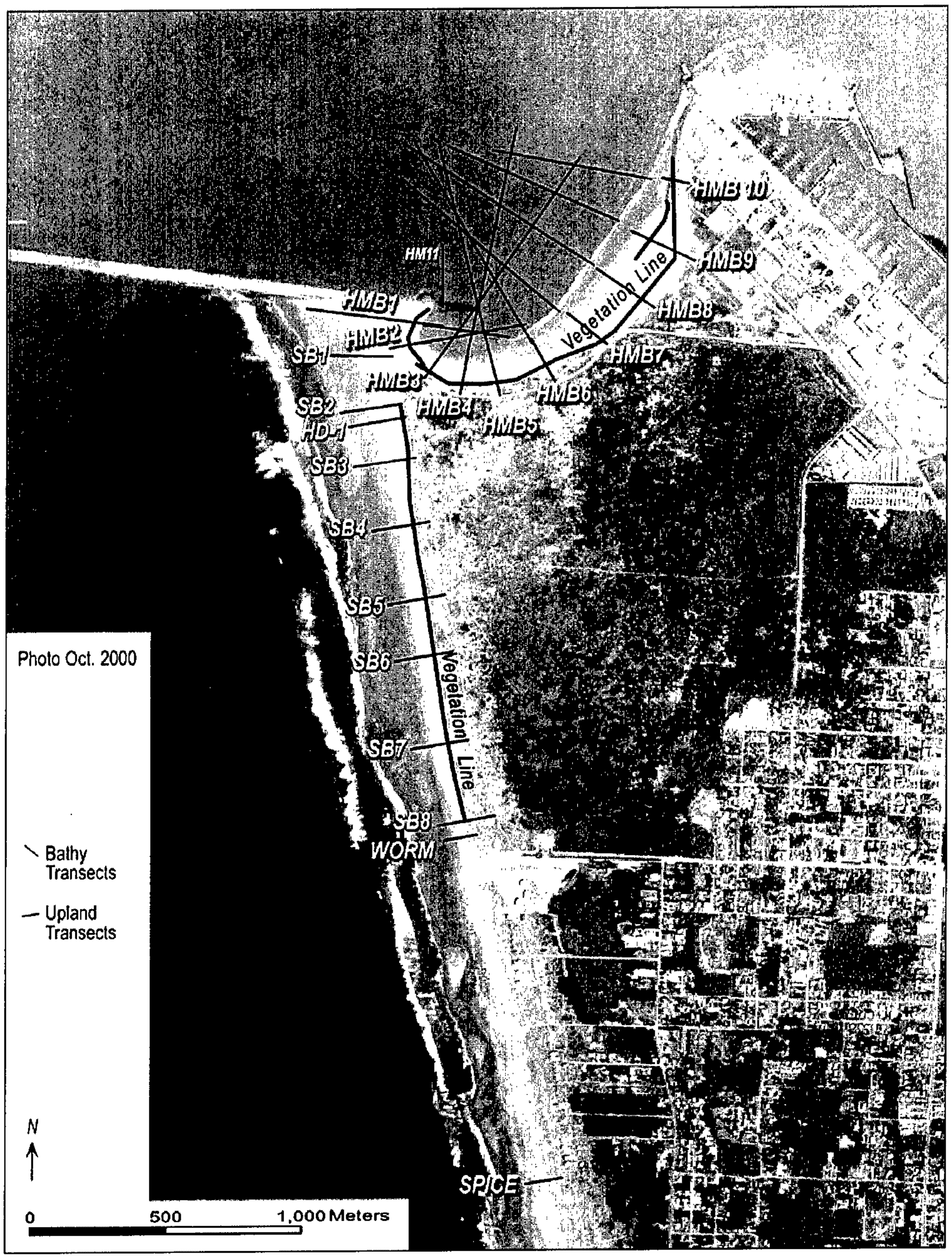



Figure 7. South Beach/Half Moon Bay survey transect locations

Similarly, 3-D surface maps of the intertidal foreshore have been collected at regular intervals since 1997 (Ruggiero and Voigt 2000). The surface maps span the region between the primary dune and mllw and extend approximately 4,000 m along the shoreline southward from the south jetty.

### Shoreline change analysis

Shoreline positions for Half Moon Bay were derived from digital orthophotos for the years 1996-2002 (Appendix A, Figures A-11 through A-26). The aerial photography was acquired by North Bay Resources, Ltd., under contract to PI Engineering. Original photographs reproduced at a scale of 1 in. to 555 ft were digitized at 600 dots per inch (dpi) and ortho-rectified using the PCI-Geomatica Ortho-Engine software. At least six ground-control points in each image were selected from a digital ortho-rectified quadrant (DOQ) photograph purchased from the USGS and a digital elevation model also acquired from USGS. The photographs were rectified by using available camera and lens information. Root-mean-square (rms) error in horizontal pixel position of the ortho-rectified photographs was approximately 2.4 pixels, with pixel resolution of 0.61 m.

Shoreline position time series were created following a methodology similar to that described by Kaminsky et al. (1999). The shoreline change reference feature (SCRF) defined as the average high water line (AHWL) was digitized using Arc/Info software. The AHWL is a horizontal reference line that represents an average excursion of water between the most recent high tides of unequal height. The AHWL is based on features visible in the aerial photograph and is usually taken as a line between the waterline and the debris on the beach marking the landward extent of wave runup during the most recent high tide. The AHWL is a smooth line, not showing transient features such as cusps. Some interpretation of the aerial photographs is necessary in delineating the SCRF and, as a consequence, the uncertainty is greater than the shoreline locations derived from surveyed data and a defined vertical elevation. A proxy-based SCRF cannot be assumed equivalent to a vertical datum such as mean high water (mhw) (Kaminsky et al. 1999; Ruggiero, Kaminsky, and Gelfenbaum 2002). Locational variability of the AHWL determined from aerial photographs has been analyzed and is discussed in detail by Daniels, Ruggiero, and McCandless (2000) and Ruggiero, Kaminsky, and Gelfenbaum (2002).

The rectified aerial photographs are accurate to within ±1.5 m in terms of measuring a line on the photograph as determined by the rms pixel error (shoreline source error). The uncertainty of interpreting where the AHWL appears on the photographs (shoreline interpretation uncertainty) was assessed at each of the 10 transects in Half Moon Bay. The interpretation uncertainty ranged from 2 to 10 m, with an average of 2.4 m. In addition, there is natural shoreline variability occuring over days and weeks, resulting in uncertainty in the true shoreline location for a particular year and season. The total measurement uncertainty, not including scatter caused by natural variability, is therefore ±3.5 m to ±11.5 m with an average of ±3.9 m for the aerial photographs considered here. To minimize the potential bias associated with seasonal variability in shoreline position and shoreline source error, annual photographs were selected from the database at a similar time of year, at a similar wave and water level relative to high tide, and with an identifiable SCRF in the area of interest.

Figure 8 shows the shoreline positions digitized from the annual aerial photographs using the techniques previously described. Horizontal shoreline movement is measured along Transects HMB1 to HMB9 relative to the transect origin. The algorithm selected for use in this study searches for the nearest shoreline points on either side of the transect lines. Linear interpolation is used between the points to determine the intersection between the shoreline and the shore-normal transect. The distance from the transect origin to the shoreline position on each transect is then determined from that intersection.

Figure 9 shows the change in shoreline position (AHWL) at Half Moon Bay Transects (HMB1 to HMB9) relative to the 1996 shoreline position. The shoreline positions document the extent of adjustment of the shoreline to the local sediment transport. The time series show that net shoreline recession has occurred at Transects HMB1, HMB2, HMB3, HMB5 and HMB6; no significant net change has occurred at Transects HMB4 and HMB7; and net advance has occurred at Transects HMB8 and HMB9. Overall, the shoreline position data between 1996 and 2002 reveal a pattern of net shoreline recession of between 2.5 to 12 m/year at the western end of Half Moon Bay west of Transect HMB7 and shoreline advance of approximately 7 m/year east of Transect HMB7.

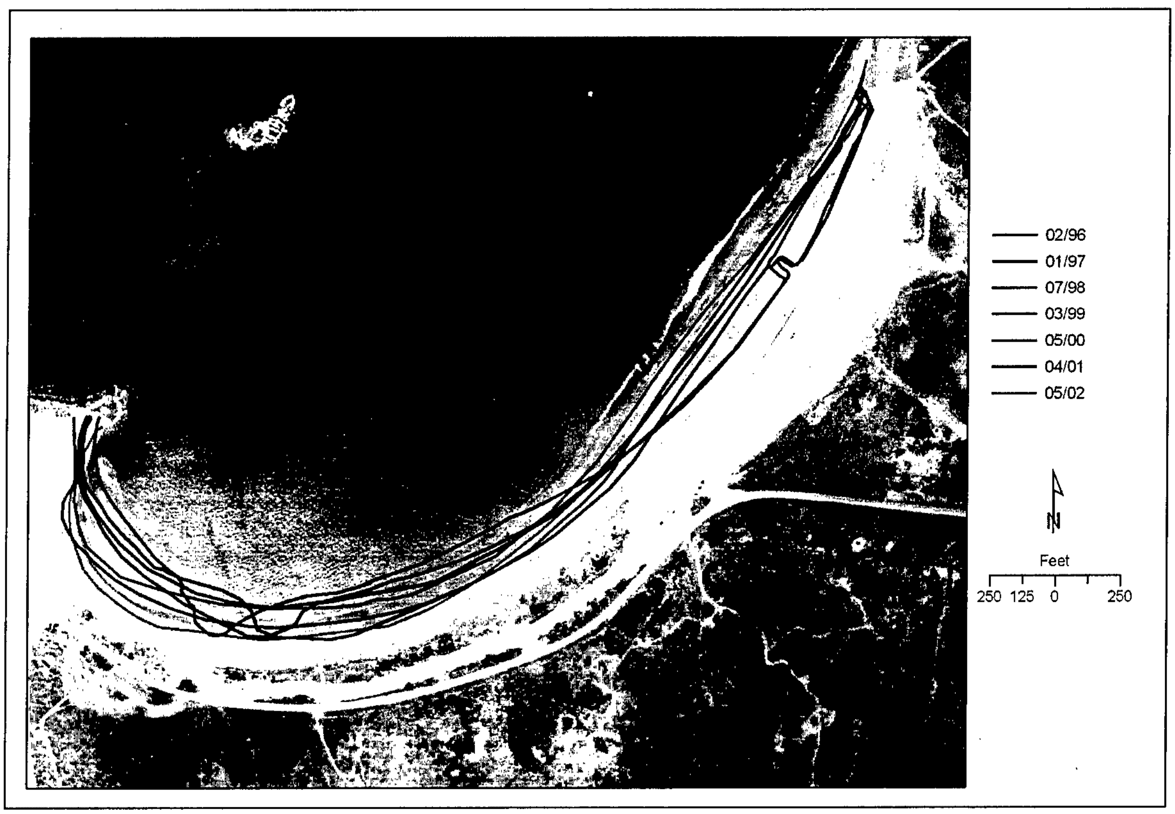



Figure 8. Half Moon Bay shorelines digitized from annual aerial photographs

The recent trends in shoreline recession in the western end of Half Moon Bay are similar to the historical long-term recession rates reported by USAED, Seattle (1997). The advance and stability of the shoreline at the eastern end, near Point Chehalis revetment, is a relatively recent reversal of the long-term recession in this area and may reflect recent nearshore and upland placements of dredged sediment.

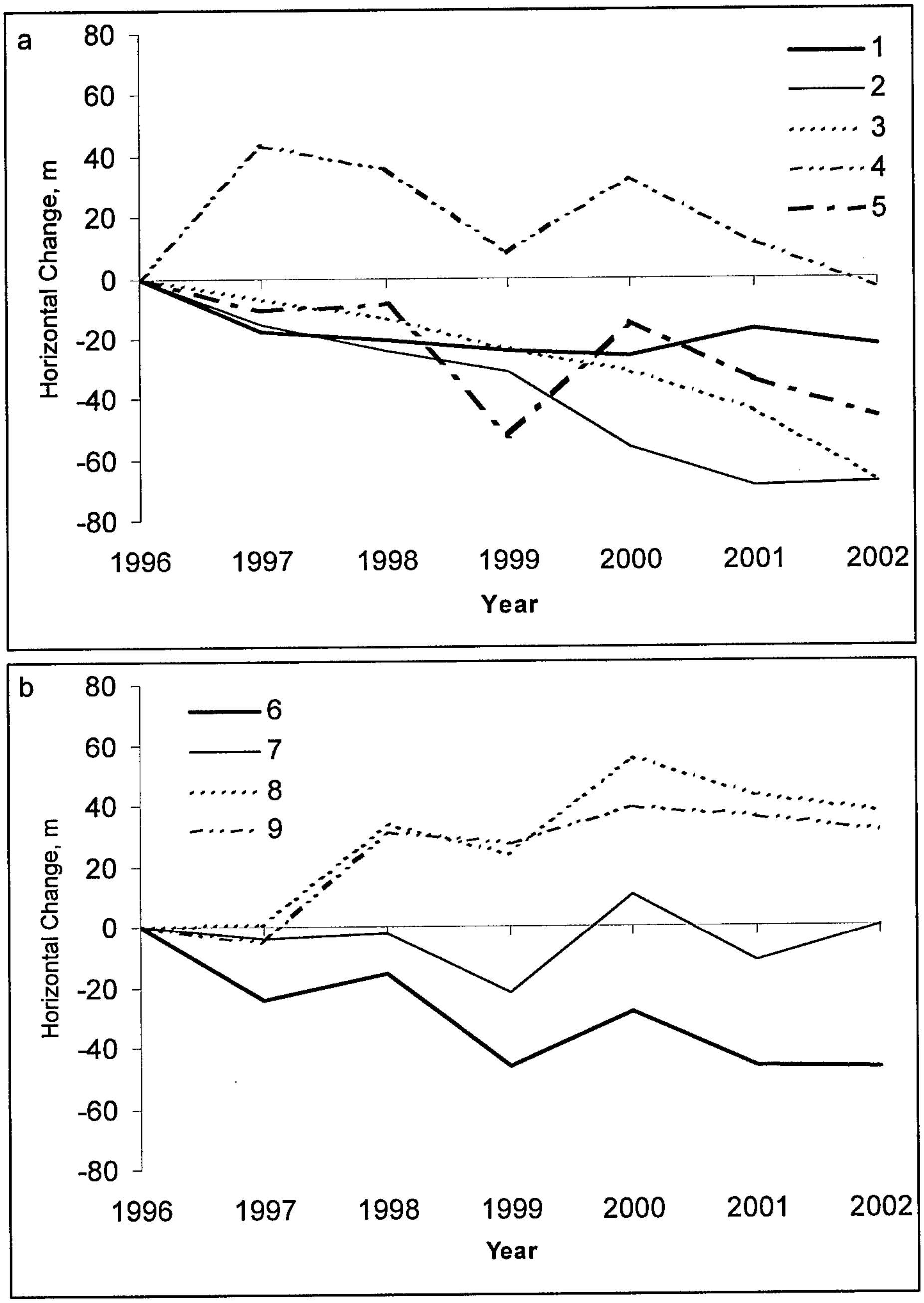



Figure 9. Half Moon Bay shoreline position change relative to 1996 position at (a) Transects HMB1 to HMB5, and (b) Transects HMB6 to HMB9

In 2000, the shoreline began to recede, and its present position is near that of 1996. An indentation in the shoreline is present in the 1996 and 1997 photographs near Transect HMB4. The indentation migrated east approximately 60 to 75 m between 1996 and 1997 and is not present in later photographs. Although Transect HMB1 (in the lee of the diffraction mound) shows net recession, nearly all the recession occurred between 1996 and 1997; the shoreline position has been approximately stable since 1997. Recession at Transect HMB2 (downdrift from Transect HMB1) accelerated between 1999 and 2000, then at Transect HMB3 between 2001 and 2002.

### Beach profile change

Beach profile measurements originate landward of the primary dune and extend seaward to wading depth during a low tide. The methodology for the collection of beach profile data is outlined by Ruggiero and Voigt (2000). Profile surveys in easting-northing-elevation form were imported into spreadsheets and the horizontal coordinates plotted in Cartesian space. The alignment of best fit is calculated for each profile with the best visible cross-shore trend and central tendency. All measurements are then rotated in a horizontal plane, using Cartesian geometry, around the start point to a new northing and easting position that lies on the line of best fit closest to the measured horizontal position. The distance along the line to each point starting from the landward most point or defined station is then calculated. The resulting data are distance and elevation coordinates rectified to a common transect suitable for intercomparison. Elevation data are not changed and are relative to the 1988 North American Vertical Datum (NAVD88).

The beach profile surveys provide accurate data for determining the horizontal position of a vertical datum, in this case the 2-m contour (mllw). The measurement uncertainty in the horizontal location of a contour in this dataset is ±2 m. This uncertainty does not include natural short-term spatial and temporal variability in the beach profile. The total uncertainty of a vertical datum derived from beach profile data considering these factors is ±10-17 m (Ruggiero, Kaminsky, and Gelfenbaum 2002). In the present situation, the uncertainty is comparable to that of the AHWL positions derived from aerial photographs (previously discussed).

**South Beach profiles.** South Beach transects HD-1, Worm, and Spice were surveyed biannually starting in summer 1997 and quarterly since fall 1998. Transects SB1-8 were surveyed for the first time by the WDOE in December 2001. Figure 10 shows the rectified profiles at the HD-1, Worm, and Spice transects. Transects have been separated into winter and summer profiles. These profiles exhibit significant intra-annual variability seaward of the foredune, with erosion of the shore in winter months and accretion in summer.

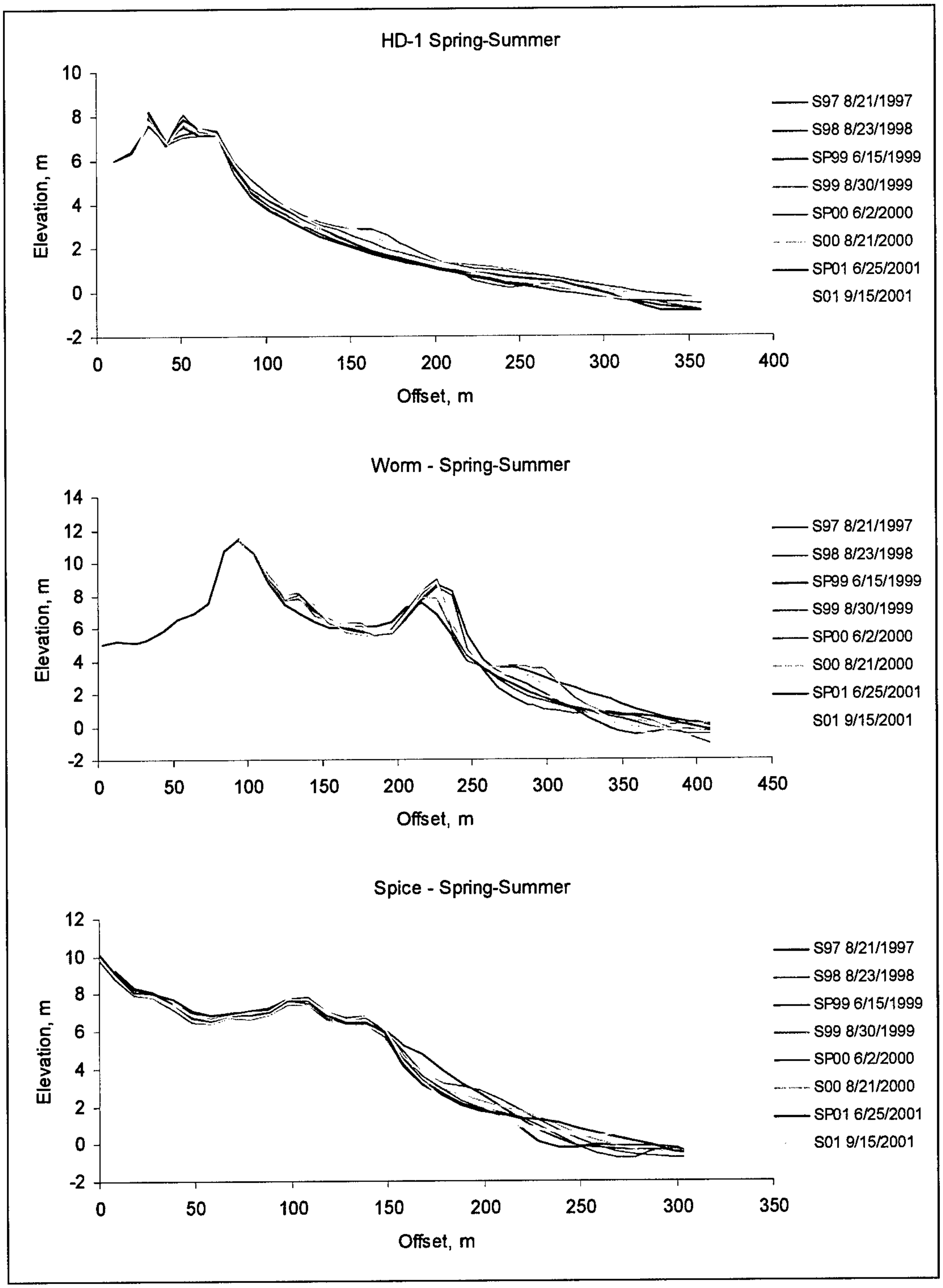



Figure 10. South Beach profiles (Continued)

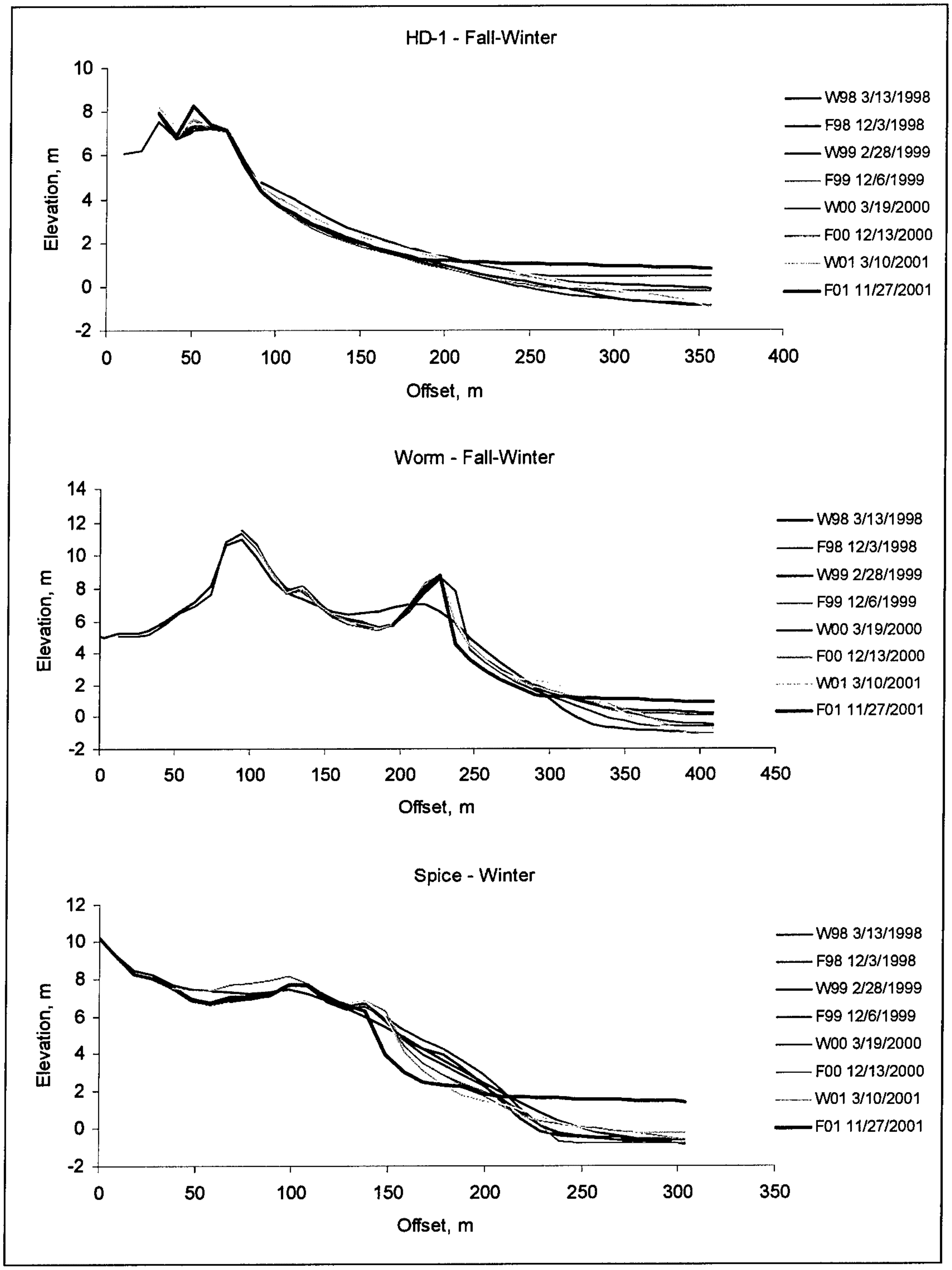



Figure 10. (Concluded)

The horizontal distances from the common starting point for each profile to the elevation of the 2-m contour is determined for each profile at Transects HD-1, Worm, and Spice on South Beach. A time series of the distance from the start point to the 2-m contour for each profile is plotted in Figure 11. The time series reveal that significant seasonal variation in the contour position occurs between 27 August 1997 and 27 November 2001 at Transects HD-1 and Worm. The variation consists of landward migration of the contour between summer 1998 and winter 1999 and seaward migration of the contour between winter 1999 and summer 2000. The variations at Spice are within the uncertainty of the data. The conclusion is that there is no significant net change in the position of the 2-m contour between 27 August 1997 and 11 November 2001 at any of the three profiles. The analysis only considers short-term seasonal and interannual variability; long-term trends may differ significantly from short-term trends.

**Half Moon Bay profiles.** Transects HMB1 to HMB10 were surveyed for the first time in December 2001 and resurveyed in April 2002. Transects HMB2 to HMB4 were resurveyed on 26 June 2002. During the April survey, a hydrographic survey system mounted on a personal watercraft and equipped with RTK GPS, echo sounder, and navigation software (Ruggiero and Voigt 2000) was operated to extend transects HMB1 to HMB10 from the intertidal areas across the nearshore. Figure 12 shows rectified profiles of Transects HMB1 to HMB10 in Half Moon Bay. Progressing eastward from the diffraction mound around Half Moon Bay, the beach elevation rises and steepens. The longshore trend in profile change suggests sediment is transported from west to east along the shoreline.

### Beach surface maps

The beach profile surveys provide the highest quality data for resolving the shore-normal variations in the upper beach profile at a single point in the alongshore direction. However, the profile data set for South Beach in the study area contain limited resolution of the spatial variation alongshore. To improve alongshore resolution and to account for more spatial variability alongshore, 3-D topographic surveys of the beach surface were analyzed.

The surface maps span the intertidal zone from the base of the primary dune to approximately mllw, and extend approximately 4,000 m along the South Beach shoreline from the south jetty. The surface maps show 3-D topography (northing, easting, elevation) in a portion of the study area. The area covered encompasses SB1 to SB8, HD-1, Worm, and Spice. Seven surface maps were surveyed biannually between 21 August 1997 and 25 September 2000. The beach was mapped by the WDOE using the CoastaL All-terrain Morphology Monitoring and Erosion Research vehicle (CLAMMER). The methodology is described in Ruggiero and Voigt (2000). Data points are spaced approximately 5-10 m apart. The horizontal and vertical uncertainty of each data point is ±0.1 m. The total uncertainty of a derived contour location (e.g., +2 m contour) is ±10-17 m, not including natural shoreline variability caused by changes in the beach morphology over days and weeks (Ruggiero, Kaminsky, and Gelfenbaum 2002).

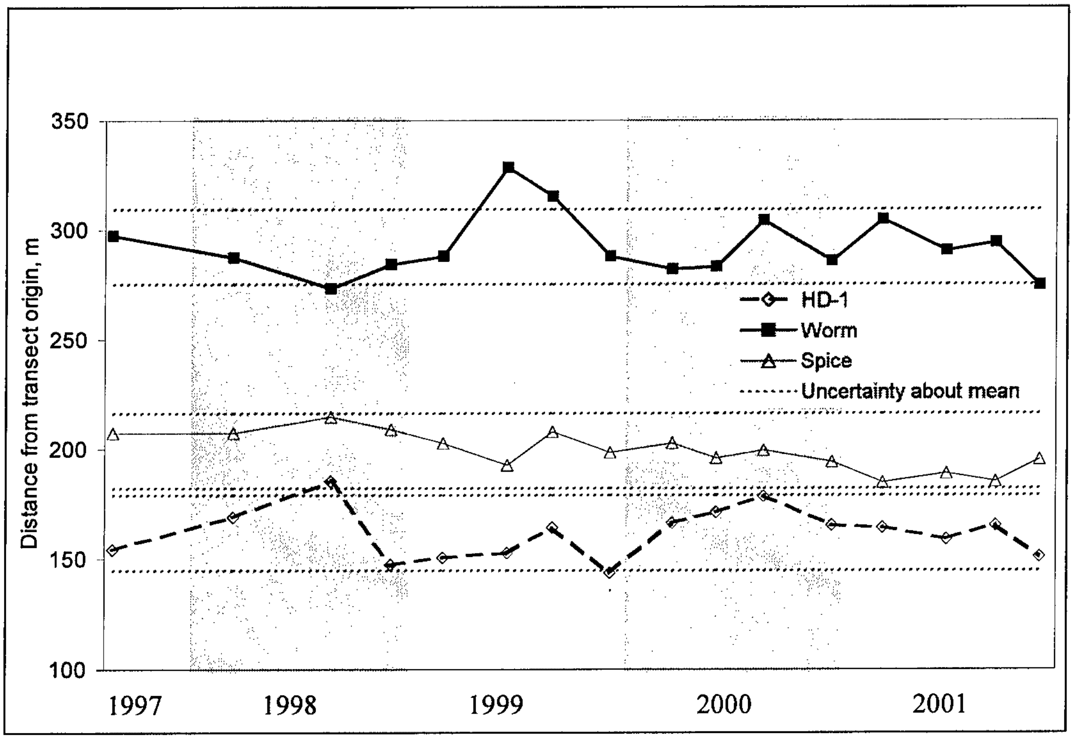



Figure 11. Temporal variation in horizontal position of 2-m contour

Each of the seven beach surface surveys was imported in easting-northing-elevation form into a gridding software program to enable interpolation of a surface map. An approximate shore parallel baseline was defined and 20 shore-normal transects are extracted from the surface maps at intervals of 200 m along the baseline. Shore-normal was determined by aligning transects perpendicular to a smoothed 2001 shoreline position measured from aerial photographs as previously described. This analysis enabled assessment of the spatial and short-term seasonal variability in erosion and accretion patterns in the study area. Figure 13 shows the contoured surface map surveyed on 25 September 2000 with the baseline and transects superimposed.

The net change in the horizontal position of the 1- and 2-m contours relative to the baseline is shown in Figure 14. Both contours exhibit net accretion of the foreshore at the north end of the beach near the south jetty and slight net erosion of the foreshore at the south end between 3 and 4 km from the jetty. Figure 15 shows the temporal variation in the alongshore-averaged position of the 1- and 2-m contours along the shoreline south of the south jetty between 1997 and 2000 derived from the surface maps. There is a distinct seasonal cycle in the 1- and 2-m contour positions but no significant trend over the period of observation. These results are consistent with the analysis of the beach profile Transects HD-1, Worm, and Spice over the same period of time.

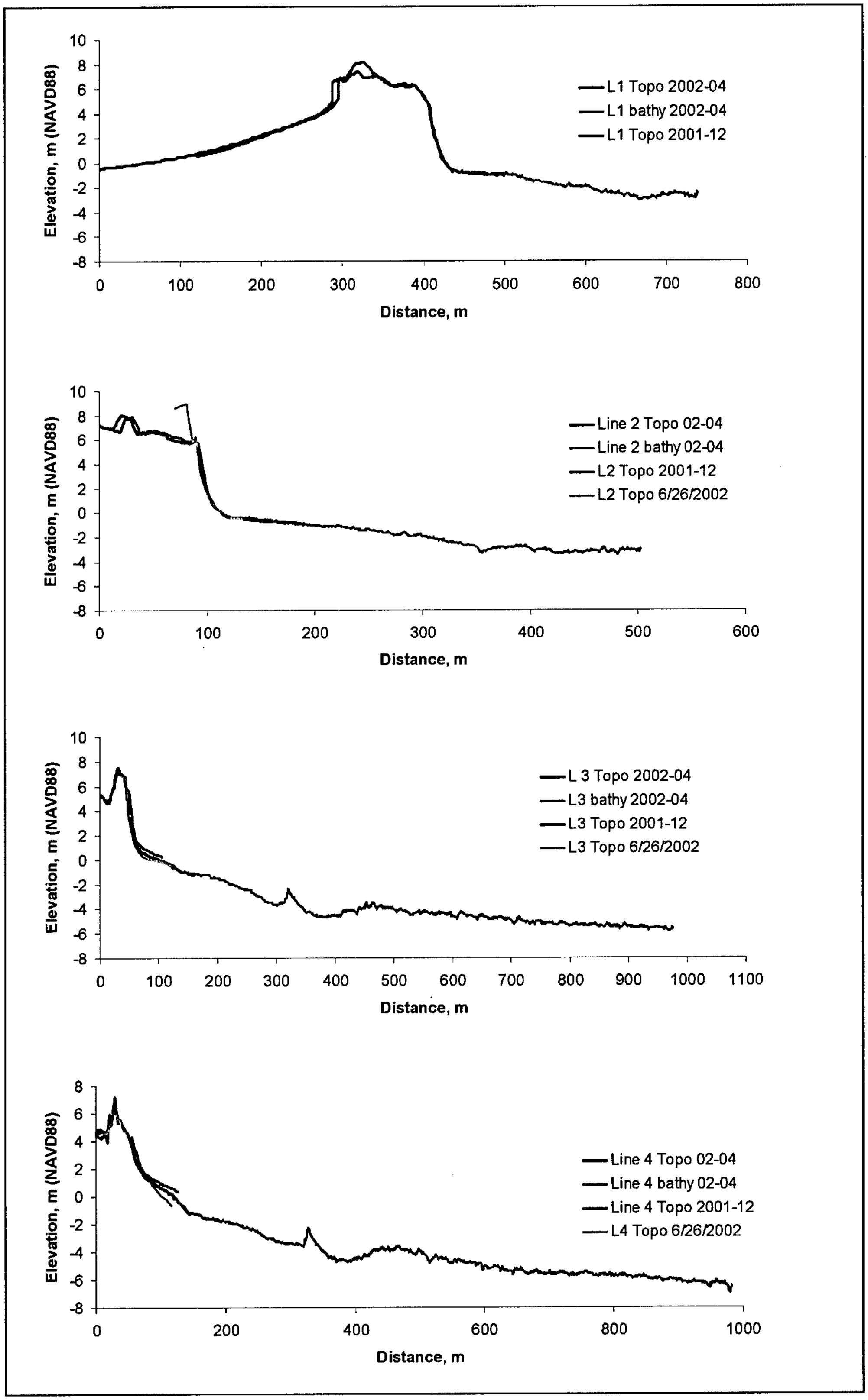



Figure 12. Half Moon Bay profiles (Sheet 1 of 3)

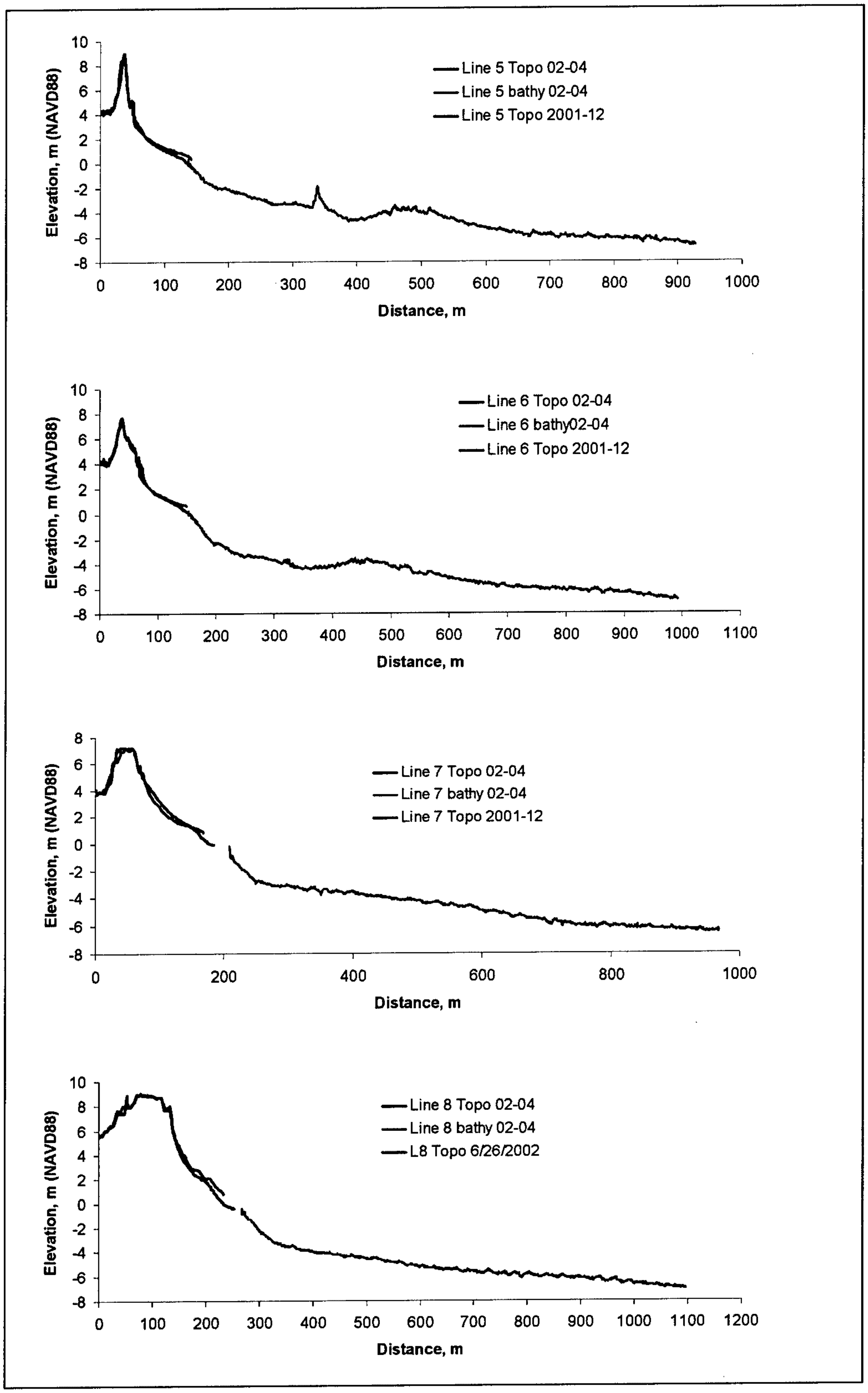
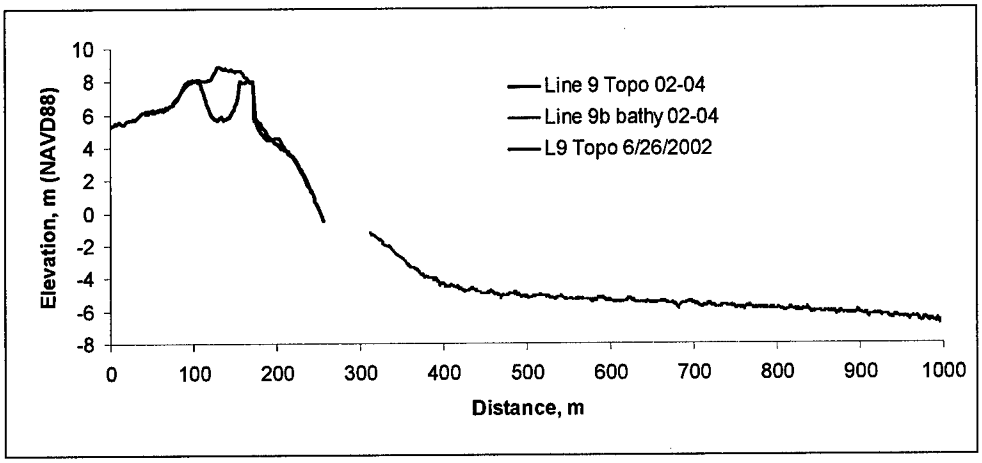



Figure 12. (Sheet 2 of 3)



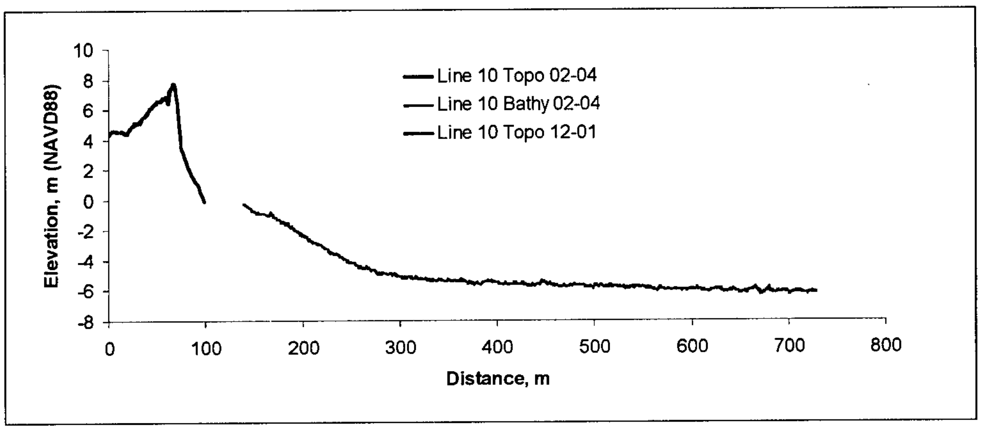




Figure 12. (Sheet 3 of 3)

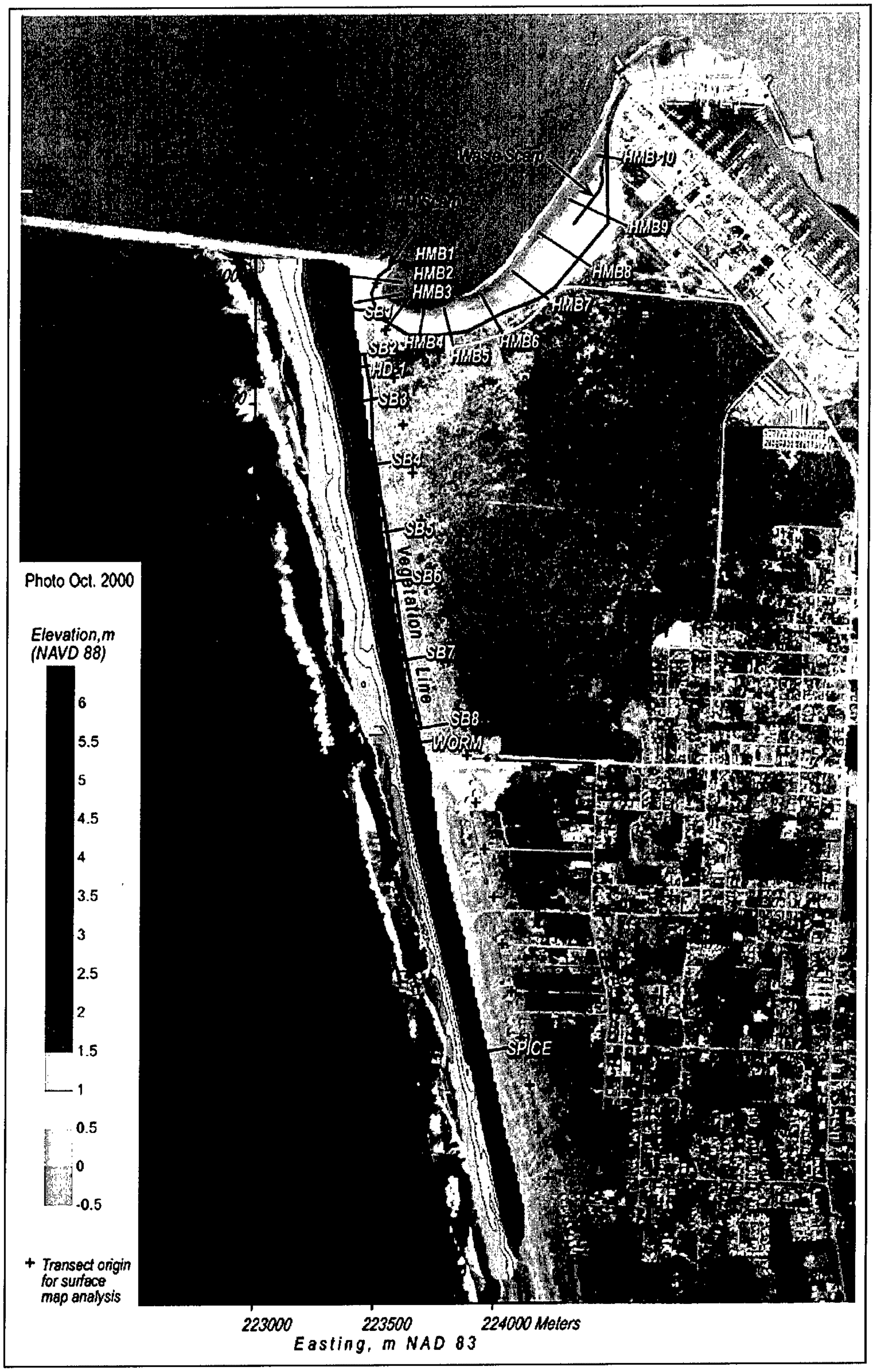



Figure 13. Surface map surveyed on 25 September 2000

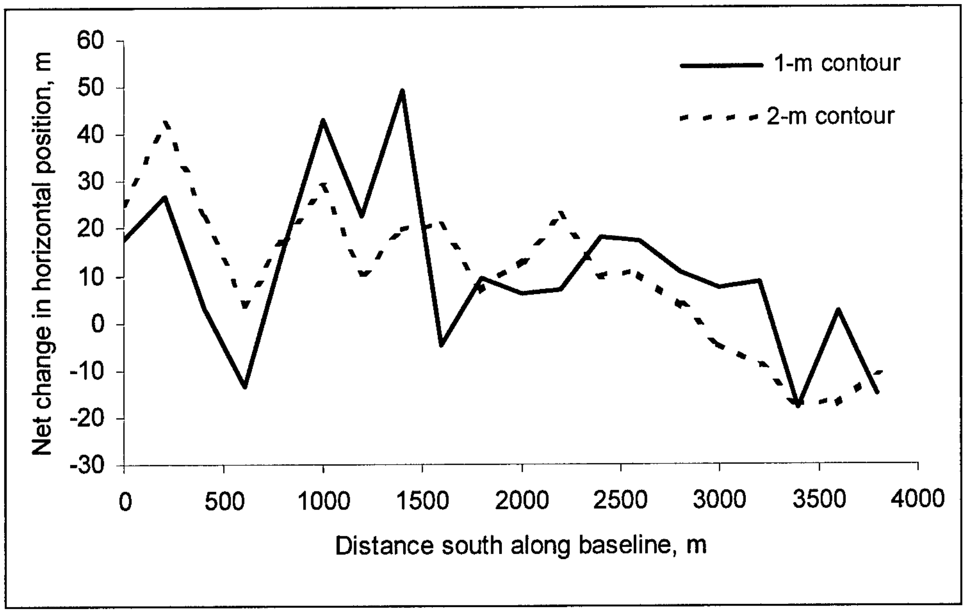



Figure 14. Net change in contour position south of south jetty between 21 August 1997 and 25 September 2000

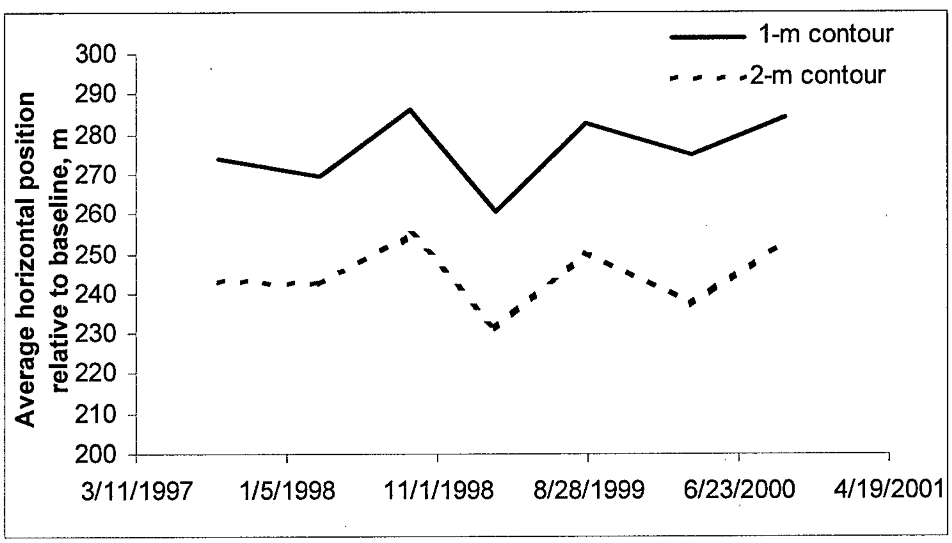



Figure 15. Alongshore-averaged horizontal position of South Beach contours

## Gravel transition in Half Moon Bay

Field observations and shoreline positions interpreted from aerial photographs reveal that the transition gravel was successful in stabilizing the shoreline in the location where it was placed. However, in the 2001-2002 winter, the sandy shoreline at the terminus of the gravel receded as much as 4 m. High waves occurred at times of high water early in the storm season, which is inferred to have been significant to the shoreline recession. Rain saturation and channelization of the fill upland of the shoreline is also thought to have been a factor, but the relative proportion of the causative agents in modifying the shoreline and beach profile shape is not known.

From December 2001 to January 2002, the transition gravel was extended eastward around the Half Moon Bay shoreline terminating between Transects HMB3 and HMB4 to stop shore erosion that was progressing towards the road that serves the State Park. A sustained period of strong rainfall and high waves in the winter of 2001-2002 deteriorated the breach fill and led to shoreline recession in the lee of the wave dissipation mound. An emergency fill was placed and the gravel transition zone was rehabilitated and extended.

Profiles measured in December 2001, April 2002, and June 2002 at Transects HMB2, HMB3, and HMB4 (see Figure 8 for location) are shown in Figure 16. Transects HMB2 and HMB3 are in the gravel transition zone and Transect HMB4 is just beyond the eastward limit of the extended gravel zone. Comparison of the June 2002 survey of Transect HMB2 with the previous surveys illustrates the amount of material placed in the breach fill area during the emergency repair in May 2002. Transect HMB2 shows a net horizontal recession of approximately 1.5 m between 2- and 6-m elevation with most of the erosion occurring between December and April. Transect HMB3 shows a net recession of up to 4 m and lowering of the profile at all elevations below 6 m. Transect HMB4 shows a net accretion of the profile above the elevation of 2 m between December 2001 and April 2002.

Figure 17 shows the reworked gravel embankment near Transect HMB3 on 14 January 2002. Figure 18 illustrates the gravel type and size relative to the 1-ft square in the photograph at approximately elevation 12 ft above mllw. Figure 19 illustrates the sediment sorting and mixing with sand at the surface of the profile at about elevation 5 ft above mllw. Figure 20 illustrates the sediment sorting with depth below surface at elevation approximately 3 ft above mllw. Sediment samples were taken in June 2002 for gradation analysis. Shore material gradation at Transects HMB2, HMB3, and HMB4 are listed in Table 7.

Beach profiles and median grain size in the gravel transition are responding to wave action. The profile change analysis shows that the profile adjustment is orderly around the Half Moon Bay shoreline. Changes that have occurred at Transect HMB4 suggest that the beach at that location is receiving sediment from updrift (Transects HMB2 and HMB3) to the west. The back beach is currently at the natural angle of repose for the sediment and, therefore, not at a long-term equilibrium position. At lower elevations on the beach profile, the gravel-sand mix results in a lower beach slope. Higher on the beach profile, there is a higher proportion of gravel, and the beach steepens. A longer series of observations is required to more fully evaluate the gravel transition performance.

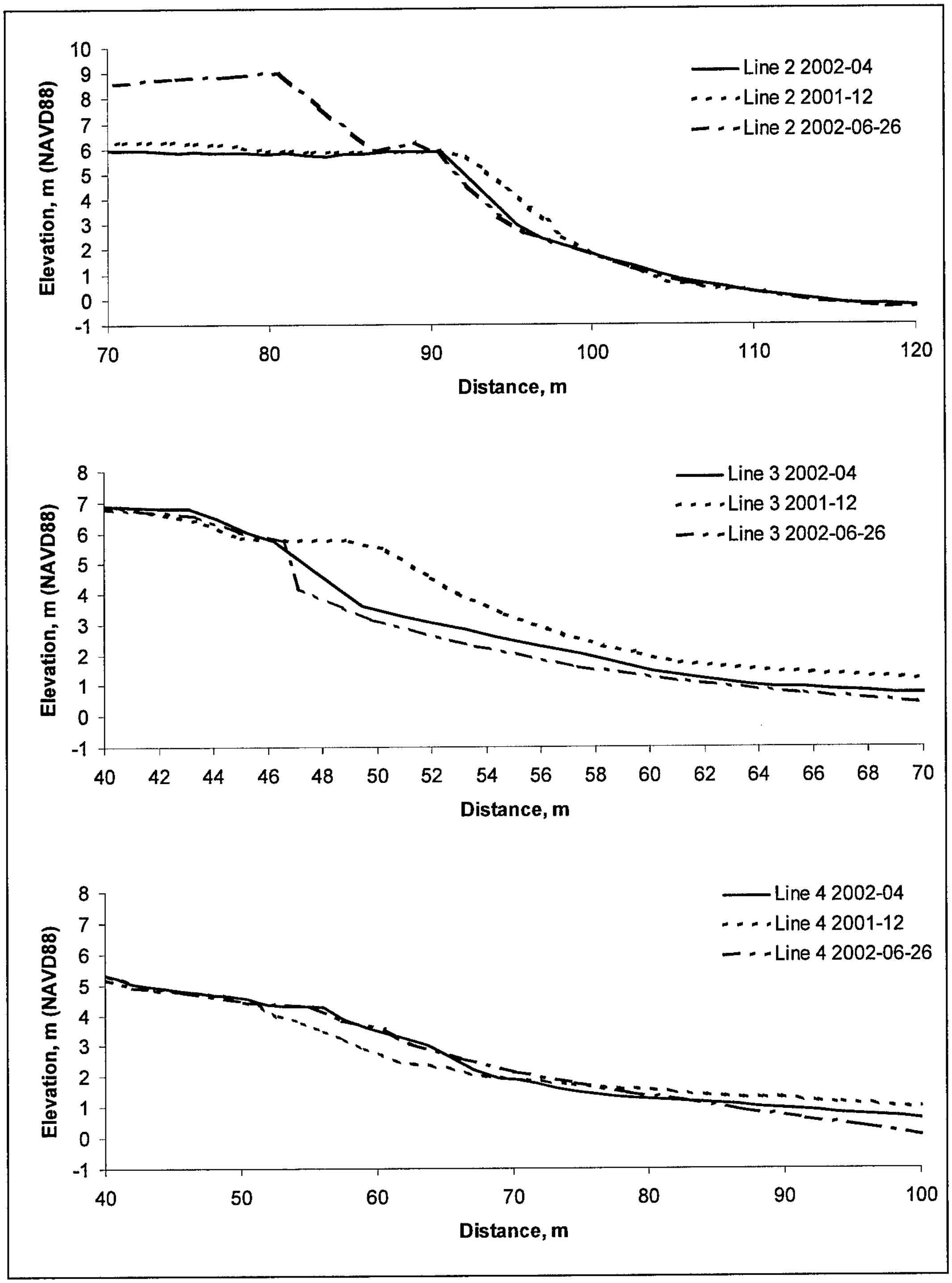



Figure 16. Profiles at Transects HMB2, HMB3 in gravel transition and Transect HMB4 east of transition

Figure 17. Gravel embankment at Transect HMB3, 14 January 2002

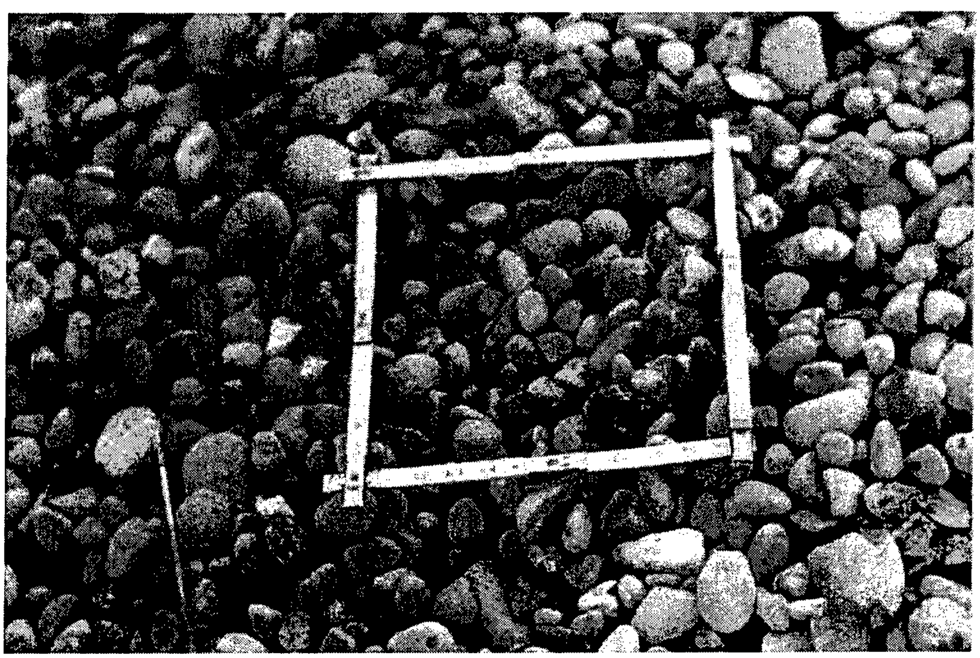


Figure 18. Transition gravel near el 12 ft above mllw, Transect HMB3, 14 January 2002

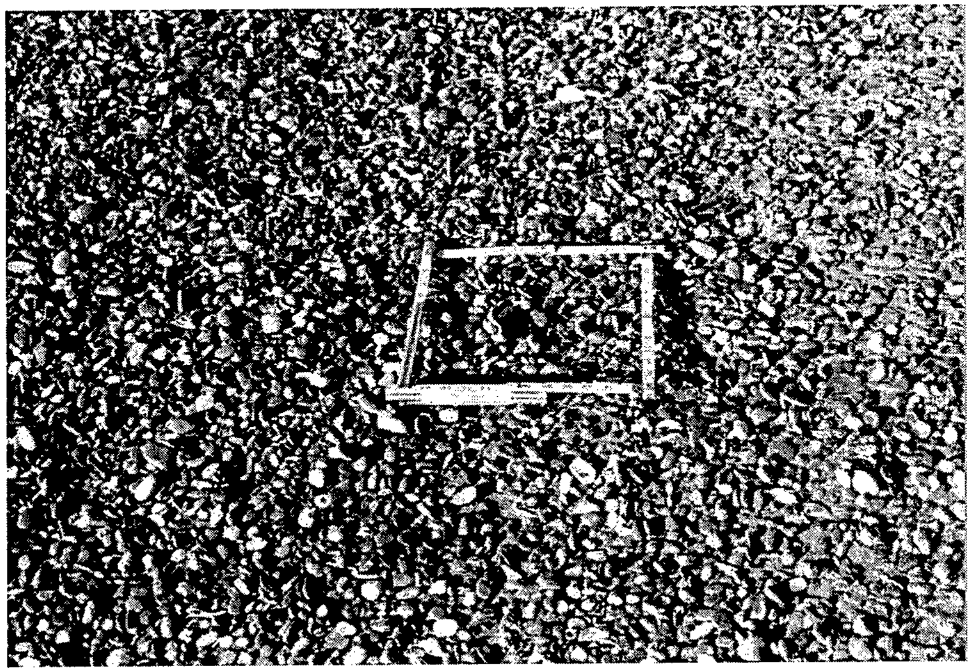


Figure 19. Transition gravel mixed with beach sand on lower profile, Transect HMB3, 14 January 2002


Figure 20. Transition gravel sorting on lower profile, 26 June 2002

**Table 7**
**Gradation of Shore Material in Western End of Half Moon Bay**

| Transect | Source | Elevation (ft) | Gravel (%) | Sand (%) | Fines (%) |
|---|---|---|---|---|---|
| 2 | Surface | 3 | 33.9 | 65.9 | 0.2 |
| 2 | Subsurface | 3 | 21.4 | 77.8 | 0.8 |
| 3 | Surface | 3 | 5.2 | 93.3 | 1.5 |
| 3 | Subsurface | 3 | 0.2 | 98.8 | 1 |
| 4 | Surface | 3 | 13.1 | 86.6 | 0.3 |
| 4 | Subsurface | 3 | 2.4 | 97.1 | 0.5 |
| Note: Date of sampling is 26 June 2002. | | | | | |

# Point Chehalis Revetment Fill

This section documents the analysis of the revetment fill at Point Chehalis and evaluates the performance of the fill in terms of its lifespan relative to estimations and reduction of shoreline recession in Half Moon Bay. The Point Chehalis revetment extension and fill was constructed from November 1998 to March 1999 and the Point Chehalis Revetment Extension Project, Interagency Mitigation Agreement with a plan dated 7 October 1998 authorizes periodic renourishment. The analysis includes comparison of repetitive beach profiles and shoreline position time series derived from aerial photographs for the South Beach and Half Moon Bay shorelines.

## Shoreline change analysis

Figure 9b shows the shoreline position changes in the revetment fill area. Overall, the shoreline in this area has advanced between 1996 and 2002. Some of the shoreline response can be attributed to construction of the Point Chehalis revetment extension and fill placement in 1998-1999, and again in 2002. Evolution of this portion of the shoreline can be analyzed with surveys dated only after construction was complete (March 1999).

## Beach profile change

Figure 21 shows profiles at Transects HMB7 to HMB9 in December 2001 and April 2002 in the revetment fill section of the beach. Figure 12 shows the complete profile including bathymetry. All of the profiles have a steep scarp between elevations of +4 and +8 m, NAVD88. At the eastern end (Transect HMB9), the beach has a steep (1V:13H) slightly convex upwards foreshore that transitions to a broad gently sloping shelf (1V:240H) at approximately elevation -4 m, NAVD88 and extends at least 600 m seaward. To the south and west, the profiles at HMB8 and HMB9 become progressively more smoothly varying and concave upwards, and the scarp is less developed.

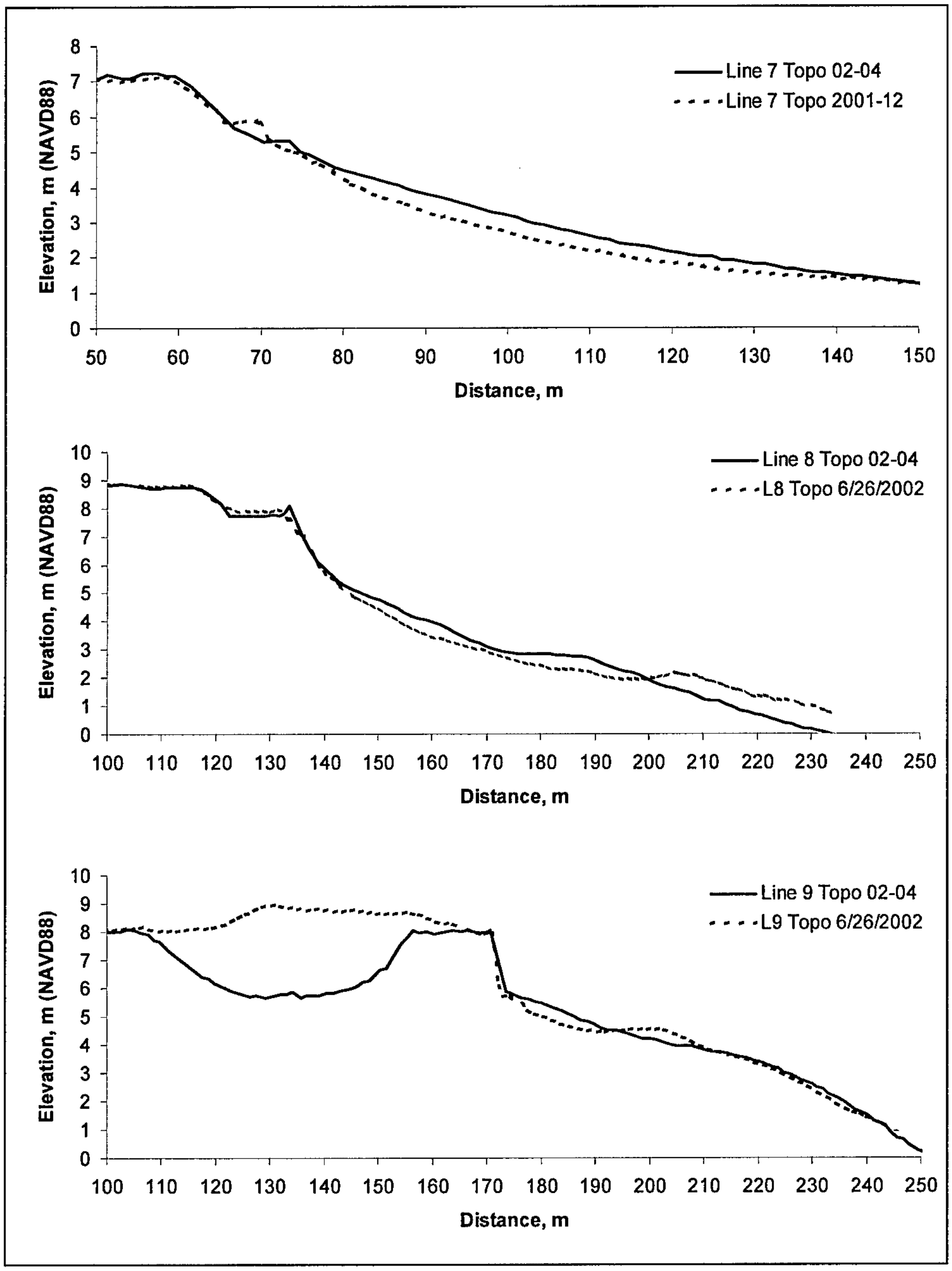



Figure 21. Beach profiles at Transects HMB7-9 above 0 m elevation

The interpretation from this pattern of profile shapes is that the shallow submerged zone at the eastern end of Half Moon Bay is a depositional area, at least temporarily, for sediments moving alongshore from the western end of the bay. The steep scarp in the upper profile indicates the sand placed seaward of the revetment in 1999 is being redistributed in response to wave attack and transport by the wave-induced and tidal currents. During periods of constructive waves, sand on the shallow shelf likely moves onshore to raise the beach elevation. Following winter storms, the beach has been observed to be lower than in summer and it is interpreted that sand from the scarp face is redistributed to create a more stable slope in the wave environment. The scarped appearance of the sand fill and the measured slope of the profile indicate this adjustment is continuing.

## Diffraction Mound

This section documents the analysis of the wave diffraction mound constructed to terminate the inner end of the south jetty and evaluates its performance for reducing erosion on the adjacent Half Moon Bay shoreline. The advantageous property of a wave diffraction mound structure is that it can modify the wave approach angle along the shore and reduce or spread wave energy. The ideal mound performance is creation of wave approach angles and heights along the shore that produce a longshore transport rate matching the imposed sediment load. In the case of minor or no sediment input to the Half Moon Bay system, the ideal wave direction would be normal to shore at all locations. Normal wave incidence would be indicative of a shoreline that is in equilibrium, i.e., a shoreline that is neither receding nor advancing under the prevailing wave exposure. Such an equilibrium shape implies that longshore transport dominates cross-shore transport of sediment and that there are no permanent losses of sediment resulting from cross-shore transport processes. At Half Moon Bay, it is possible that sediment may be carried offshore from the erosion scarp during times of large waves and high water levels by cross-shore processes such as undertow and rips and lost from the system once it is captured by the ebb-tidal stream.

In November 1998, the Seattle District requested investigators at CHL to conduct "fast-track" physical model tests of a proposed wave diffraction mound and modifications to the south jetty. The diffraction mound concept was being investigated by the Coastal Inlets Research Program (CIRP) as a means of reducing bank erosion that commonly occurs at the landward ends of jetties (Seabergh 2001). The Seattle District study was to take advantage of the existing base jetty configuration and capabilities of the CIRP physical model facility (Seabergh 1999b) to investigate proposed modifications at the Grays Harbor south jetty. Tests were conducted according to Seattle District specifications for two design wave conditions: moderate waves with a height $H$ of 5 ft and a period $T$ of 10 sec and storm waves with $H = 10$ ft and $T = 13$ sec. Tests were run at two tide elevations, +8 ft mllw, representing mean high water elevation, and +12 ft mllw representing a high-tide storm condition. The waves were monochromatic. The physical model showed that the mound turned the wave crests such that they approached more perpendicularly to the shore of Half Moon Bay.

The diffraction mound was then constructed from December 1999 to February 2000. The core of the diffraction mound was placed at a 1 vertical on 3 horizontal (1V:3H) slope. The core was constructed of approximately 1,500 tons of jetty rock removed from the eastern 250 ft of the existing south jetty. The outer layer of the diffraction mound was constructed with 30,000 tons of rock ranging in size from 100 to 10,000 lbs with side slopes ranging from 1V:5H to

1V:10H on the north side, and from 1V:7H to 1V:10H on the south side. The exposed northern face of the mound was constructed with 300 to 10,000 lb graded riprap and the southern face was constructed with 100 to 1,000 lb quarry spalls. The maximum elevation of the diffraction mound was approximately +17 ft mllw. Construction of the south jetty mound included removal of existing jetty rock over the eastern 250 ft of the jetty. This jetty remnant top elevation of +8 ft mllw was lowered to about +2 ft mllw during construction. However, the preceding physical model was configured such that the eastern remnant of the existing jetty was completely removed.

Questions arose as to the validity of the physical model results because the configuration tested did not include the jetty remnant. The following section describes application of the numerical Coastal Gravity Wave Model (CGWAVE) (Demirbilek, Xu, and Panchang 1996; Demirbilek and Panchang 1998; Panchang, Xu, and Demirbilek 1999; Panchang and Demirbilek 2001) to evaluate the performance of the constructed mound with the jetty remnant in place and compares the results to the design modeled in the laboratory.

### Numerical model calibration and setup

The goals of the numerical study were to replicate the earlier physical model laboratory experiments and to evaluate the functioning on shoreline position of an eastward-extending remnant of the jetty rubble-mound base. The numerical model was first calibrated to reproduce the physical model results. The incident monochromatic waves of $H = 10$ ft and $T = 13$ sec were tested at two water levels, +8 and +12 ft mllw, as was done in the laboratory. Predicted wave height information was extracted at eight output grid points in the numerical model called gauge locations for comparison to the physical model data. The gauge locations are shown in Figure 22. With the exception of Gauge 1, numerical model calculations compare well with the physical model data (Figure 23). Gauge 1 was located near a rigid boundary in the physical model study. The difference between the numerical model calculations and the laboratory measurements at Gauge 1 is attributed to wave reflection. Because the numerical model calculated satisfactory results for the primary area of interest, it was not recalibrated to improve results near the boundary.

Once the physical model results were replicated, the bathymetry in the numerical model was modified to represent the constructed configuration. The bathymetry included the top of rock elevation at +2 ft mllw at the east end of the diffraction mound to represent the jetty remnant. Incident monochromatic waves were prescribed along the open boundary of the model. Tests were run at two tide elevations, +8 ft mllw and +12 ft mllw. Storm waves recorded by the Grays Harbor buoy during storms of 2001-2002, when the Half Moon Bay shoreline receded, led to selection of different wave periods for simulating prototype performance. For the +8 ft mllw water level, an incident wave of $H = 8.5$ ft and $T = 13$ sec was simulated. The storm condition was simulated with an $H$=10 ft and $T$=18 sec wave.

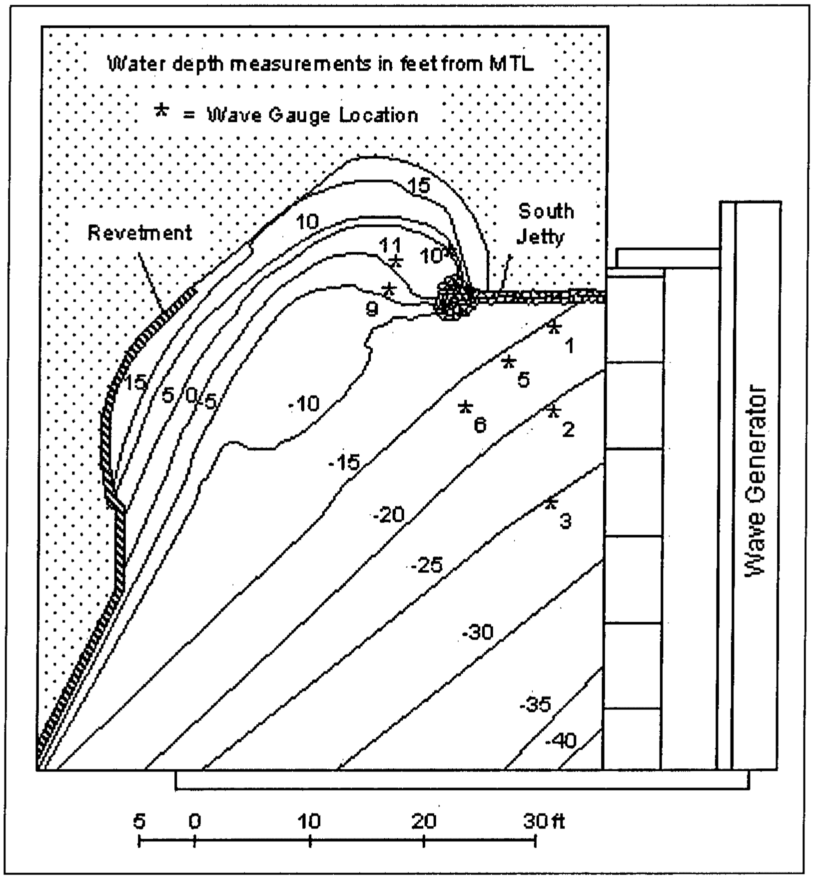



Figure 22. Physical model gauge locations model comparison

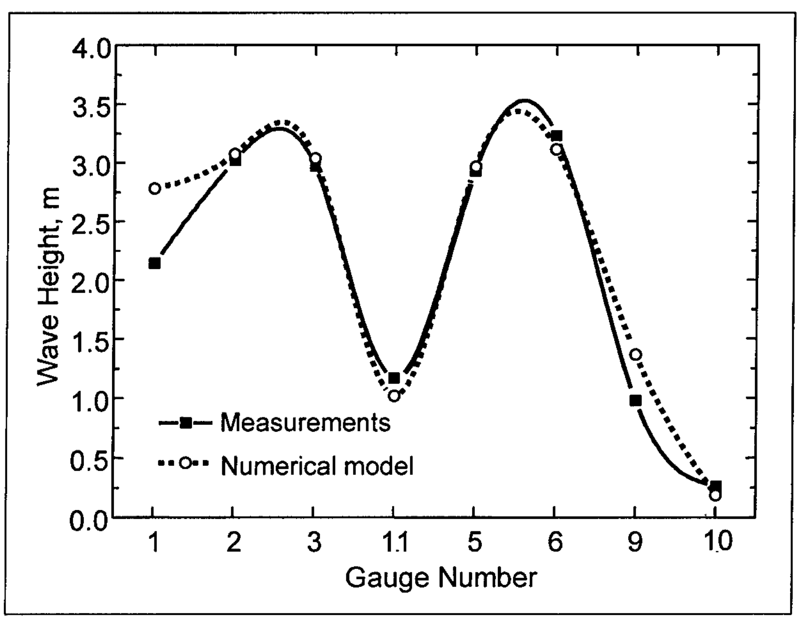



Figure 23. Comparison of physical model data and numerical model results for $H$ = 10 ft, $T$ = 13 sec wave, water surface at +8 ft mllw

## Numerical model results

The calibrated model results show that waves wrap around the structure, becoming nearly normal to the Half Moon Bay shoreline in the lee of the rubble mound (Figures 24 to 26). As waves propagate along the shore away from the shadow region of the mound and down the curved shore of Half Moon Bay, wave fronts approach the shore at changing bearings. The calculated diffraction patterns are similar for all tests. At the +8 ft mllw water level, the simulation with the remnant structure shows the waves approach the shoreline more perpendicular than they do without the remnant. The remnant structure has little or no effect on wave direction for the +12 ft mllw simulation.

Whether the beach at Half Moon Bay erodes or accretes will depend on the combinations of wave height and direction, dependent in part on water level. The predicted average wave heights along various transects across Half Moon Bay and along its shoreline are given in Table 8. The transects are defined in Figure 27. Overall, there is little change in wave height between the with- and without-jetty remnant simulations for both the +8 ft mllw and the +12 ft mllw tests. Wave heights along the Half Moon Bay shoreline change by less than 0.4 ft for large inner harbor waves. The numerical model calculations indicate that the remnant structure has not adversely altered the functioning of the wave diffraction mound.

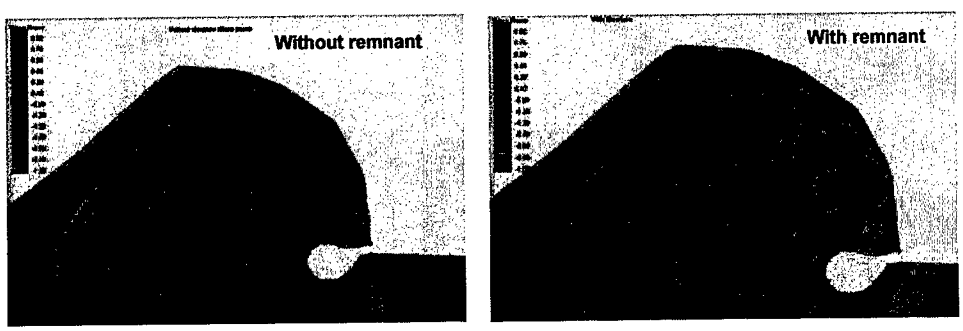



Figure 24. Wave phase, indicative of wave crest and trough direction, for $H$ = 8.5 ft, $T$ = 13 sec wave, water surface at +8 ft mllw

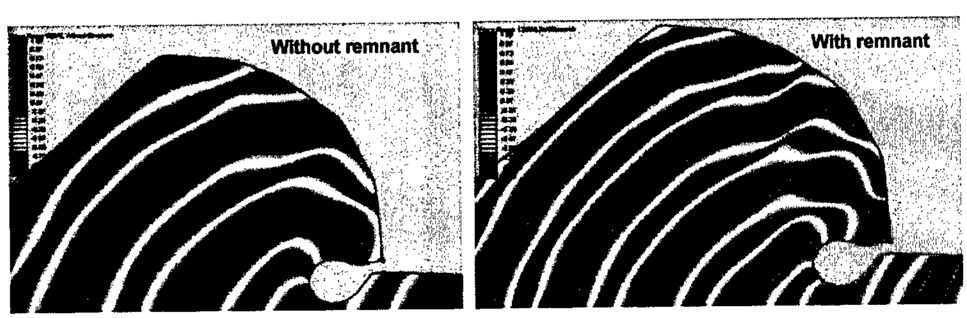
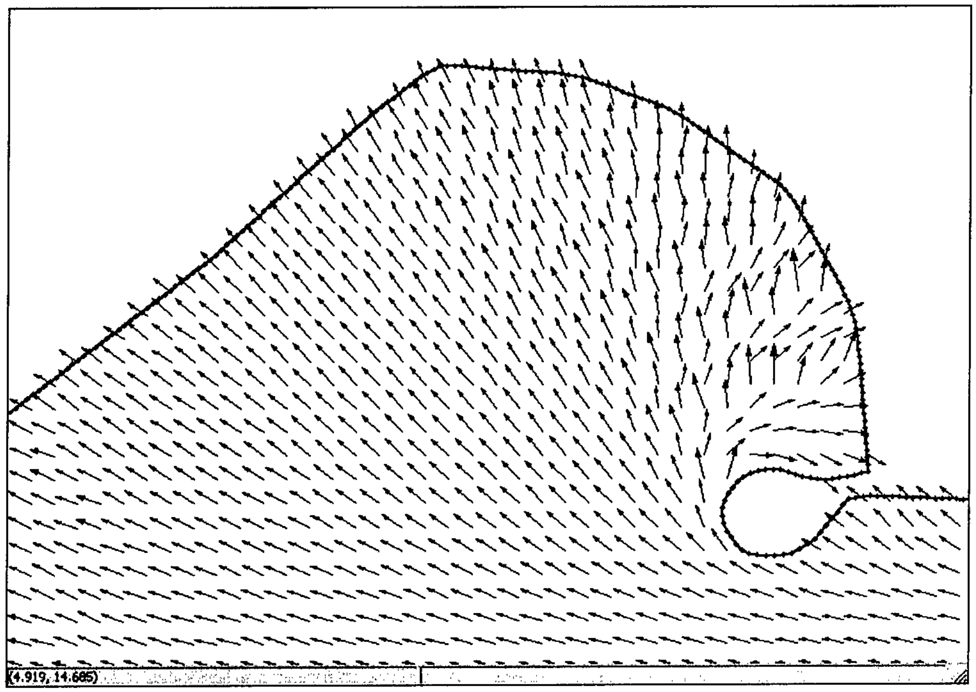
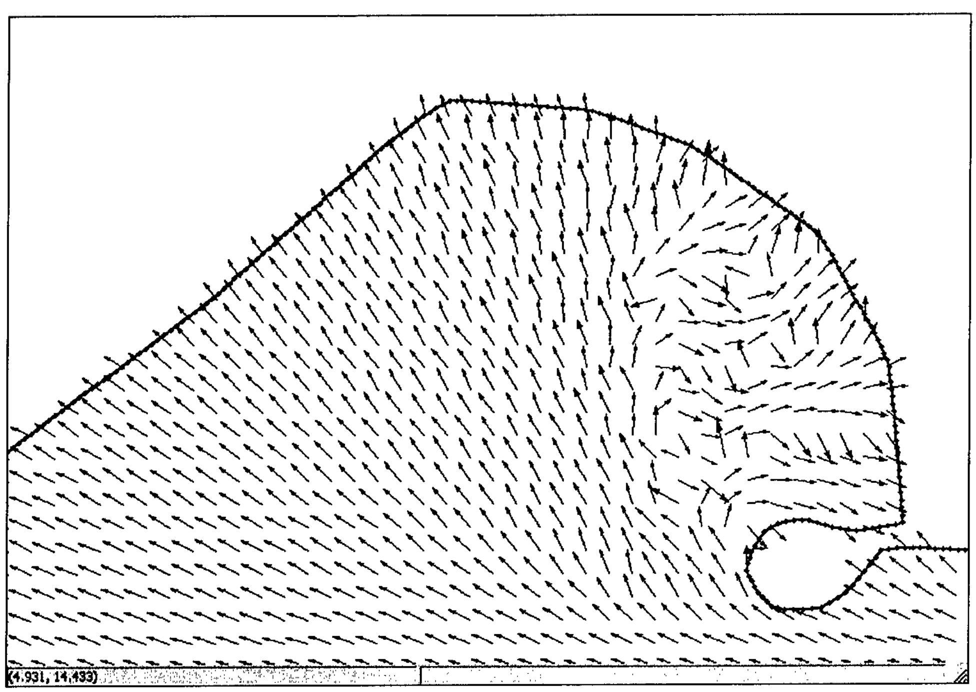



Figure 25. Wave phase, indicative of wave crest and trough direction, for $H$ = 10 ft, $T$ = 18 sec wave, water surface at +12 ft mllw

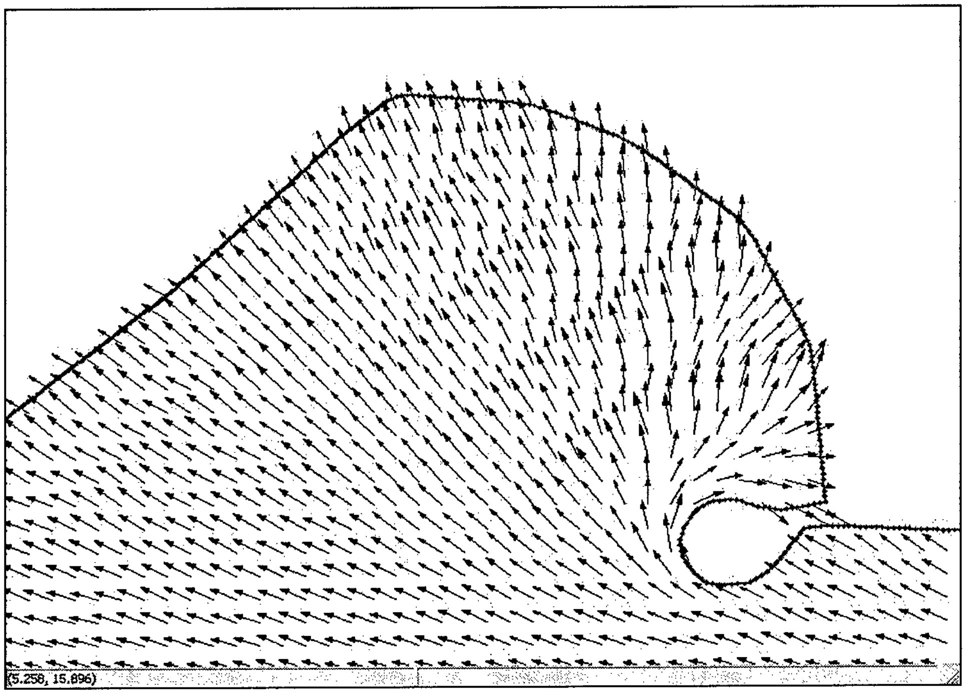



a. No rock, +8 ft wl, 8.5 ft, 13 sec wave

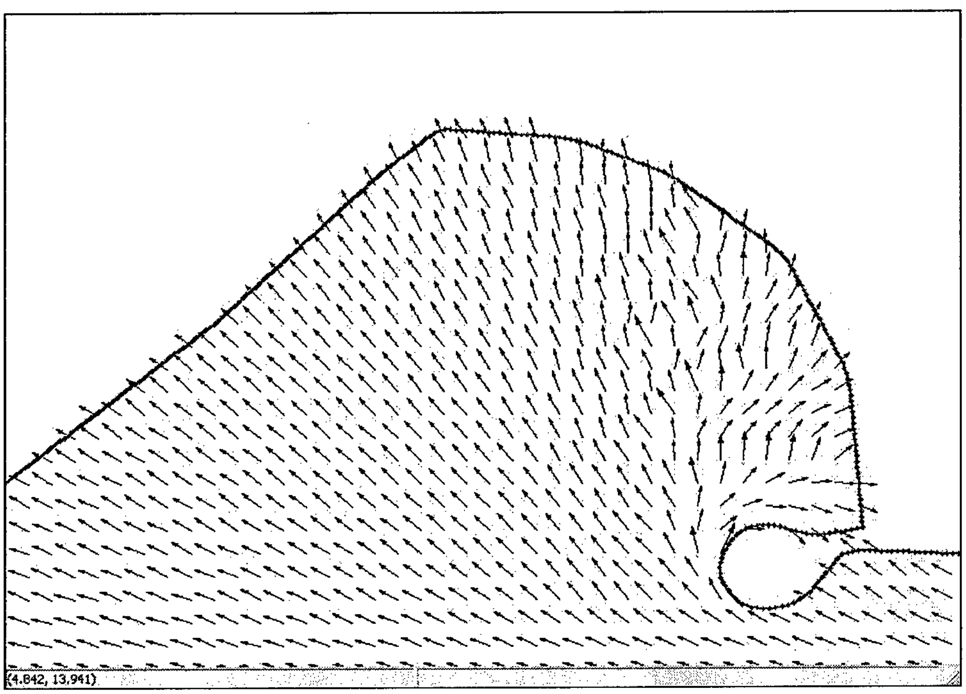



b. +2 ft rock, +8 ft wl, 8.5 ft, 13 sec wave

Figure 26. Wave direction vectors (continued)




c. No rock, +12 ft wl, 10 ft, 18 sec wave




d. +2 ft rock, +12 ft wl, 10 ft, 18 sec wave

Figure 26. (Concluded)

**Table 8**
**Numerical Simulation Average Wave Heights, m**

| Transect | +8-ft Water Level | | +12-ft Water Level | |
|---|---|---|---|---|
| | Without Remnant | With Remnant | Without Remnant | With Remnant |
| T1 | 0.13 | 0.18 | 0.19 | 0.18 |
| T2 | 0.14 | 0.17 | 0.26 | 0.19 |
| T3 | 0.23 | 0.18 | 0.35 | 0.29 |
| T4 | 0.48 | 0.46 | 0.55 | 0.58 |
| T5a-T5f | 0.18 | 0.21 | 0.25 | 0.24 |
| T5a | 0.11 | 0.17 | 0.15 | 0.15 |
| T5b | 0.12 | 0.18 | 0.19 | 0.15 |
| T5c | 0.09 | 0.14 | 0.19 | 0.12 |
| T5d | 0.17 | 0.09 | 0.22 | 0.13 |
| T5e | 0.21 | 0.19 | 0.30 | 0.29 |
| T5f | 0.40 | 0.51 | 0.45 | 0.56 |

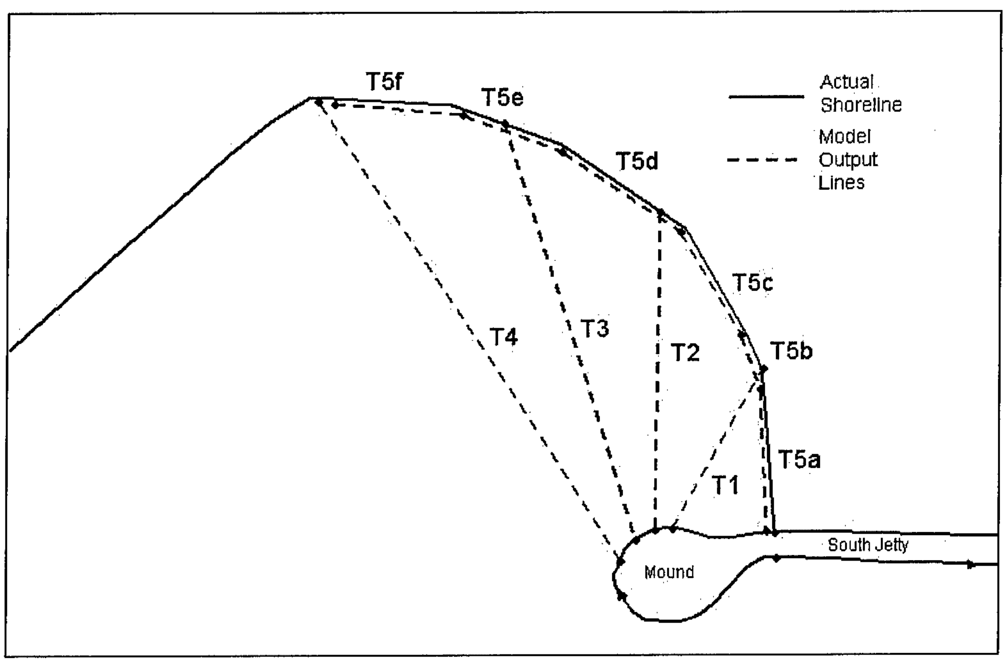



Figure 27. Transect locations

## Summary

Data from maintenance dredging reports and dredging contract documentation for the period 1991 to 2001 were analyzed to identify patterns in sediment distribution along channel reaches. The data reveal no significant temporal trends because the dredging volumes of a particular incorporate reflect not only channel infill, but also, dredge availability, weather, funding, scheduling, and other factors. Significant spatial variability is evident in the long-term average data. Most sediment from the Bar Channel is dredged near the eastern end of the bar reach, whereas the majority of sediment dredged from Entrance and Point Chehalis reach is taken from the dogleg section adjacent to Half Moon Bay. The estimated volume of sand material dredged from the channel between 1991 and 2001 is approximately 1.1 million cu yd/year (Table 5). This estimate assumes that 50 percent of the dredged material from Crossover Channel is sand and that only silt material (no sand) is dredged in the north channel.

Dredged material from the channels was disposed at six different sites in the bay and at the open ocean. Currently, the Seattle District uses disposal sites at Point Chehalis, Half Moon Bay, South Beach, the south jetty, and the southwest site (Figure 6). Selection of specific disposal sites for the dredged material disposal is controlled by economic and environmental considerations, and attempt to maximize a beneficial use of dredged material for habitat enhancement and beach restoration. For example, sites in Half Moon Bay and Point Chehalis are designated for the disposal of dredged material that benefits beach nourishment and shore protection at Point Chehalis and Half Moon Bay. The amount of dredged material placed at the site is controlled by water depth that allows a hopper dredge safe maneuvering during disposal operations. Sites in Half Moon Bay receive dredged material predominately from South Reach, Point Chehalis, and the entrance channel, characterized by sand material typical of Half Moon Bay beach material, whereas the sediment dredged from upper reaches of the navigation channel containing higher percentages of silty material are disposed in Point Chehalis and south jetty disposal sites. Maintenance dredging and disposal volumes are included in the sediment budget analysis presented in Chapter 4.

The performance of the nourishment, restoration, and transition gravel needs to be considered in terms of life span of the fill relative to predicted life and contribution to reduction of shoreline recession in Half Moon Bay. The fill was originally expected to be effective in protecting the project for 5 to 10 years. During the seventh winter that the fill was in place (2001-2002), a series of storms damaged the fill placed at South Beach and modified the Half Moon Bay shoreline. Since then, the gravel transition placed as part of the mound construction has been extended eastward.

Field observations since the time of diffraction mound construction in early 2000 and shoreline positions interpreted from aerial photographs reveal that the transition gravel has been successful in reducing shoreline recession in the location where it was placed. The beach profiles and analysis of sediment size characteristics reveal that the beach is still adjusting to wave attack. Shoreline position data derived from aerial photographs show a pattern of net shoreline recession at the western end of Half Moon Bay and shoreline advance at the east end. The longshore trend in profile change in Half Moon Bay suggests sediment is transported from west to east along the shoreline. No significant net change in the position of the 2-m contour was observed between 27 August 1997 and 11 November 2001 at any of the three profiles. The data set is not of sufficient length to discern long-term trends greater than approximately 5-7 years.

The primary function of the wave diffraction mound is to modify the wave approach angle along the shore and reduce or spread wave energy. The physical model demonstrated that waves wrap around the rubble-mound structure such that they arrive at the Half Moon Bay shoreline more perpendicular than they do without the rubble mound. The numerical model was calibrated to reproduce the physical model results and then applied to simulate the rubble mound as it was constructed with the jetty remnant extending east from the rubble mound. The numerical model results show that waves approach the shoreline similar to or at a more perpendicular angle with the jetty remnant in place. Wave heights along the Half Moon Bay shoreline change by less than 0.4 ft for large inner harbor waves. The rubble mound appears to be functioning as designed and the remnant structure has not adversely affected the functioning of the wave diffraction mound.

A longer period of monitoring is required at South Beach and Half Moon Bay to fully evaluate the performance of the engineering measures so that seasonal and longer-term cyclic variations can be distinguished from erosion and accretion trends associated with sediment supply.

# 4 Sediment Budget

## Introduction

This chapter documents a sediment budget analysis for Half Moon Bay and the adjacent inlet to a few hundred meters north of the navigation channel including Entrance Reach and Point Chehalis Reach. A sediment budget provides a framework for integrating a conceptual understanding of coastal processes with a quantitative assessment of net sediment volume changes derived from analysis of morphological survey data. Understanding the sediment transport patterns and morphodynamics in and around Half Moon Bay is necessary for identifying an appropriate dredging and disposal management strategy and for determining the effectiveness of the engineering facilities near the south jetty. The task of developing a sediment budget involves the identification of sediment transport pathways in the study area, morphological change analysis based upon available survey data for the period and region of interest, and the integration of these data in the analysis.

## Sediment Transport Paths

Sediment pathways are defined based on a conceptual understanding of coastal processes developed from analysis of field measurements and numerical simulation of waves, tides, currents, and sediment transport. Field measurements of directional waves, currents, and suspended sediments in the southern half of the inlet in 1999 and from Half Moon Bay 2002 are analyzed to gain insights regarding current patterns and the interaction of waves and currents in driving sediment transport. These measurements form part of a series of deployments covering a wide area in Grays Harbor that have been used to verify and enhance the predictive numerical simulation tools developed for Grays Harbor.

Numerical simulation of circulation by combined waves and currents is accomplished with the Steady-State Spectral Wave Model (STWAVE) and the Advanced Circulation Model (ADCIRC) run within a steering module (Cialone et al. 2002). The simulated currents are coupled with a Lagrangian sediment transport model (Davies, Serrer, and Watson 2000) to identify sediment mobility and particle paths for Half Moon Bay and the southern half of the inlet between Point Chehalis and the south jetty.

## Analysis of 1999 and 2002 field measurements

Between September and November 1999, eight instrumented tripods were deployed in the inlet entrance region of Grays Harbor. The tripod referred to as sta 5 was located in the outer Half Moon Bay area in approximately 9.5-m depth mllw (inset B, Figure 28). Directional wave gauges were installed at three locations in Half Moon Bay from 3 March to 29 April 2002 to document the directional wave field in Half Moon Bay and incident to the shoreline at the Point Chehalis beach fill. The pressure sensor on Gauge HMB3 did not function correctly, and Gauge HMB2 was not recovered, being lost in severe wave conditions. Therefore, wave data are available from Gauge HMB1, and near-bottom currents are available from sta 5, HMB1 and HMB3.

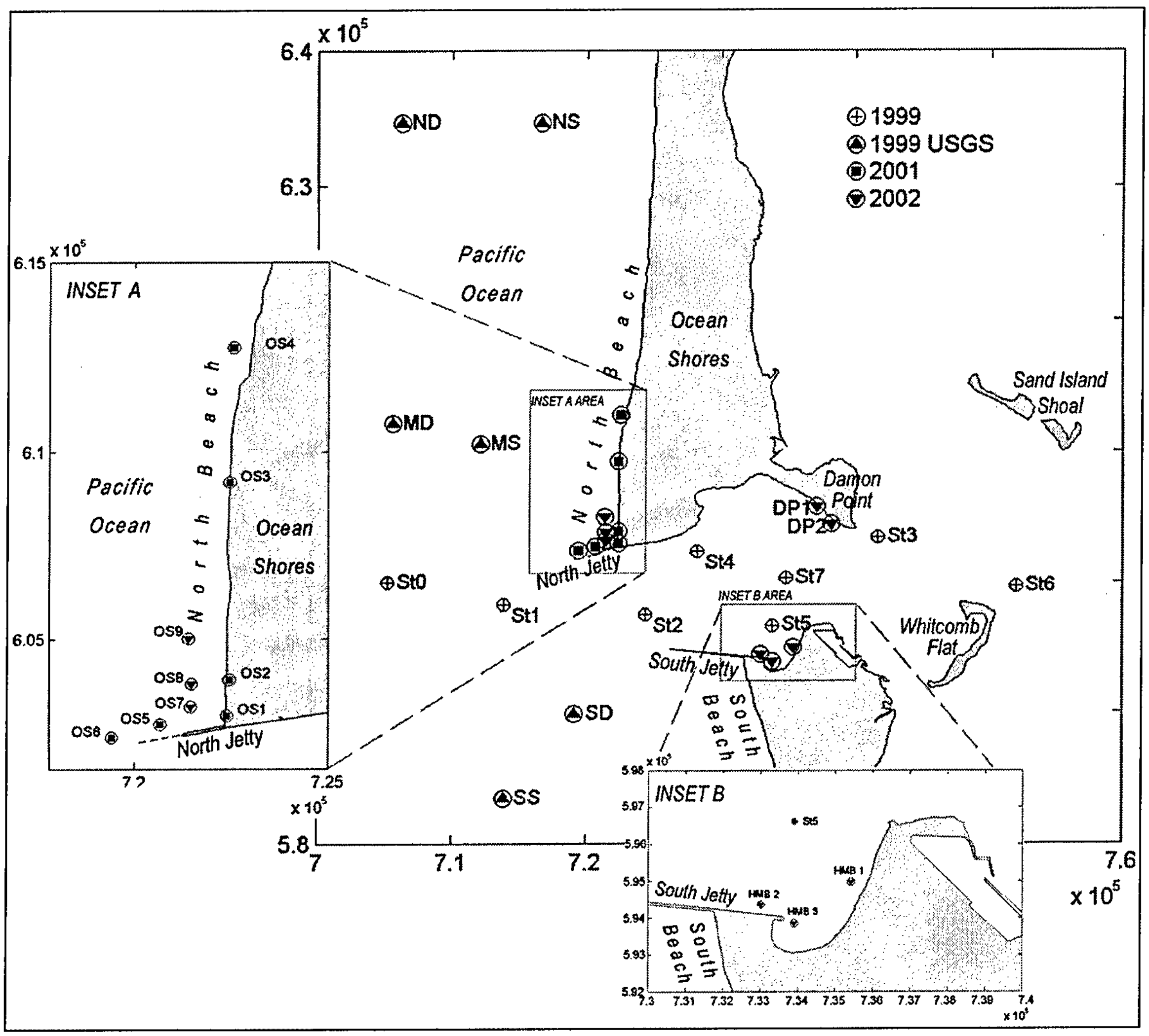



Figure 28. Location of instruments deployed in Grays Harbor

Descriptive parameters including significant wave height $H_s$, spectral significant wave height $H_{m0}$, significant wave period $T_s$, spectral peak wave period $T_p$, average wave period $T_{av}$, and mean direction of wave approach at peak frequency *DIR* were calculated from measured time series of water-surface elevations using standard techniques (e.g., Earle, McGehee, and Tubman 1995). Plots of $H_{m0}$, $T_p$, and *DIR* measured at sta 5 near Half Moon Bay and at the CDIP buoy are shown in Figure 29. Similar plots for HMB1 and the CDIP buoy are shown in Figure 30. $H_s$ in outer Half Moon Bay is 57 percent lower on average than $H_s$ at the CDIP buoy between September and October 1999. During the same period, the average direction of wave approach occurred in a narrow band centered at approximately 280 deg with standard deviation of 8 deg, while at the CDIP buoy the average wave direction was 270 deg with standard deviation of 27 deg. $H_s$ near Point Chehalis revetment fill is 46 percent lower on average than $H_s$ at the CDIP buoy between March and April 2002. Waves at the CDIP buoy greater than 3 m in height are attenuated more than waves smaller than 3 m as a result of depth-controlled breaking. As with sta 5, *DIR* at HMB1 occurs in a narrow band centered on 288 deg, whereas the CDIP buoy average for the same period is 266 deg. The variation in $T_p$ between sta 5 and the CDIP buoy and between HMB1 and the CDIP buoy was insignificant in both deployments.

The wave measurements reveal that, although ocean waves are attenuated by both tidal currents and by refraction, diffraction, and dissipation as they propagate from the open ocean into Grays Harbor inlet, $H_s$ in Half Moon Bay approaches 3 m as the offshore $H_s$ exceeds 5 m. Statistical analysis of the offshore wave records between 1994 and 2002 indicates that $H_s$ greater than 5 m occurs 2.1 percent of the time at the CDIP buoy, overall, and 4.4 percent of the time in winter months. Wave direction approaching Half Moon Bay is constrained by the presence of the jetties so that only a narrow band of incident wave directions occur. Once past the eastern end of the south jetty, wave direction in Half Moon Bay is a function of diffraction imposed by the mound and refraction by depth contours near the shoreline.

Time series of current vectors at sta 5 during a storm between 27 October and 2 November 1999 are shown in Figure 31. Similar time series at HMB1 and HMB3 for a storm that occurred 10-15 March 2002 are shown in Figure 32. Despite the large waves, the mean current at sta 5 is dominated by tidal forcing and oscillates between northeast and southwest on flood and ebb tide, respectively. Peak ebb and flood currents at sta 5 are capable of eroding sediment from the bed. The net current is ebb dominated and directed southwest. Although there is tidal period modulation of the current at HMB1, the current speeds also increase and decrease with wave height. Current vectors during the storm are directed northeast approximately parallel to the shore. Currents are generally less than 0.1 m/sec except at the peak of the storm. At HMB3 the currents are significantly weaker (< 0.1 m/sec) than at HMB1, with net current to the northeast.

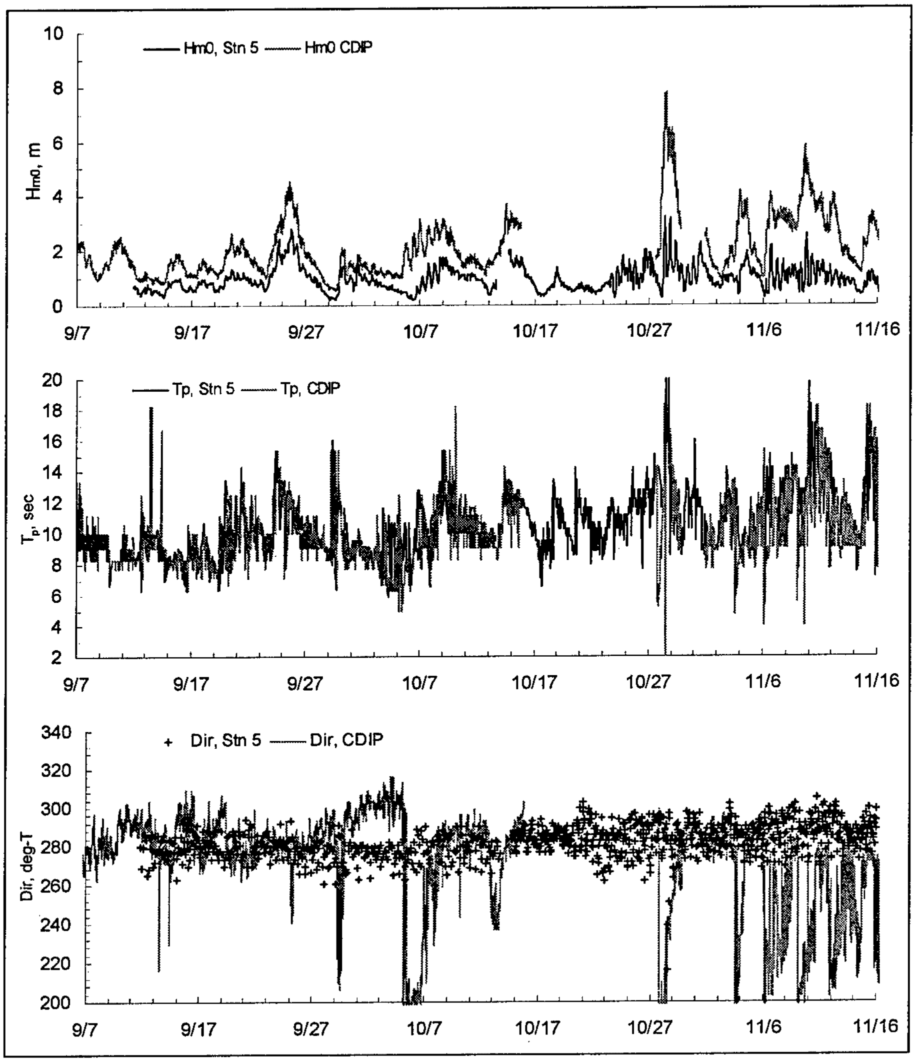



Figure 29. Time series of wave parameters at sta 5

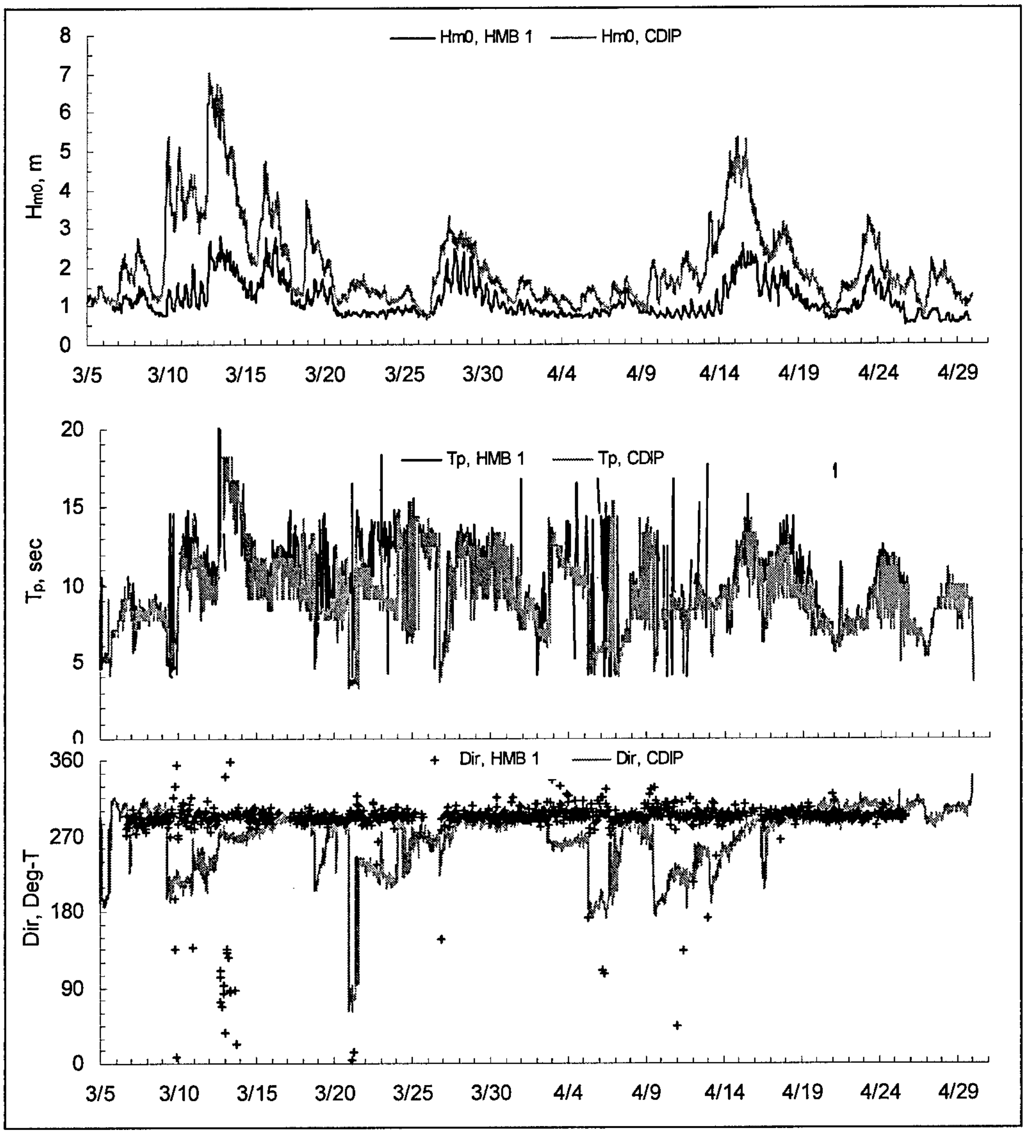



Figure 30. Time series of wave parameters at HMB1

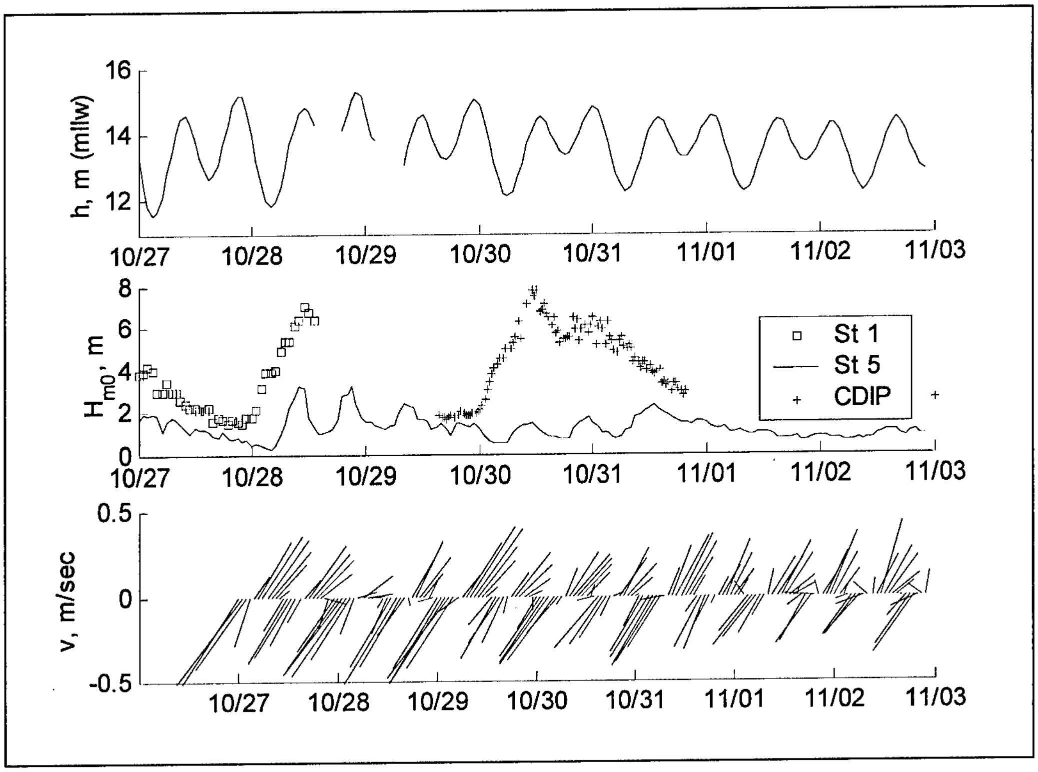



Figure 31. Time series of depth $h$, $H_{mo}$, and current vectors at sta 5 during a 1999 storm

Quantitative estimates of sand transport rates at sta 5 were calculated in two approaches. In one approach, the tripod measurements of currents and suspended sediment concentrations were analyzed to make direct at-a-point calculations. In the other approach, the van Rijn (1989a, 1989b, 1993) total load sediment transport model was applied by inputting the tripod measurements of waves, water depth, and mean currents. Sediment transport rates calculated from direct measurements of suspended load and mean current compared with the computations of the van Rijn model agree within a factor of 2.

Figure 33 shows cumulative time series of the easting and northing components of the total load sediment flux according to the van Rijn formula at sta 5. The results indicate that the transport due to steady currents is episodic, responding mainly to large waves that entrain large quantities of sediment. The cumulative flux calculations indicate a net transport to the west-southwest over the period of deployment at sta 5. Tidal period fluctuations between northwest and southeast transport are apparent in the time series. The cumulative transport to the west-southwest is consistent with an ebb-dominant current that prevails on the south side of the Grays Harbor entrance. Although the measurements do not indicate a significant wave-induced sediment transport at sta 5, it is likely that wave-induced currents and transport increase significantly in proximity to the shoreline at Half Moon Bay.

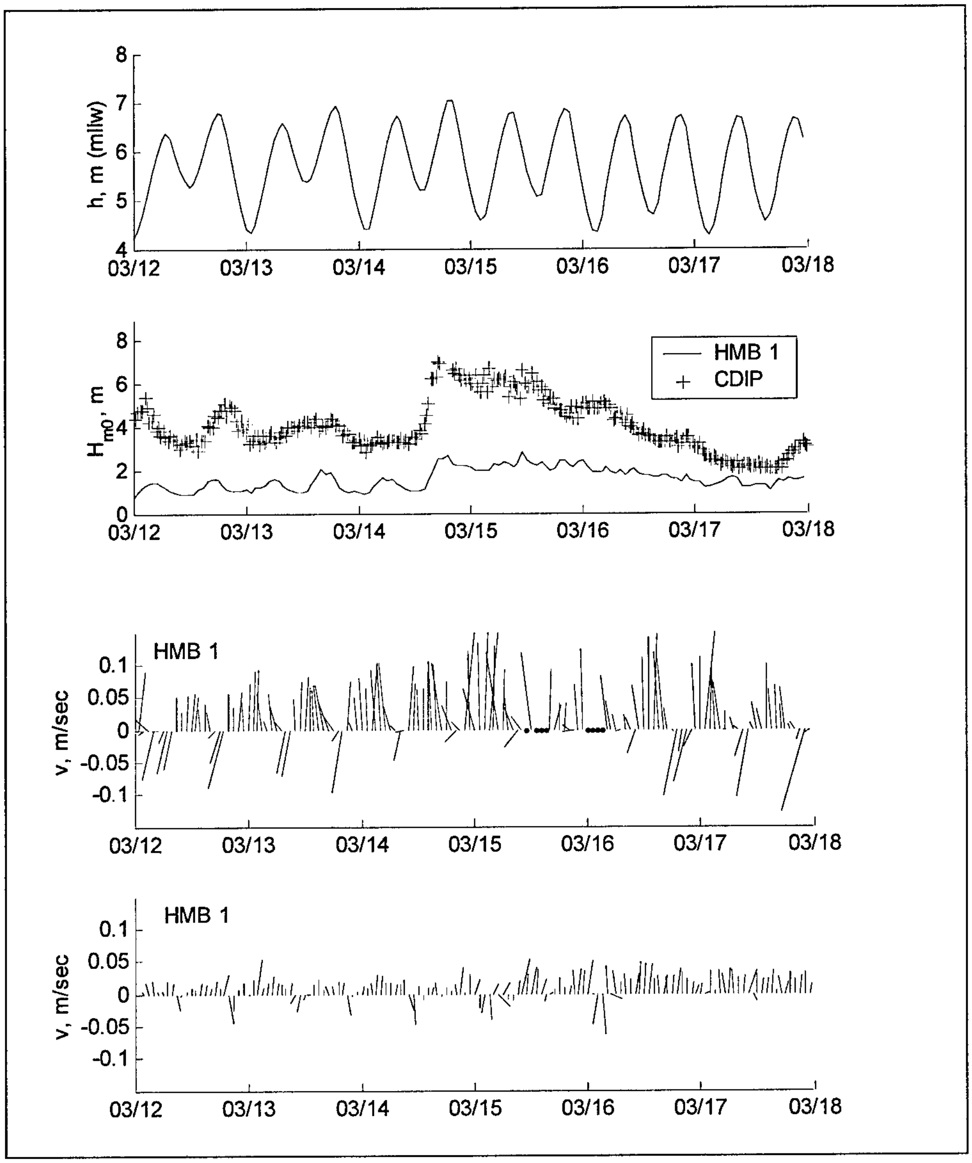



Figure 32. Time series of $h$, $H_{mo}$, and current vectors at HMB1 and HMB3 during a 2002 storm

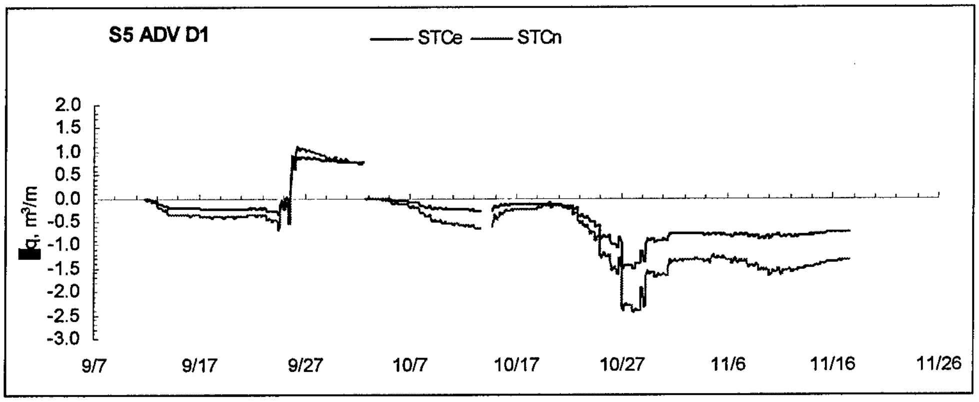



Figure 33. Cumulative time series of easting and northing components of sediment transport between September and November 1999 calculated with van Rijn formula and input parameters measured at sta 5

## Analysis of sediment mobility and transport pathways

A 5-day simulation of depth-averaged currents resulting from tides and wave-induced radiation stresses was run with the ADCIRC/STWAVE steering module (Cialone et al. 2002) to represent the period 23-28 September 1999 when wave heights reached a peak of 5 m at the CDIP buoy. Although currents were simulated over the entire Grays Harbor grid, the focus is on patterns in the inlet near Half Moon Bay and the dredged material disposal sites at Point Chehalis, Half Moon Bay sites 1 and 2, and the south jetty (see Figure 1). The depth-averaged currents produced by the steering module simulations were coupled with a Lagrangian sediment particle-tracking model (PSed by Davies, Serrer, and Watson 2000) to determine sediment mobility and to analyze sediment transport pathways in the inlet.

The relative mobility of the sediment, $M$, was calculated as the ratio between the maximum bed shear stress, $\tau$, and the critical shear stress at which sediment transport will take place for a given sediment grain size, $\tau_c$:

$$M = \frac{\tau}{\tau_c} \tag{2}$$

The critical shear stress is determined using the Shields criterion as formulated by Soulsby and Whitehouse (1997). The bed shear stress is determined using the quadratic stress law and a friction factor based on the skin friction roughness and the depth-averaged current.

Maps of maximum $M$ for fine sand, medium sand, and coarse sand are shown in Figures 34 to 36. Most of the inlet bottom between the jetties is characterized by values of $M$ greater than 9 indicating that fine sand is highly mobile at maximum flow. In contrast, Half Moon Bay is characterized by values of $M$ less than 4 indicating that bed-load transport of fine sand occurs at maximum ebb and flood flows. A small area of Half Moon Bay south and east of the south jetty is

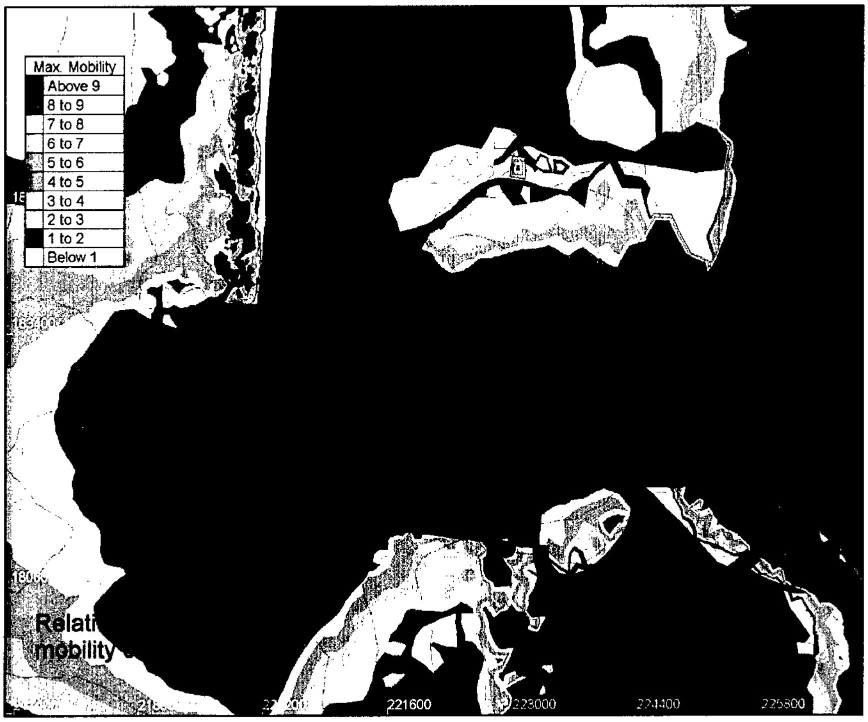



Figure 34. Relative mobility of fine sand computed for maximum steady currents from 5-day simulation including tidal currents and waves (September 1999)

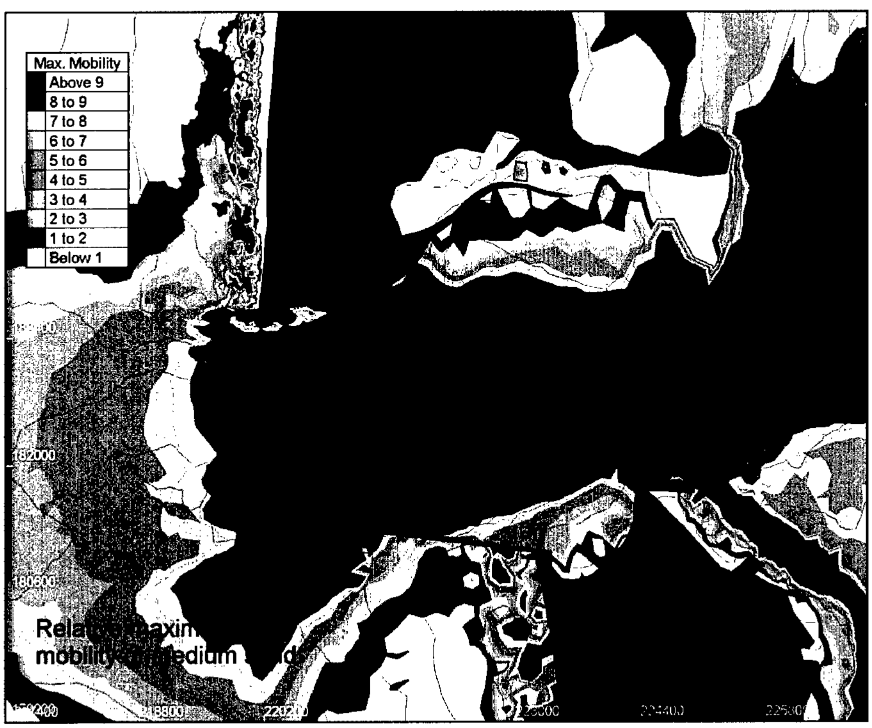



Figure 35. Relative mobility of medium sand computed for maximum steady currents from 5-day simulation including tidal currents and waves (September 1999)


Figure 36. Relative mobility of coarse sand computed for maximum steady currents from 5-day simulation including tidal currents and waves (September 1999)

indicated as having no transport of even fine sand under maximum ebb and flood flows. The area of no transport increases for both medium and coarse sand (Figures 35 and 36, respectively). Coarse sand is mostly immobile under maximum tidal current conditions in Half Moon Bay. The calculations of bed shear stress are based on the depth-averaged steady currents from the steering module and, therefore, do not include the contribution of wave orbital velocity and wave asymmetry. Wave orbital velocities are more effective at entraining sediment than steady currents and would be expected to increase the relative mobility.

Transport pathways in the inlet for fine, medium, and coarse sand were evaluated by application of the PSed model coupled to currents output from the same steering module simulation previously described. The fate of fine, medium, and coarse sand originating at the disposal sites in Point Chehalis Reach, Half Moon Bay and near the south jetty were evaluated using the 5-day simulation. The sediment parcels are color coded in the model by sediment grain size, yellow representing the smallest grains in the distribution (0.1 mm), brown representing the largest grains (1 mm) as shown in Figure 37. Figures 38 and 39 show sequences of frames output from the PSed model at 2-hr intervals for day one of the 5-day simulation for sediment sources located at Point Chehalis and the south jetty disposal sites respectively.

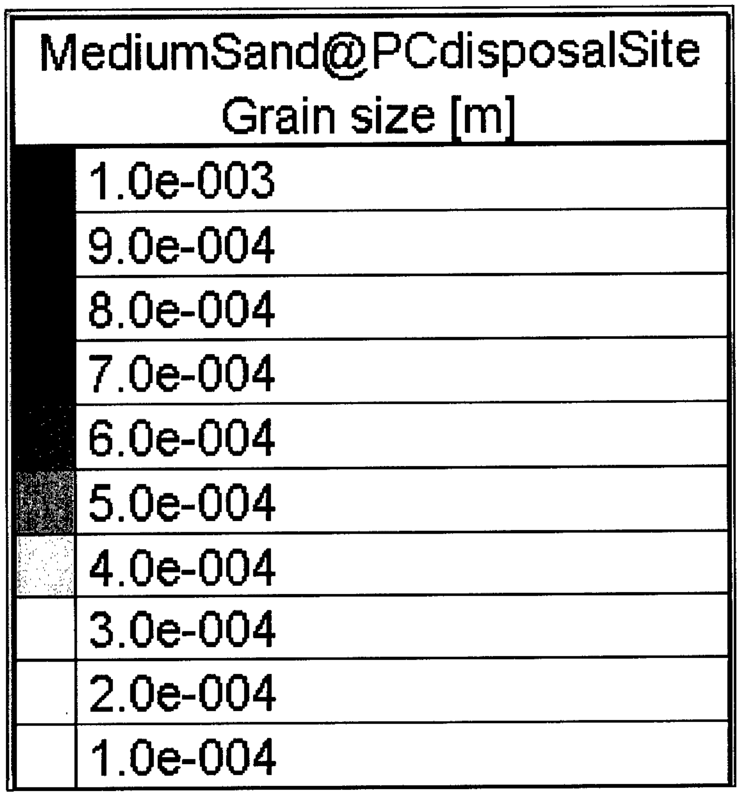



Figure 37. Color coding of sediment parcels as function of grain size displayed in Figures 38, 39, and 41

To evaluate sediment disposal in Half Moon Bay, five separate sediment-loading sites were assessed. No sediment activity was observed for medium sand at those sites nearest the shore. Figure 40 shows the locations of the inactive and active loading sites. Figure 41 shows a sequence of frames at 2-hr intervals for medium sand at the third position in Figure 40, which coincides approximately with the position of nearshore berm placement in May 2002.

The simulations indicate that the majority of sand particles are transported westward out of the inlet to the ebb shoal from the disposal sites by the ebb-dominated current in this region. A small proportion of medium and coarse sand particles is deposited in Half Moon Bay and also move onto tidal flats to the east and back into the navigation channel. These results neglect the contribution of wave orbital velocities to local bed shear stress in the calculation of transport.

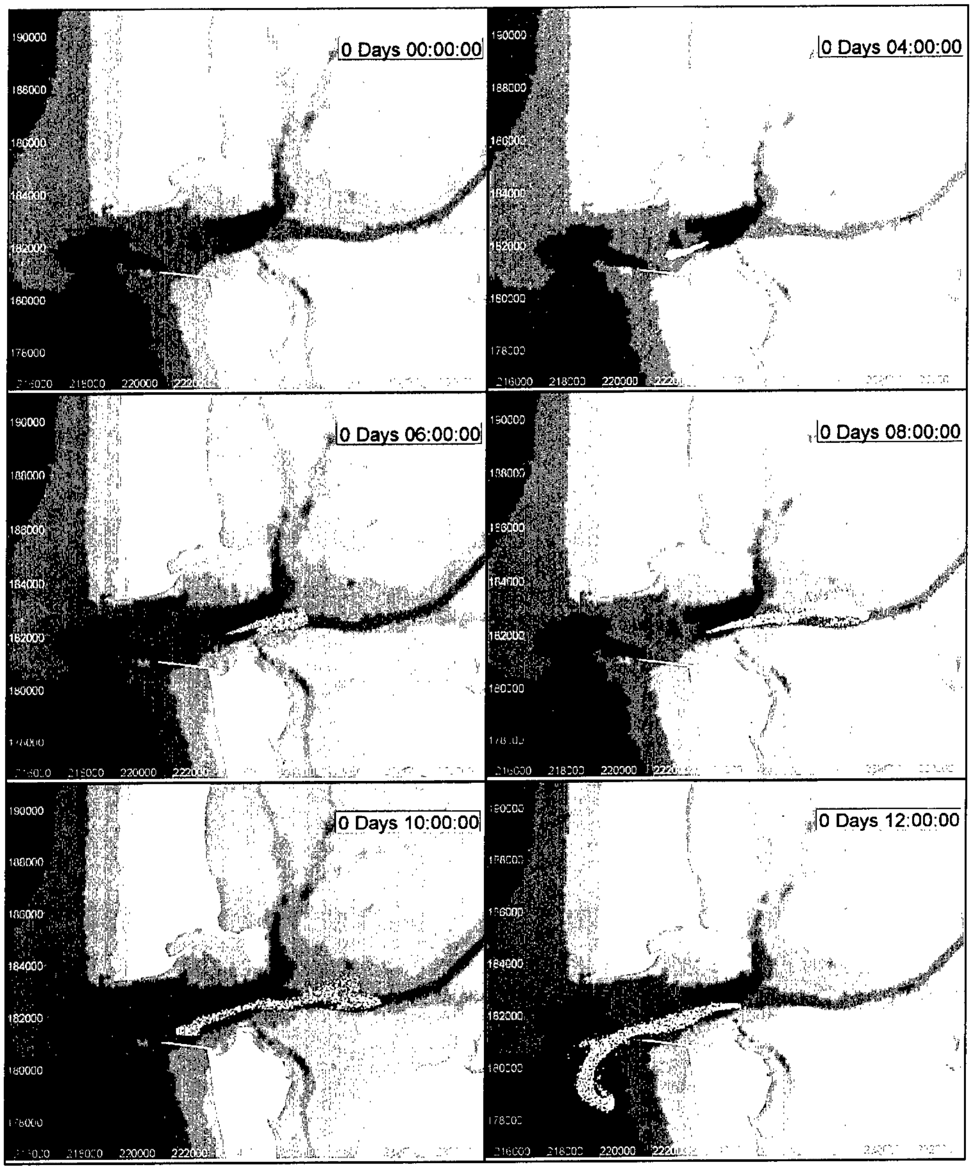



Figure 38. Frames output from the Lagrangian sediment transport model at 2-hr intervals for medium sand released at Point Chehalis disposal site (Continued)

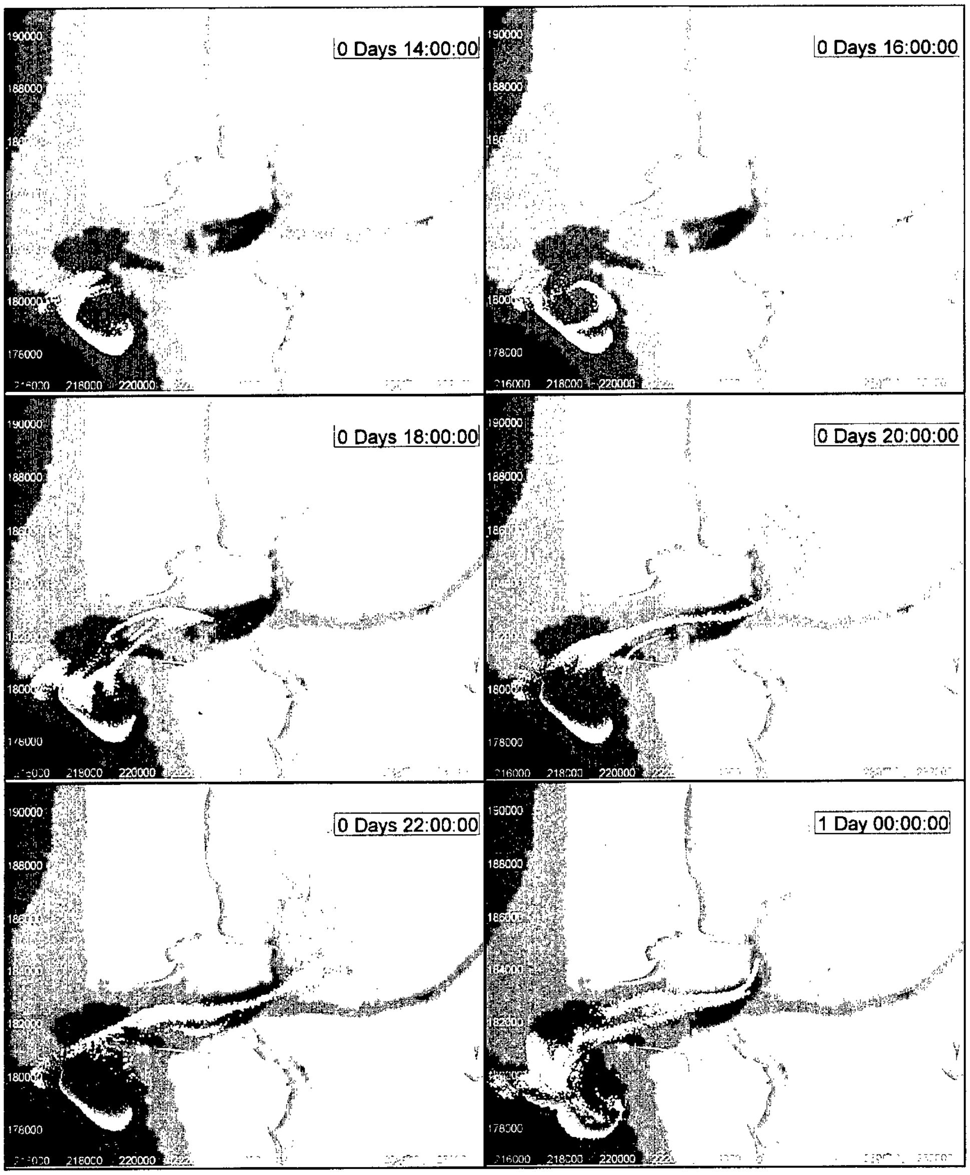



Figure 38. (Concluded)

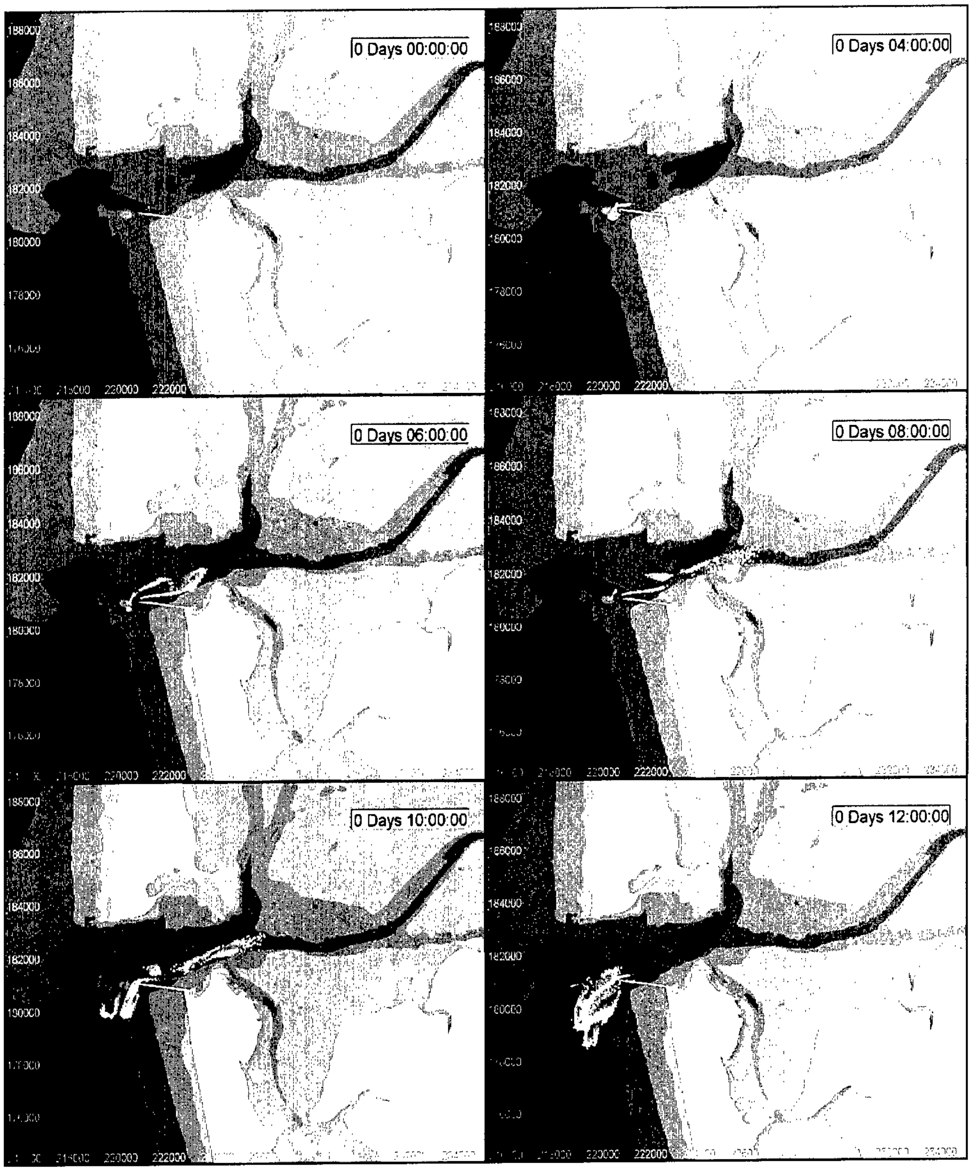



Figure 39. Sequence of frames at 2-hr intervals output from PSed module for medium sand originating at south jetty disposal site (Continued)

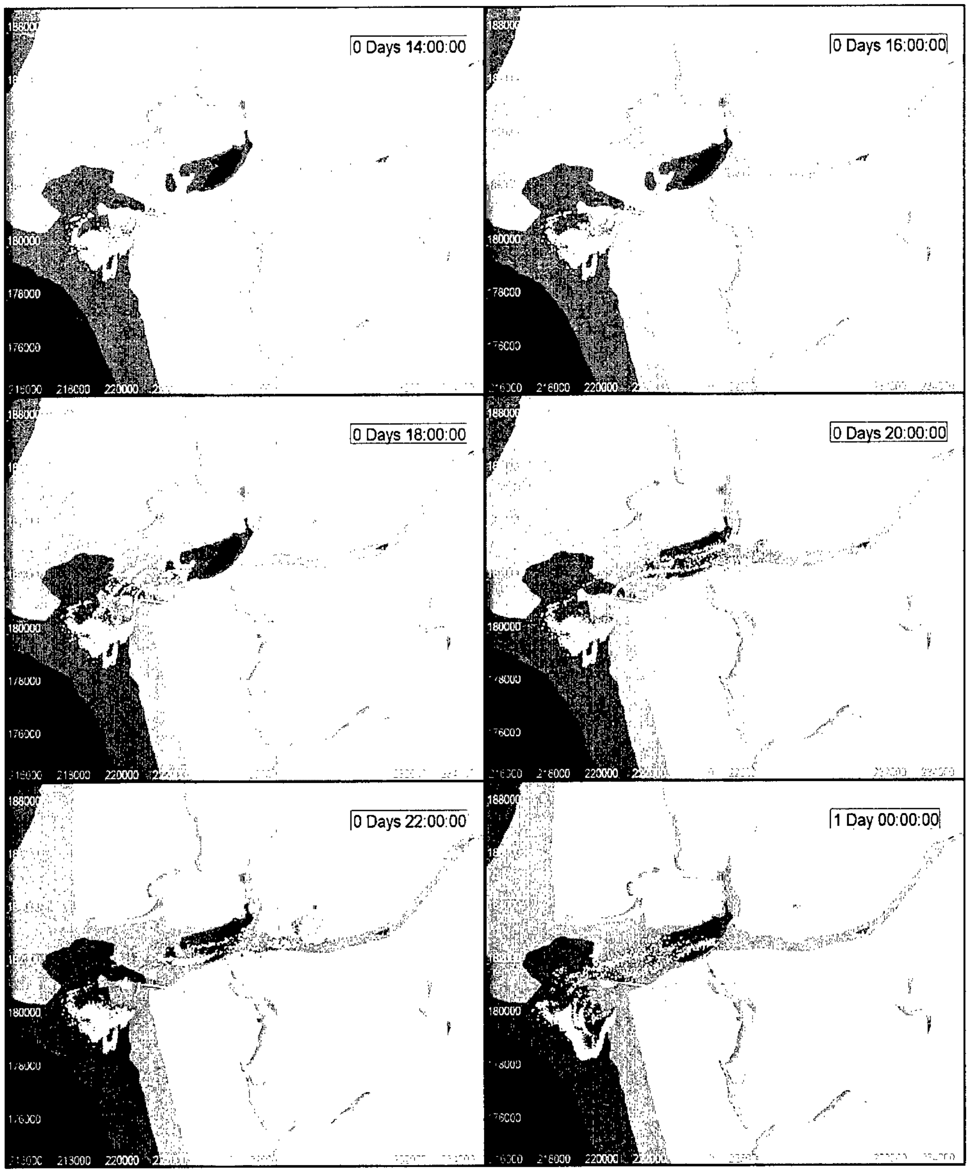



Figure 39. (Concluded)

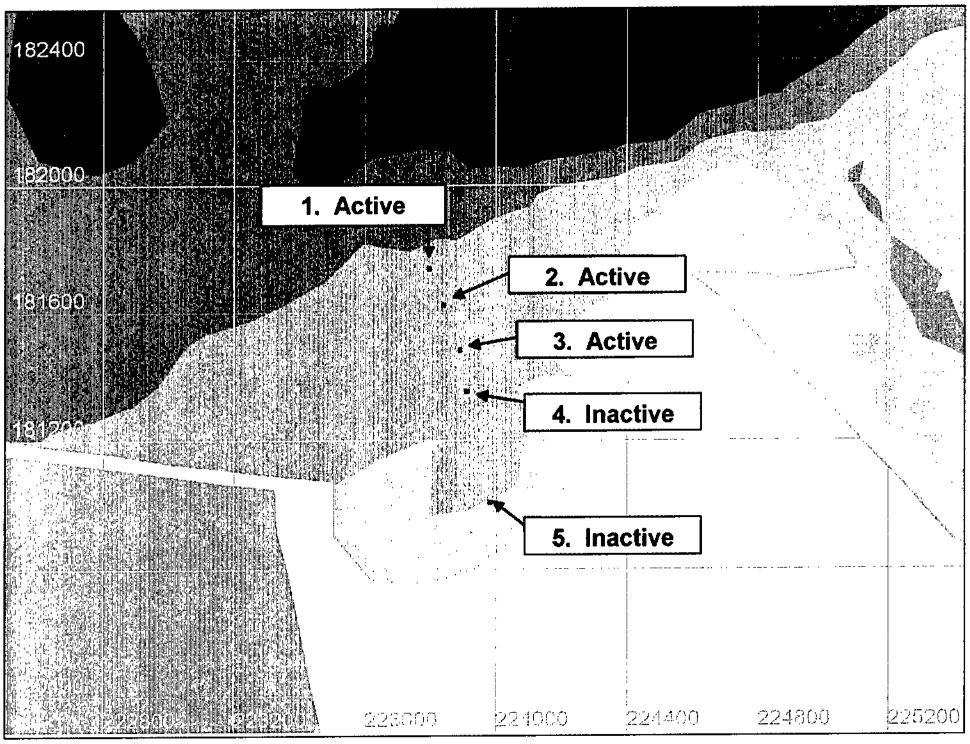



Figure 40. Location of active and inactive sites for sediment sources in PSed module for medium sand in Half Moon Bay

## Morphological Change and Sediment Budget Analysis

Twenty-one bathymetric surveys of the Half Moon Bay/south jetty area provided by the Seattle District conducted between 1996 and 2002 were contoured, and the overlapping portions of the resulting surface maps were differenced to analyze morphological changes in the study area. Appendix B lists the surveys and corresponding file names used to create the bathymetric surfaces for the morphological change analysis. The net difference between the first and last surveys (7 June 1996 and 26 February 2002) is shown in Figure 42. The survey area was divided into eight polygons determined by the navigation channel boundaries and on the basis of patterns in net bathymetry change. Notable features in the bathymetry change map include the large area of erosion in the Point Chehalis Reach and northeast portion of the map, and the areas of net gain south of Point Chehalis that correlates with dredged sediment disposal areas (Point Chehalis, Half Moon Bay, and the south jetty). Alternating patches of erosion and accretion to the north of the navigation channel are associated with large sand waves that migrate to the southwest and have been interpreted as being responsible for much of the shoaling in the entrance reach.

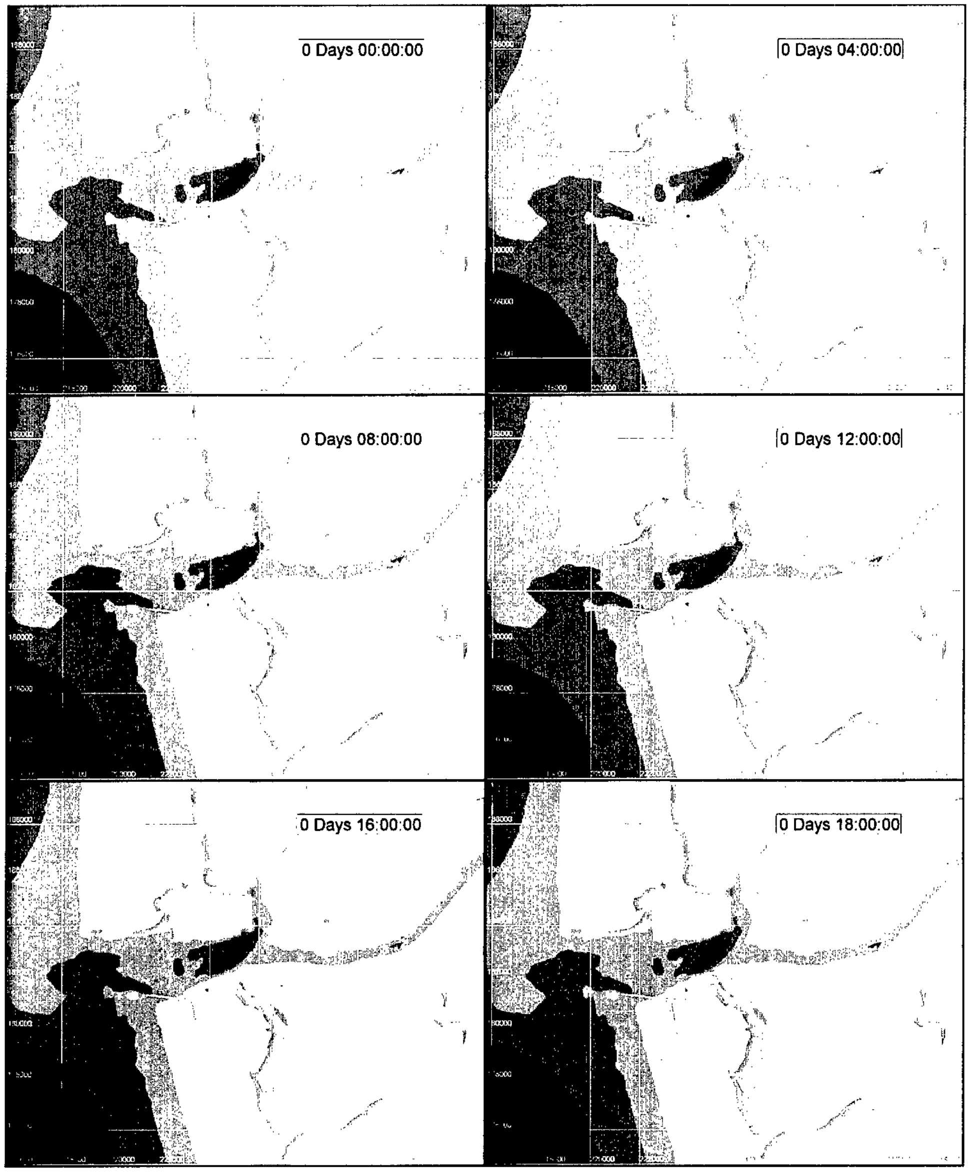



Figure 41. Sequence of frames at 4-hr intervals and then 2-hr intervals from PSed module for medium sand originating at Half Moon Bay disposal site (Continued)

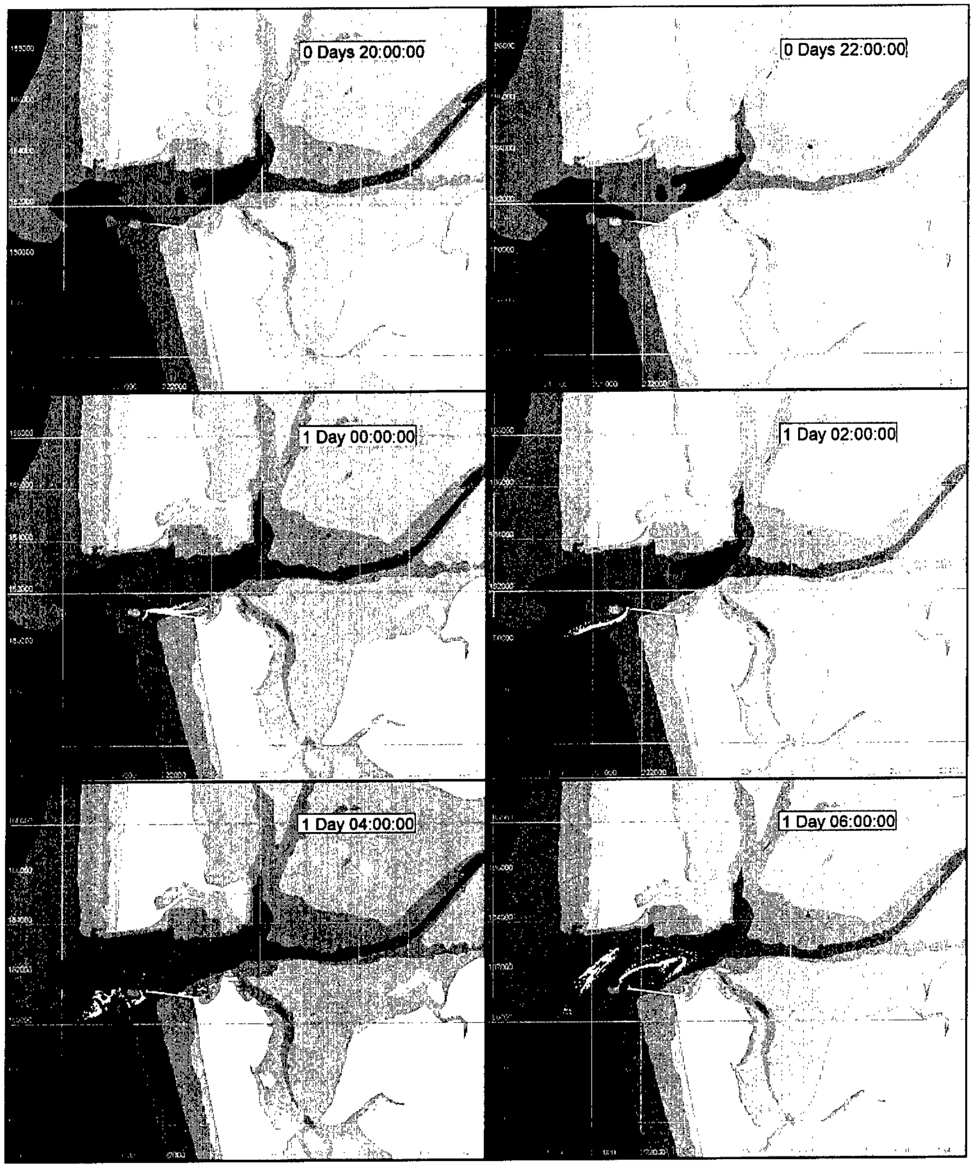



Figure 41. (Concluded)

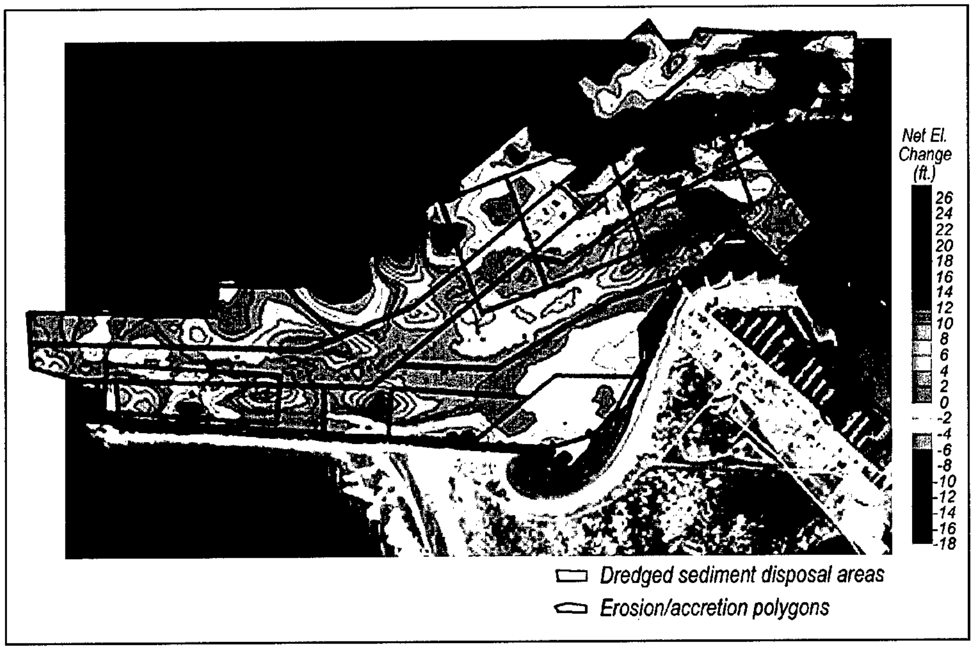



Figure 42. Net bathymetry change in Half Moon Bay and south jetty area between 7 June 1996 and 26 February 2002. Also shown are erosion and accretion zones for sediment budget analysis and dredged sediment disposal areas

The product of polygon area and integrated net bed elevation change is the net change in the volume of each polygon. The net volume change over the period 1996 to 2002, dredging and disposal data, and the conceptual understanding of coastal processes were applied to develop a sediment budget in the Sediment Budget Analysis System (SBAS) (Rosati and Kraus 2001) (Figure 43 and Table 9). Values listed in Table 9 arise directly from the SBAS and do not represent physical accuracy, which is estimated to be in the range of ±30 percent. Polygons for the buried revetment area at Point Chehalis and the breach fill at the south jetty were also included in the sediment budget. It was found through sensitivity testing that varying the number of polygons and the position of the polygon boundaries in the area through a reasonable range did not significantly alter the results. It is assumed on the basis of the sediment transport analysis previously presented that the net transport direction in the southern half of the inlet adjacent to Half Moon Bay is from northeast to southwest. Therefore, most of the net volume fluxes of sediment between cells are concluded to be in this direction. Sediment is transported from inner Half Moon Bay to outer Half Moon Bay to the northeast as a result of wave-induced alongshore and across-shore currents and by tidal currents.

The polygons in the northeast portion of the study area (sand waves, Point Chehalis Reach, and South Chehalis polygons) show a net loss of sediment, whereas polygons in the southwest portion of the study area show net gain (inner

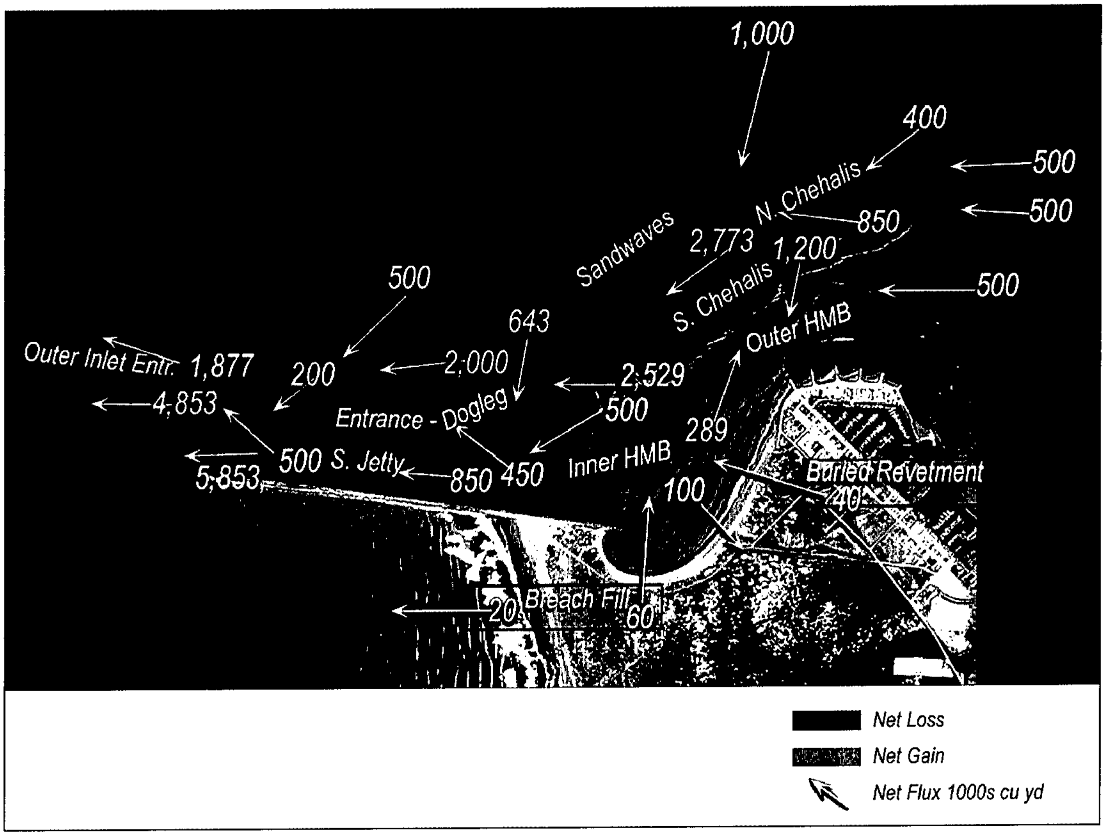



Figure 43. Sediment budget for Half Moon Bay/south jetty area developed from net morphology change between 1996 and 2002

**Table 9**
**Volume Changes in Sediment Budget Polygons Between 1996 to 2002**

| Polygon | Volume Change* (cu yd) |
|---|---|
| Inner HMB | 143,648 |
| Outer HMB | 1,458,173 |
| Entrance Dogleg | 503,131 |
| Outer Inlet | 422,745 |
| Point Chehalis Reach | -1,033,002 |
| South Chehalis | -549,968 |
| South Jetty | 200,692 |
| Sand Waves | -1,143,276 |
| **Net** | **2,143** |
| **Disposal** | **13,610,093** |
| **Dredging** | **2,592,300** |

***Number of significant figures is a calculation artifact and does not represent physical accuracy.**

and outer Half Moon Bay, entrance reach, south jetty, and outer inlet). Time series of volume changes in each polygon were computed by differencing the 21 bathymetric surfaces over the period 1996 to 2002 (Figure 44). Only points in which the survey covered at least 90 percent of the total polygon area are included in the calculations and shown in the time series. Also shown in Figure 44 are linear trend lines fit to the data for the sand waves, outer Half Moon Bay, and Point Chehalis Reach polygons. The time series confirm that the general pattern indicated in the net bed elevation change map are consistent with the temporal trends in the data. The sand waves and Point Chehalis Reach polygons lose sediment through time while the outer Half Moon Bay polygon gains sediment relative to 1996. Inner Half Moon Bay and the entrance reach show no significant trends towards erosion or accretion, although the entrance reach exhibits cycles that reflect persistent shoaling and annual maintenance dredging. The volumes summarized in Table 9 indicate the overall area has a small positive budget. The small positive budget is mostly attributed to the large volume (approximately 11 million cu yd) of dredged sediment disposed in the area that counters the erosion of sediment by waves and tidal currents from the inlet.

Although focused on the Half Moon Bay area, the sediment budget was developed within the context of regional sediment transport patterns and morphological changes within and adjacent to Grays Harbor. The sediment volume changes and fluxes were compared, and found to be consistent with, a regional sediment budget analysis prepared as part of the north jetty operations and maintenance study (see also, Byrnes, Baker, and Kraus 2003).

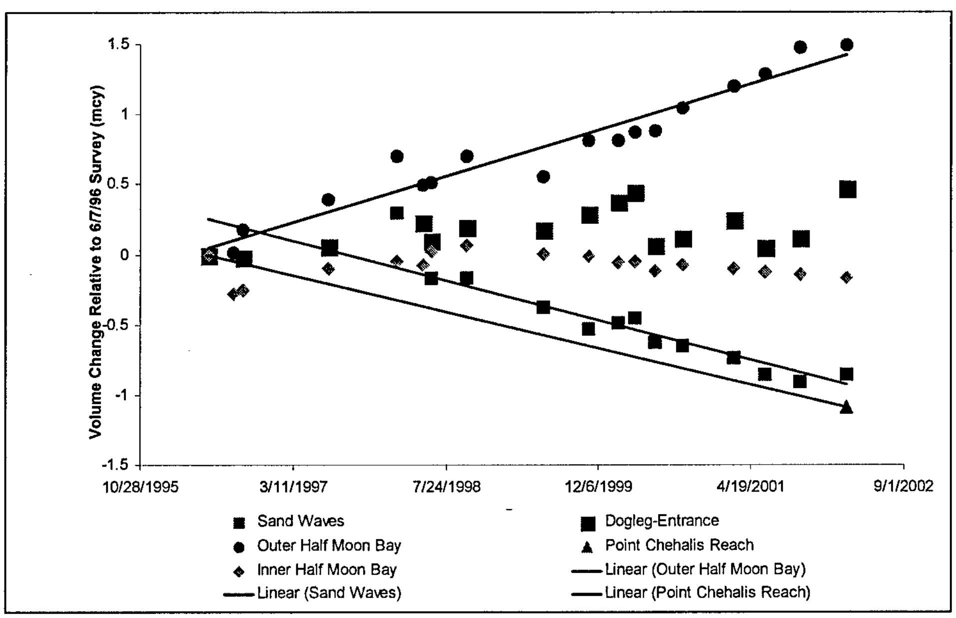



Figure 44. Time series of volume changes in erosion-accretion zones relative to 7 June1996 survey

## Summary

The sediment transport, sediment mobility, and transport path analysis indicate a tendency for fine to medium sands to be transported out of the Half Moon Bay/south jetty area to the west and southwest mainly by strong ebb currents that dominate the tidal current and sediment transport regime in the study area. Medium and coarse sand may remain in outer Half Moon Bay. Wave diffraction and refraction in Half Moon Bay create alongshore and cross-shore currents. The longshore current typically flows from the west end of the bay to the northeast. The longshore current to the northeast transports sediment entrained by wave action in Inner Half Moon Bay, where it is entrained by tidal currents. Interpretation and measurements of the currents and inferred sediment pathways are consistent with the analysis of beach profile change and the behavior of the transition gravel adjacent to the diffraction mound. The pattern of erosion and redistribution of gravel suggests that sediment is being eroded from the west end of the beach and transported eastward along the shoreline where it is eventually delivered to the tidal stream in the main channel.

It was not possible to fully assess the influence of waves on the mobility and net transport of medium and coarse sands, but it is expected that swell wave asymmetry may tend to transport sediment into Half Moon Bay, whereas storm waves would be more likely to cause removal of sand from Half Moon Bay.

A sediment budget analysis based on 21 bathymetry surveys of the study area between 1996 and 2002 indicates a small positive budget. Net gain of sediment in outer Half Moon Bay is associated mainly with dredged sediment disposal. The gain in outer Half Moon Bay correlates well with losses from Point Chehalis Reach and the central inlet that includes large sand waves that migrate to the southwest.

# 5 Summary, Conclusions, and Recommendations

This study evaluated the performance of engineering and maintenance measures that have been implemented to control breaching of the beach adjacent to the south jetty and the erosion at Half Moon Bay and the Point Chehalis revetment area. The evaluation covered the maintenance dredging and disposal program for the Grays Harbor and Chehalis River navigation project, the Point Chehalis revetment, the South Beach fill, and the south jetty wave diffraction mound with gravel transition zone.

## Dredging and Disposal in Half Moon Bay

Evaluation of dredging and disposal in the study area is based on a sediment budget formulated for the period 1996 to 2002. The sediment budget was developed based upon:

*a.* Nearshore bathymetry surveys.

*b.* Measurements of currents, waves, and suspended sediment concentrations at the site.

*c.* Upland and intertidal topography.

*d.* Shoreline position change derived from aerial photographs.

*e.* Results of numerical simulations of waves, currents, and sediment transport to define sediment volume fluxes and sediment transport pathways.

The sediment transport, sediment mobility, and transport path analysis indicate a tendency for fine to medium sands to be transported out of the Half Moon Bay/south jetty area to the west and southwest mainly by strong ebb currents that dominate the tidal current and sediment transport regime in the study area. Medium and coarse sand fractions may remain a longer time in both inner and outer Half Moon Bay. Wave diffraction and refraction in Half Moon Bay create longshore and cross-shore currents. The longshore current typically flows from the west end of the bay to the northeast. Sediment entrained by wave action in inner Half Moon Bay is transported by the longshore current to the northeast where the sediment can be entrained by tidal currents. This inferred sediment pathway is consistent with the analysis of beach profile change and the behavior of the transition gravel adjacent to the diffraction mound. The pattern of erosion and redistribution of gravel suggests that sediment in general is transported from the west end of the Half Moon Bay beach eastward along the shoreline where it may eventually be delivered to the tidal stream in the main channel.

Sediment transport pathways and analyzed sediment volume fluxes based on 21 bathymetry surveys of the study area between 1996 and 2002 were entered and analyzed within the SBAS. The sediment budget analysis indicates a small positive budget for Half Moon Bay area over the period. Net gain of sediment in outer Half Moon Bay is associated mainly with dredged sediment disposal. The gain in outer Half Moon Bay correlates well with losses from Point Chehalis Reach and the central inlet that includes large sand waves that migrate to the southwest.

A priority for sediment management in the study area should be to continue disposal of dredged sediment (particularly medium and coarse sand) in Half Moon Bay disposal sites and on the southeast edge of the Point Chehalis disposal site to minimize a sand deficit that would otherwise exist at Half Moon Bay. The sediment transport paths derived from analysis of measurements and modeling indicate that the most effective location for placement of sediment would be in the southwest portion of inner Half Moon Bay, south of the wave diffraction mound and remnant jetty. This area is interpreted to be on the updrift end of a littoral transport cell that involves wave-induced longshore currents to the east along Half Moon Bay shoreline and tidal currents that flow essentially parallel with the navigation channel. The present practice of disposal in the Half Moon Bay disposal sites is to place sediment on the downdrift end of the littoral cell. As much as possible, maintenance dredging of the entrance reach and dogleg junction with Point Chehalis Reach should be conducted primarily on the north side of the channel to further reduce losses from the Half Moon Bay area.

## Breach Fill and Diffraction Mound Performance

Performance of the diffraction mound and gravel-with-cobble rock transition was evaluated in terms of the consequences of wave approach to the Half Moon Bay shoreline and rates of shore erosion in the area influenced by the diffraction mound. Breach-fill performance was evaluated in terms of the expected project life and shoreline erosion patterns.

The purpose of the wave diffraction mound is to modify the wave approach angle along the shore and reduce or spread wave energy, thereby reducing beach erosion by longshore transport. The physical model demonstrated that waves wrap around the rubble-mound structure so that they arrive at the Half Moon Bay shoreline more perpendicularly than they do without the rubble mound. This study applied the numerical model CGWAVE to evaluate the performance of the mound as it was constructed and compares the results to the design modeled in the laboratory. The numerical model was calibrated to reproduce the physical model results and then applied to simulate the rubble mound as it was constructed with the jetty remnant extending east from the rubble mound. Simulations show that waves approach the shoreline similar to or at a more perpendicular angle with the jetty remnant in place. Wave heights along the Half Moon Bay shoreline change by less than 0.4 ft for large inner harbor waves. The rubble mound appears to be functioning as designed, and the remnant structure has not degraded the functioning of the wave diffraction mound.

Changes in the Half Moon Bay shoreline since the installation of the mound and gravel transition in 1999 were also considered in the performance evaluation of the diffraction mound and breach fill. The breach fill was originally expected to be effective in protecting the project for 5 to 10 years. During the seventh winter that the fill was in place (2001-2002), a series of storms (sustained period of high rainfall and high waves) damaged the South Beach and accelerated recession of the Half Moon Bay shoreline in the lee of the diffraction mound. In addition, it was found that the breach-fill surface elevation at the narrowest area between Half Moon Bay and Pacific Ocean was damaged during previous (summer-fall 2001) construction activities at the south jetty. As a result, wave runup from the ocean side overflowed the fill, which channelized it and contributed to the scouring of the fill.

Surveys revealed that approximately 2-4 m of erosion occurred in the steep portion of the profile in the gravel transition area of the breach fill between December 2001 and June 2002. Shoreline recession rates in the western end of Half Moon Bay have continued at historical rates in the period 1996-2002 except in the area of the gravel transition. Recession appears to be correlated with large storm waves and elevated water levels as noted. Profile surveys indicate that progressing eastward around Half Moon Bay the lower intertidal beach profile rises and steepens. The longshore trend in profile change is consistent with the interpretation of sediment transport from western Half Moon Bay to eastern Half Moon Bay and with a negative spatial gradient.

South jetty breach fill and dune restoration is possible through beneficial uses of the maintenance dredged materials. The south jetty breach-fill nourishment with dredged material is consistent with the USACE Environmental Operating Principles. Maintenance work is required to ensure longevity of any soft solution. Estimated volume of breach nourishment for the south jetty breach fill is approximately 50,000 cu yd of sand every 5 years, which is a small part of the dredged sediments managed annually at Grays Harbor.

In the process of coordination of the modified design dated 1 September 1999 for the south jetty repairs, specification of the gravel transition beach became ambiguous. There were references to the use of naturally occurring rounded gravel and cobble material (+3/8 in.) size, in contrast to material specifications calling for 12-in. minus cobbles with up to 50 percent by weight larger than 3 in. In addition, the stated expectation for the gravel transition beach material was that it would eliminate the dangerous 8-ft-high scarp on the Half Moon Bay side of the breach fill.

The transition zone in the lee of the diffraction mound needs to be modified and evaluated over the long term to provide sustained fill protection. Modifications should be based on a consideration of planview configuration, cross section, and size distribution of material. Future coordination of transition gravel must emphasize the allowable percentage of larger cobble size materials because of stakeholder sensitivity to the environmental resource and recreational beach access impacts of larger size materials. The design of modifications should be developed from results of a long-term monitoring program. Monitoring needs to be continued at end of winter and end of summer for a period of at least 5 years from the time of construction of the project and should include high-resolution aerial photographs, profile surveys from above mean higher high water to at least mean lower low water, and sampling and analysis of the gravel, cobble, and sand distribution at the profile survey locations.

Another approach is to consider design modifications to the diffraction mound and south jetty terminus to increase dissipation of the large waves that occur at high water levels during storms and that are correlated with erosion. Evaluation of the relative benefits of mound modifications as opposed to maintaining the transition zone should be based on relative costs (volumes of rock and/or cobble) over an appropriate project life.

## Point Chehalis Revetment Fill

The Point Chehalis revetment extension and fill was constructed from November 1998 to March 1999 and the Point Chehalis Revetment Extension Project, Interagency Mitigation Agreement with a plan dated 7 October 1998 requires periodic renourishment from the Operations and Maintenance budget subject to availability of funds. During the winter of 2001-2002 a series of storms caused some erosion of the revetment fill. During the storms, sustained periods of heavy rainfall occurred and probably caused piping of water from the saturated upland, which complicates the assessment of the contribution of shore processes to the relatively rapid and localized retreat of the Half Moon Bay shoreline there. Analysis of beach profile surveys and shoreline change for the period 1996 to 2002 indicate no significant trends in shoreline position in this area over the past 7 years. Construction of the fill was completed in 1999. Initial adjustment is to be expected. The period of surveys is too short for the data to conclusively reveal a change pattern or rate. The fill was designed with the expectation that occasional maintenance would be required. It is recommended that systematic monitoring of shoreline position and beach profile continue to document the evolution and trend toward equilibrium position. Availability of directional data from the Grays Harbor wave buoy is central to understanding future cause and effect for all navigation project issues at the site.

## Lessons Learned

Effective regional sediment management and beneficial use of the dredged resource needs to consider the seasonal fluctuations in wave climate and coastal change to maximize the potential benefits of placed material. At Half Moon Bay, placement of sand-sized material in the nearshore in the fall prior to the winter storm season is not as effective as placement in May. Storm waves contribute to significant losses of sandy sediment offshore, whereas summer waves promote onshore transport and beach recovery.

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# Appendix A
# Supplemental Photographic Documentation

This appendix includes vertical aerial photographs (Figures A1 through A26), oblique aerial photographs (Figures A27 through A33), and ground-based photographs (Figures A34 through A53) of Half Moon Bay, including South Beach, the south jetty, the diffraction mound, and Point Chehalis revetment fill. The photographs provide supplementary documentation to Chapters 2, 3, and 4 of this report.

# Figures A1 – A26: Vertical Aerial Photographs

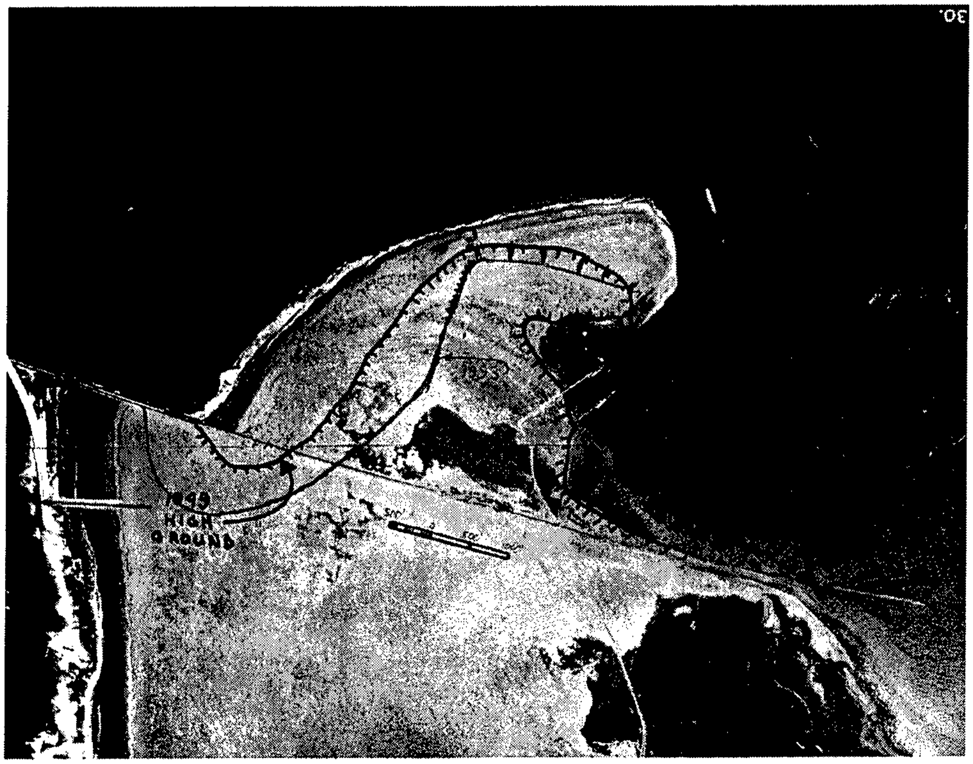


Figure A1. 1938

Figure A2. 12 June 1974

Figure A3.  23 July 1991

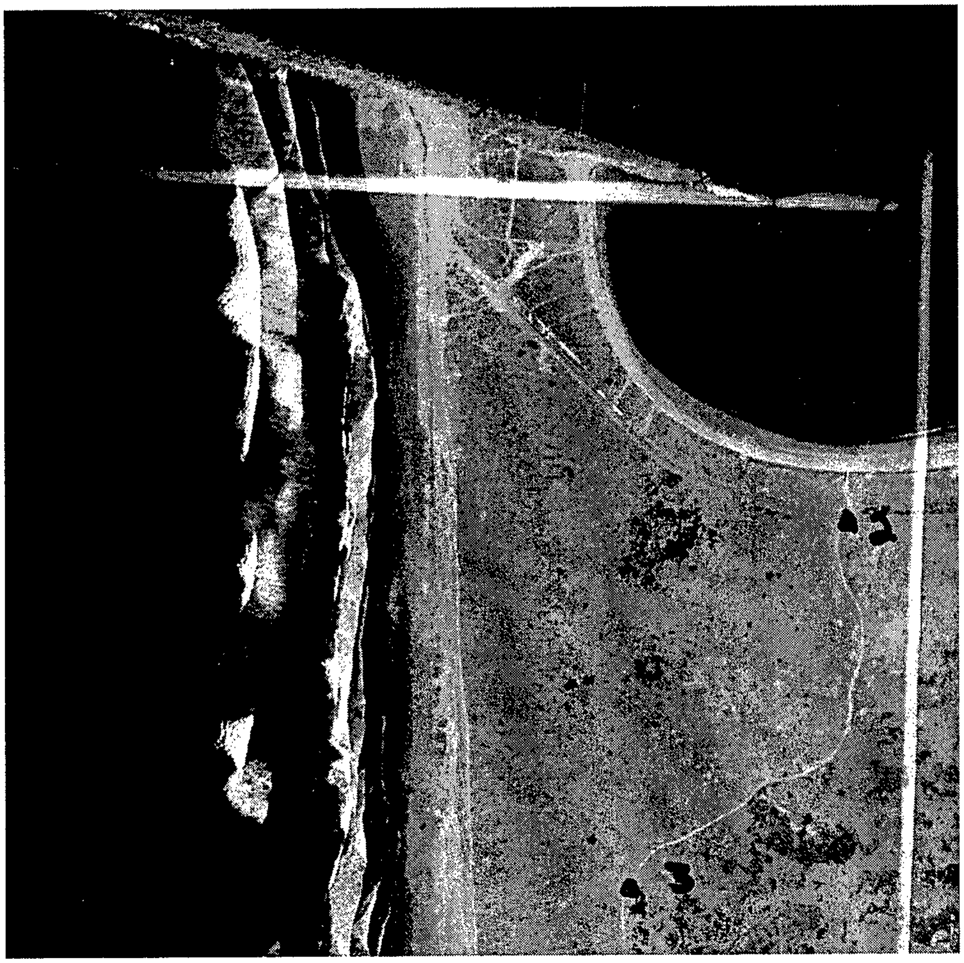

Figure A4. 15 July 1992

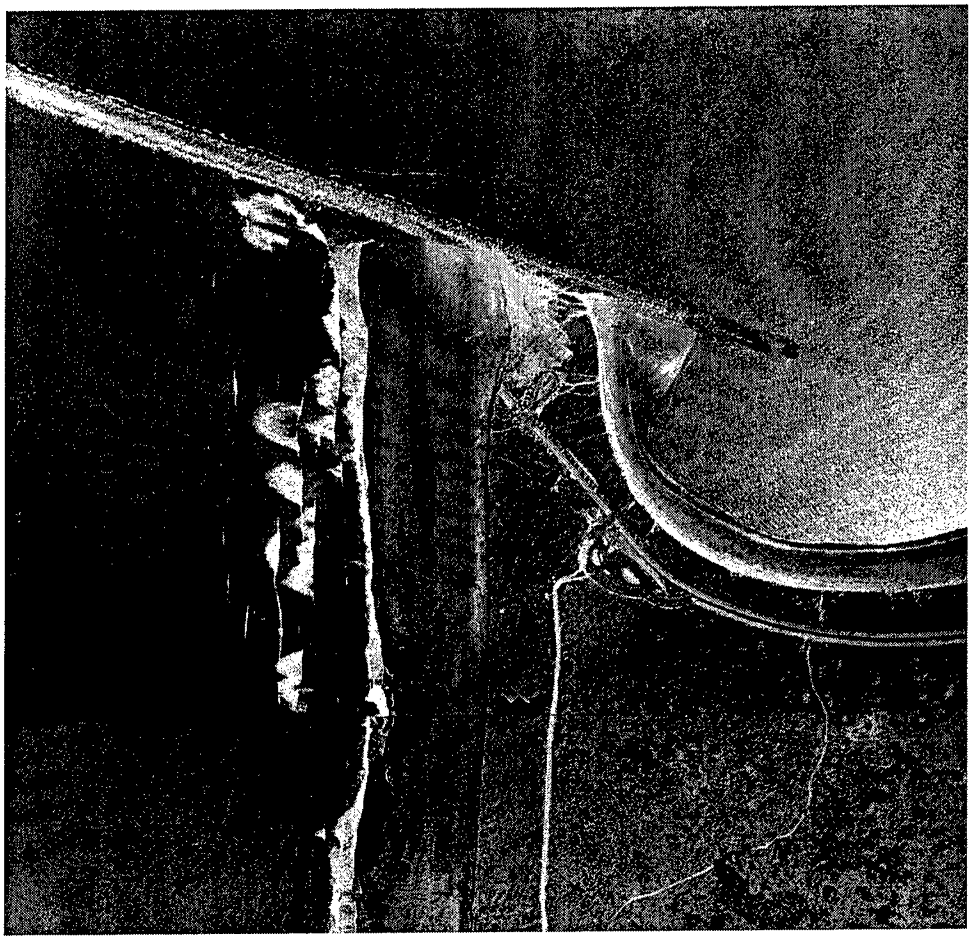

Figure A5. 23 May 1993


Figure A6. Breached area at Grays Harbor south jetty, January 1994

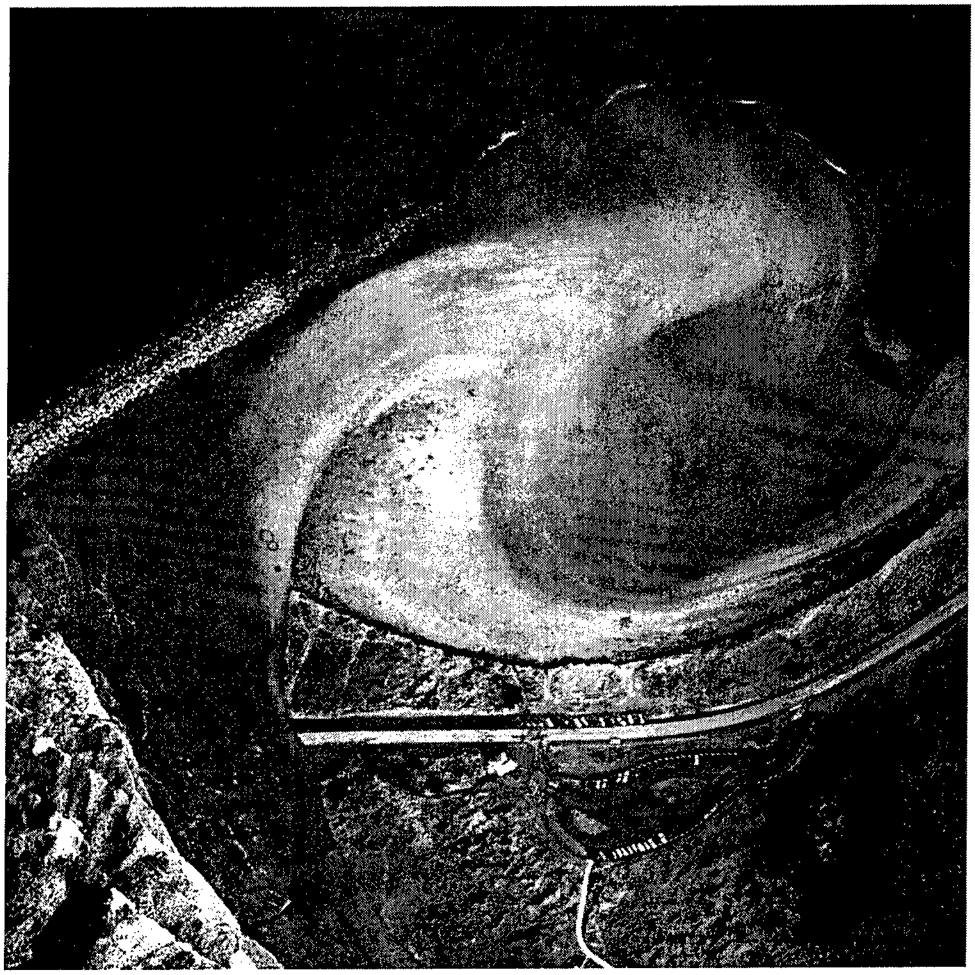

Figure A7. Breached area at Grays Harbor south jetty, 2 February 1994

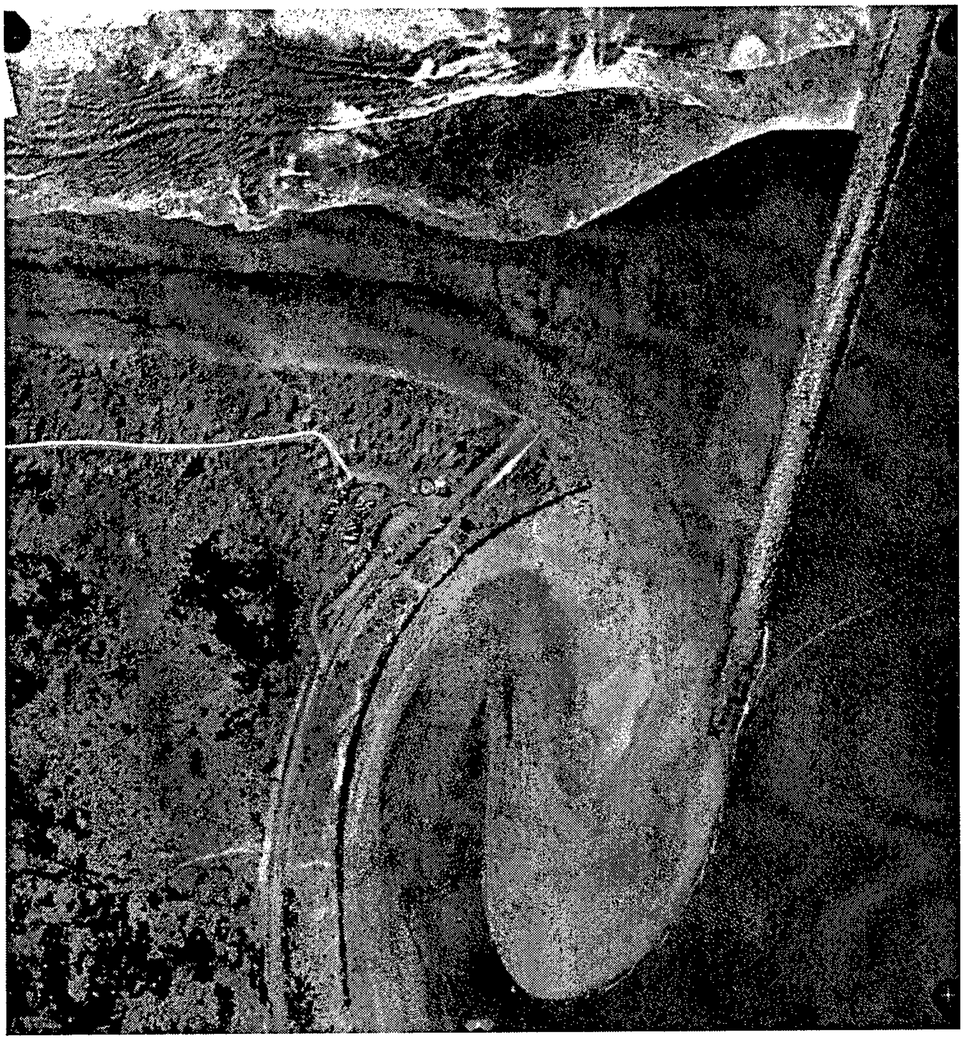

Figure A8. Breached area at Grays Harbor south jetty, 6 March 1994

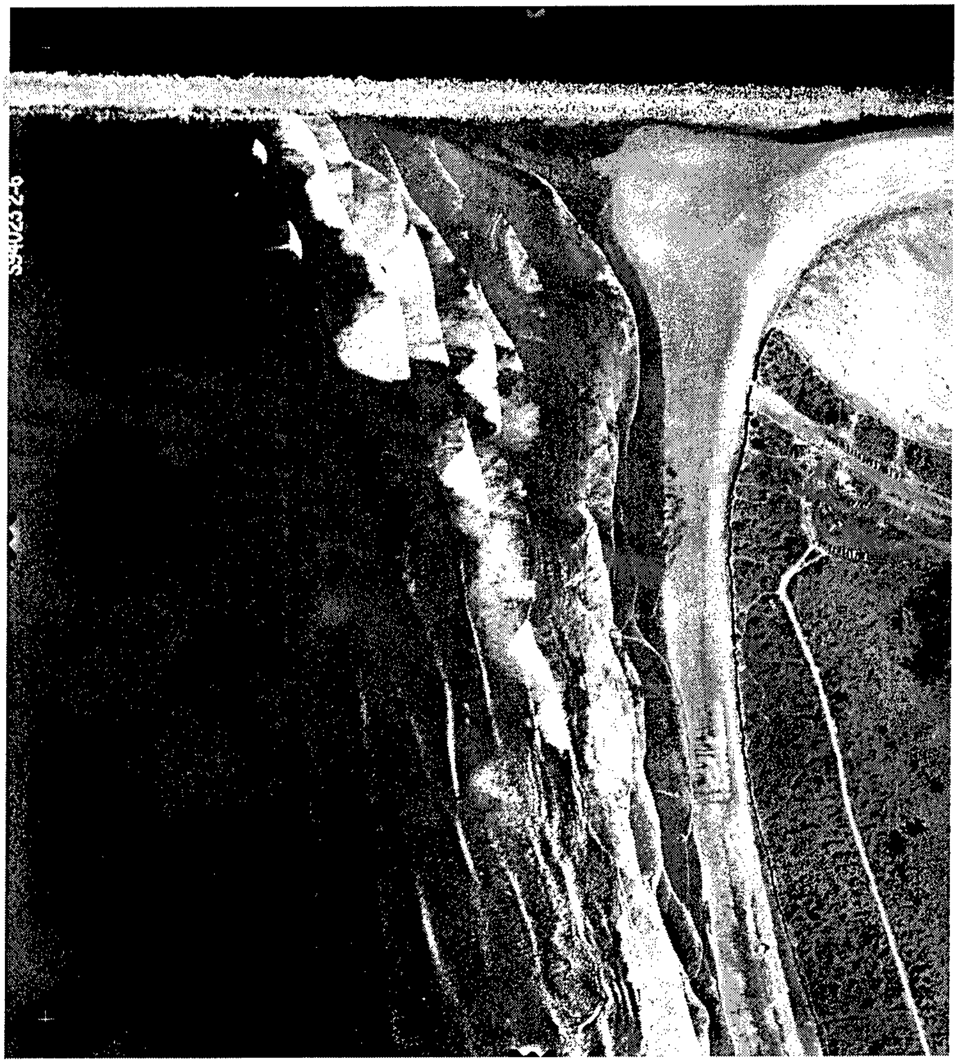

Figure A9. South Beach, 10 August 1994

Figure A10. South Beach, 30 July 1995

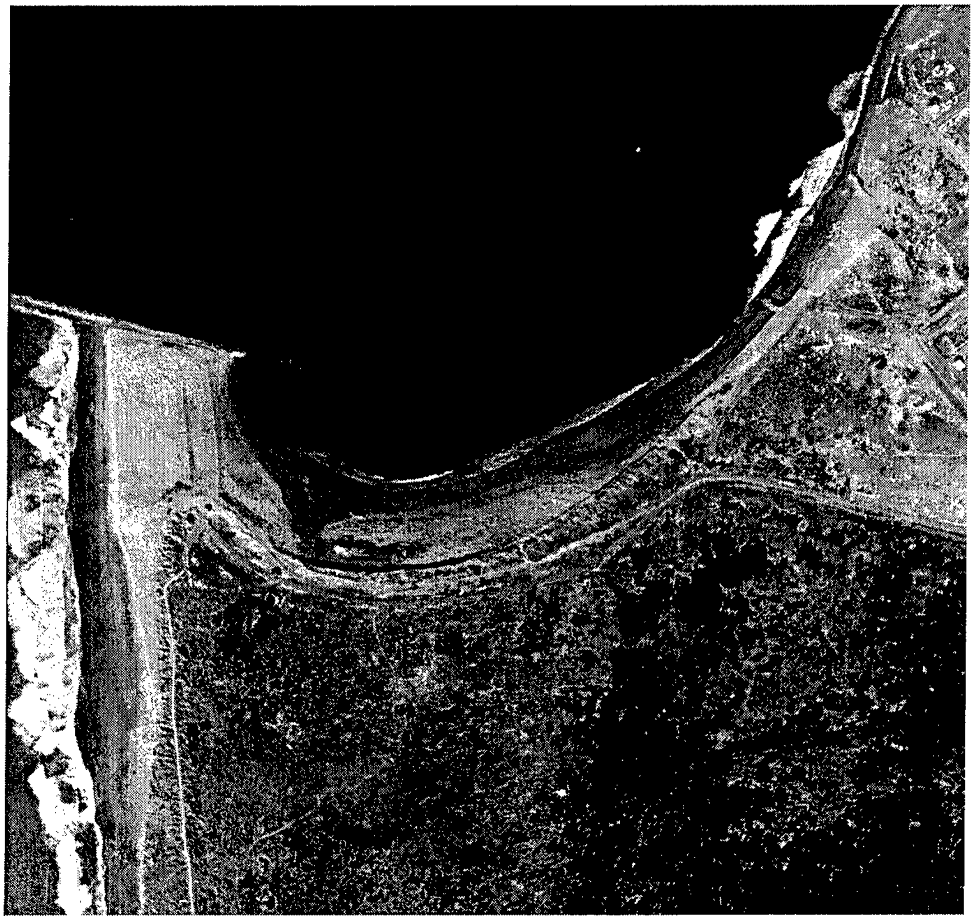

Figure A11. Half Moon Bay, 1 February 1996

Figure A12. 12 January 1997

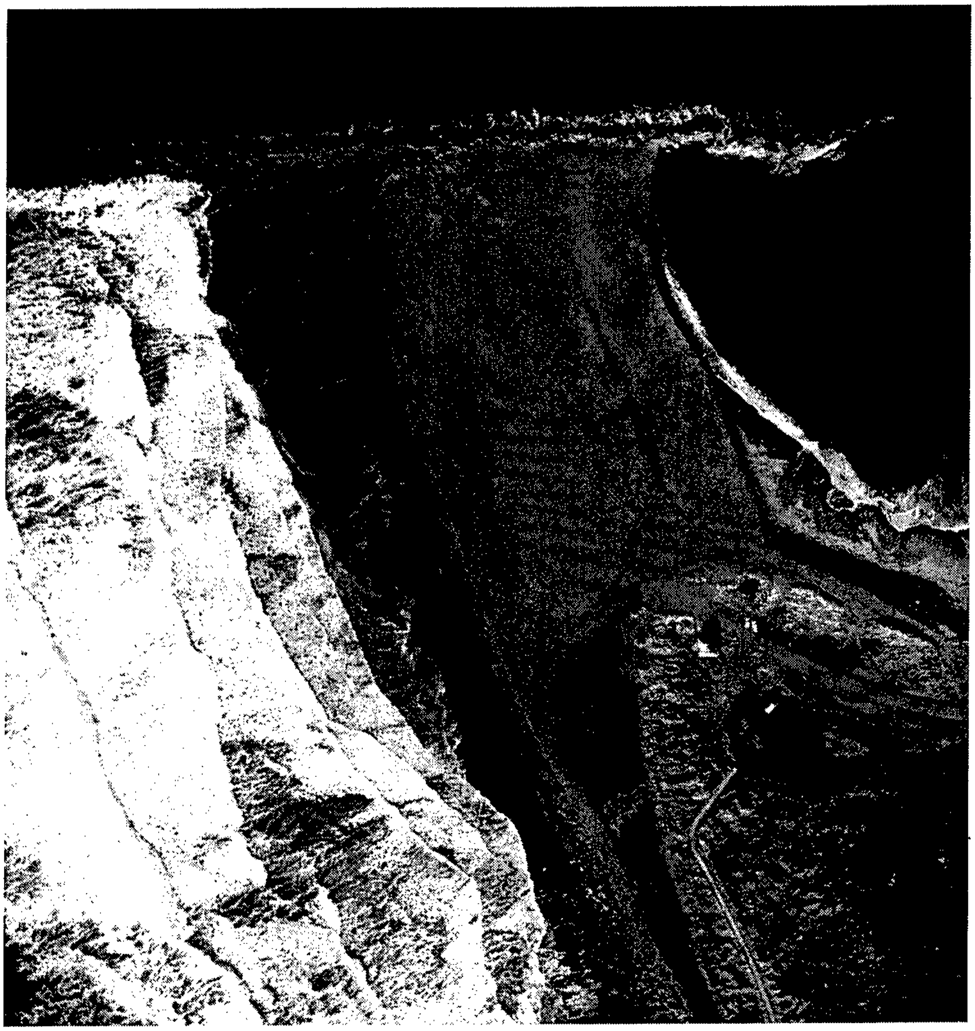

Figure A13. 30 January 1998

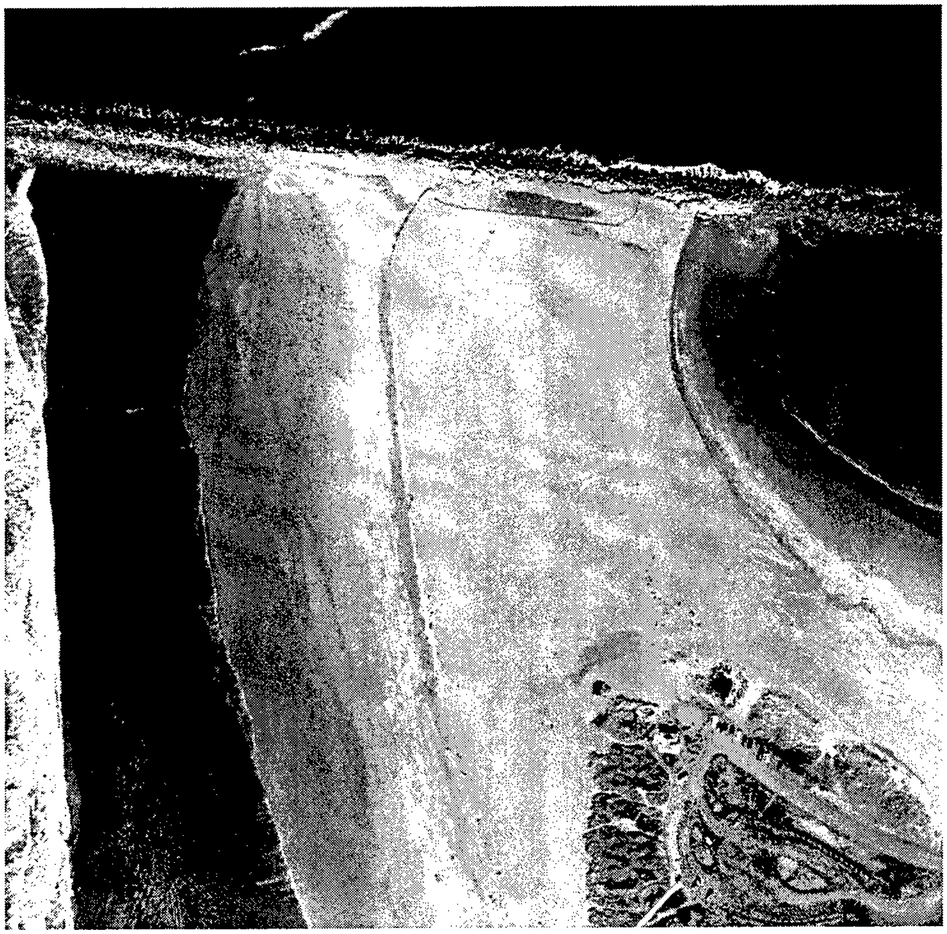

Figure A14. 1 April 1998

Figure A15. 1 April 1998

Figure A16.  16 May 1998

Figure A17. 13 July 1998

Figure A18. 26 January 1999

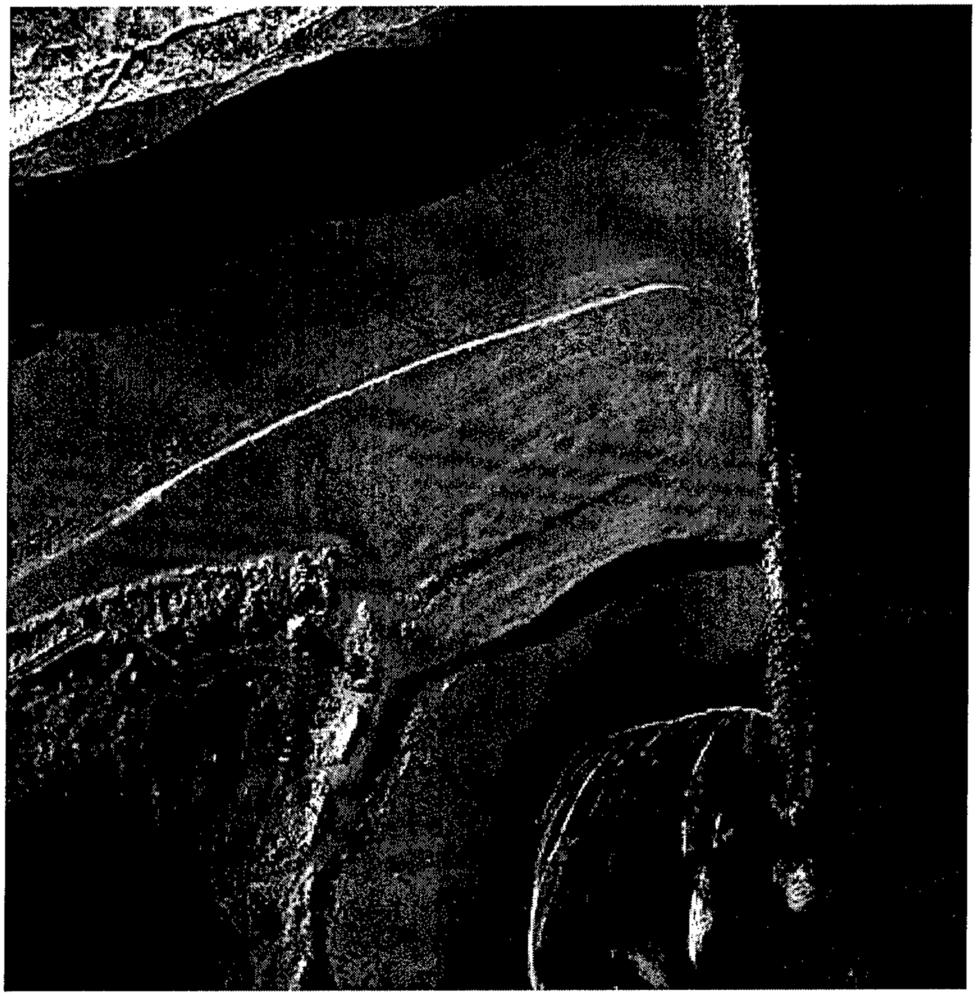

Figure A19. 26 January 1999

Figure A20. 6 March 1999

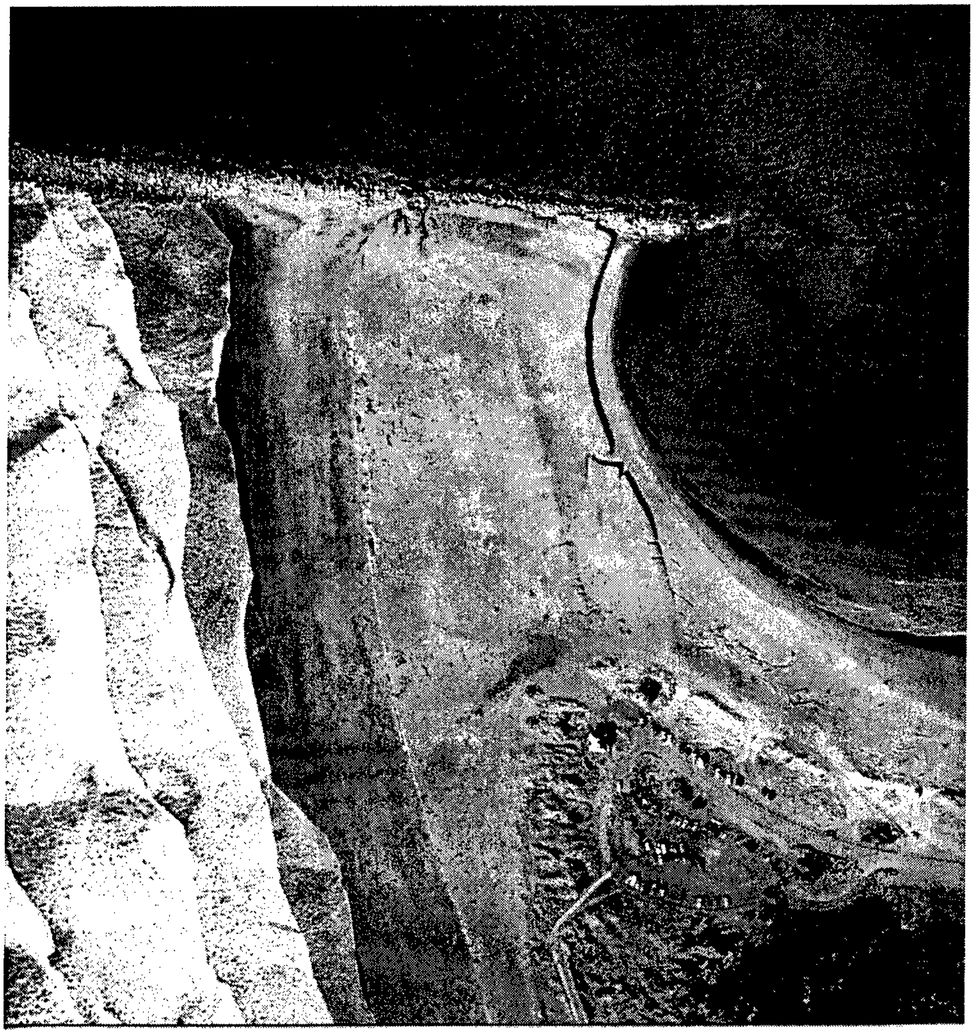

Figure A21. 6 March 1999

Figure A22. 3 June 1999

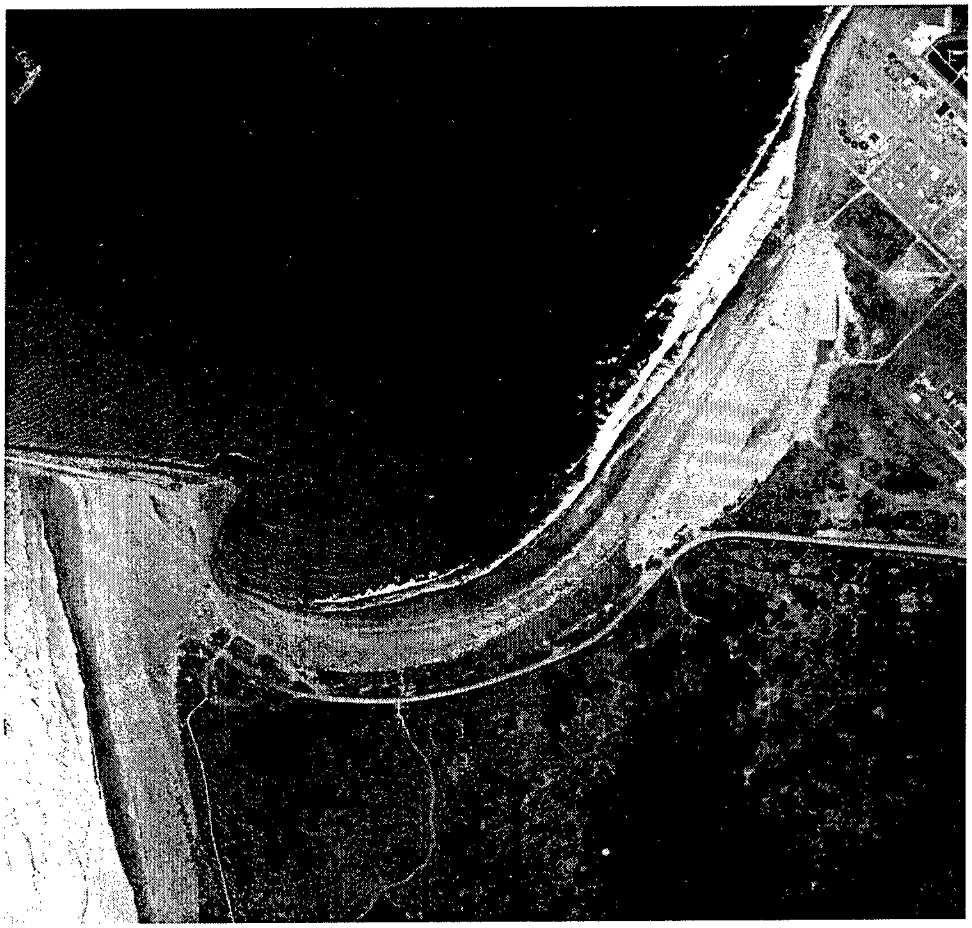

Figure A23. 23 May 2000

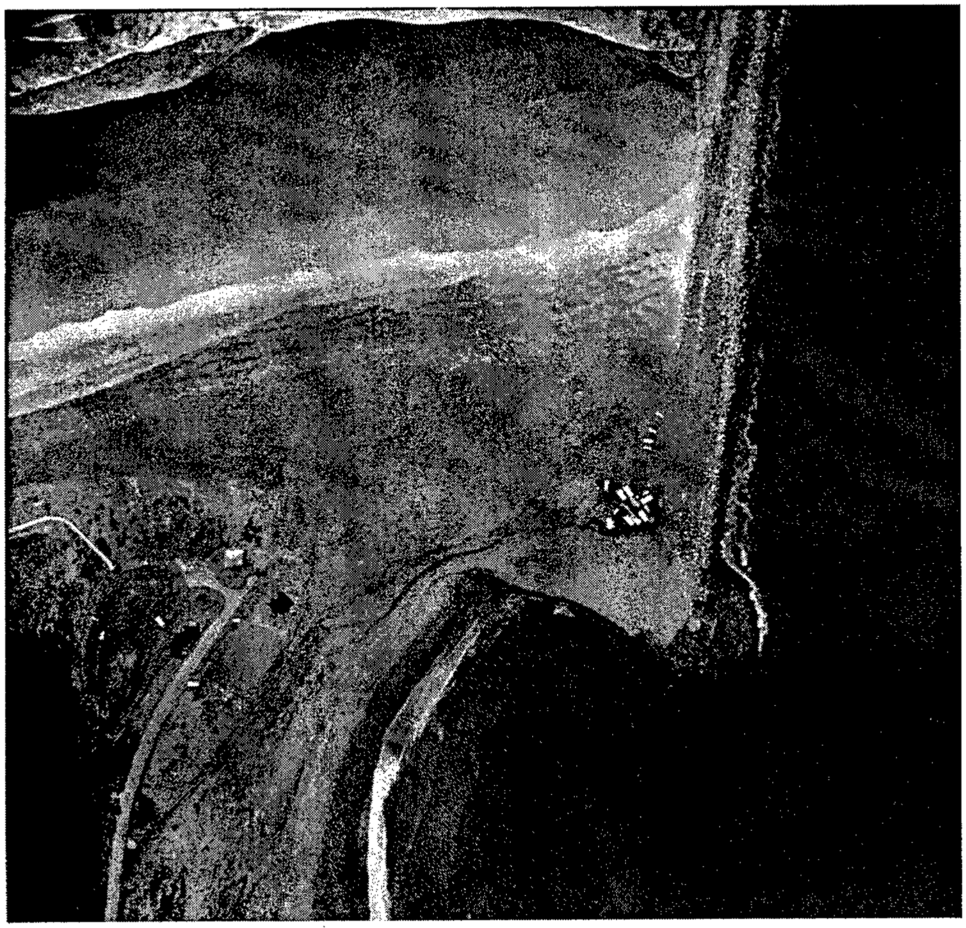

Figure A24. 6 November 2000

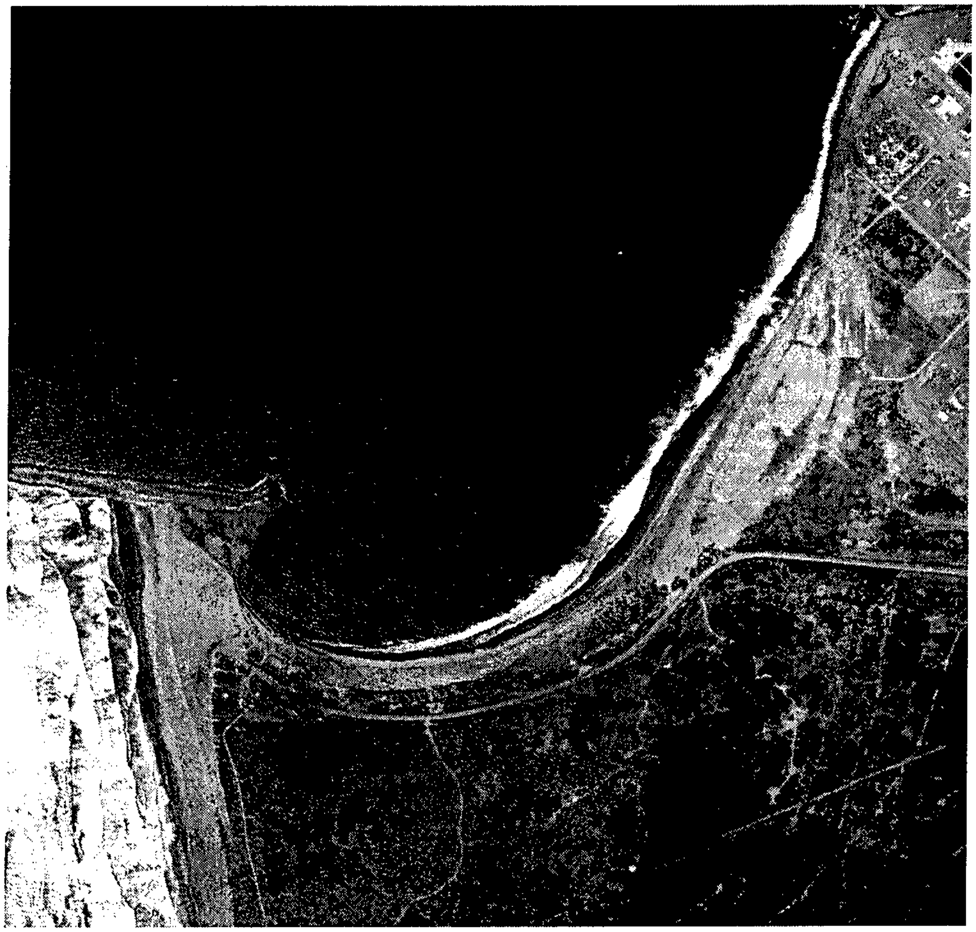

Figure A25. 25 April 2001

Figure A26. 24 May 2002

# Figures A27 – A33: Oblique Aerial Photographs

Figure A27. Breach, looking north, January 1994

Figure A28. East end of south jetty, looking southwest, 15 March 1999

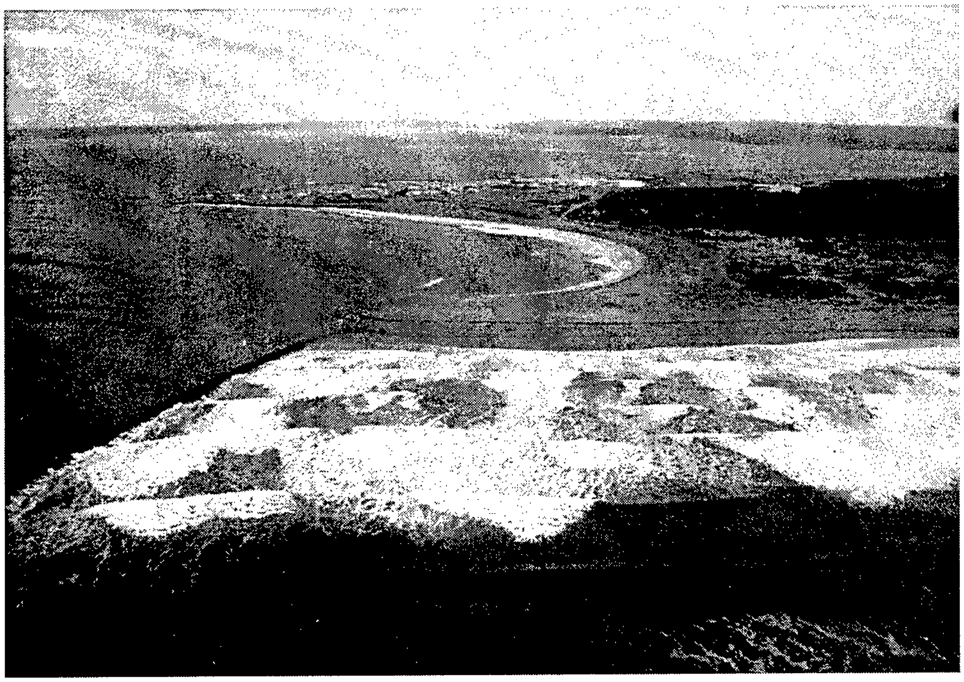

Figure A29. South jetty, looking east, 18 March 1999

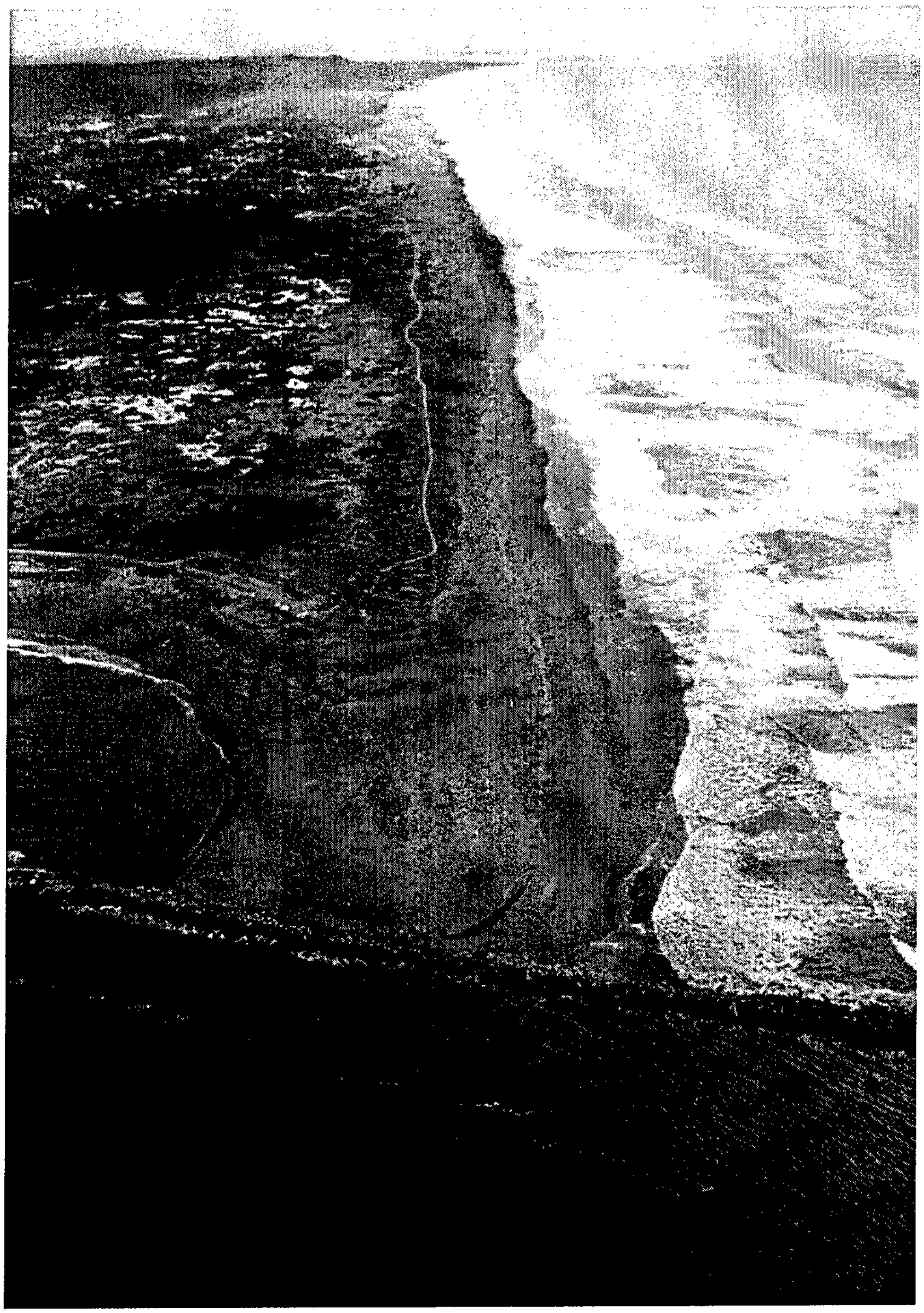

Figure A30. South jetty, looking south, 18 March 1999

Figure A31. South jetty, looking east, 25 March 1999

Figure A32. South jetty, looking south, 14 April 1999

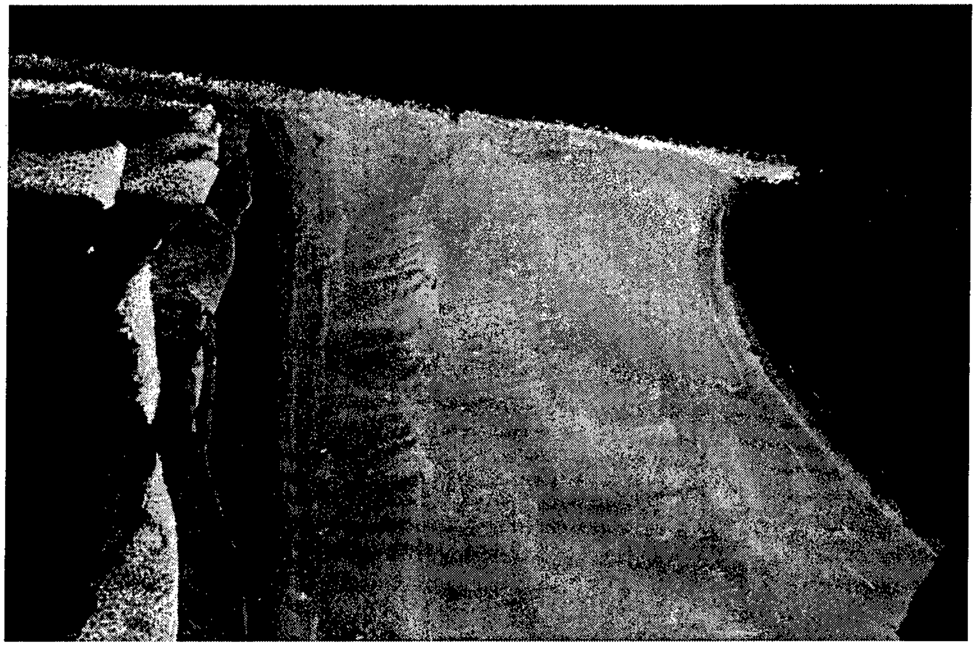

Figure A33. South Beach, 16 April 1999

## Figures A34 – A53: Ground-based Photographs

Figure A34. Half Moon Bay, looking west, 28 June 1994

Figure A35. Breach-fill transition area, looking west, 21 January 1999

Figure A36. Western end of Half Moon Bay, 6 March 2001

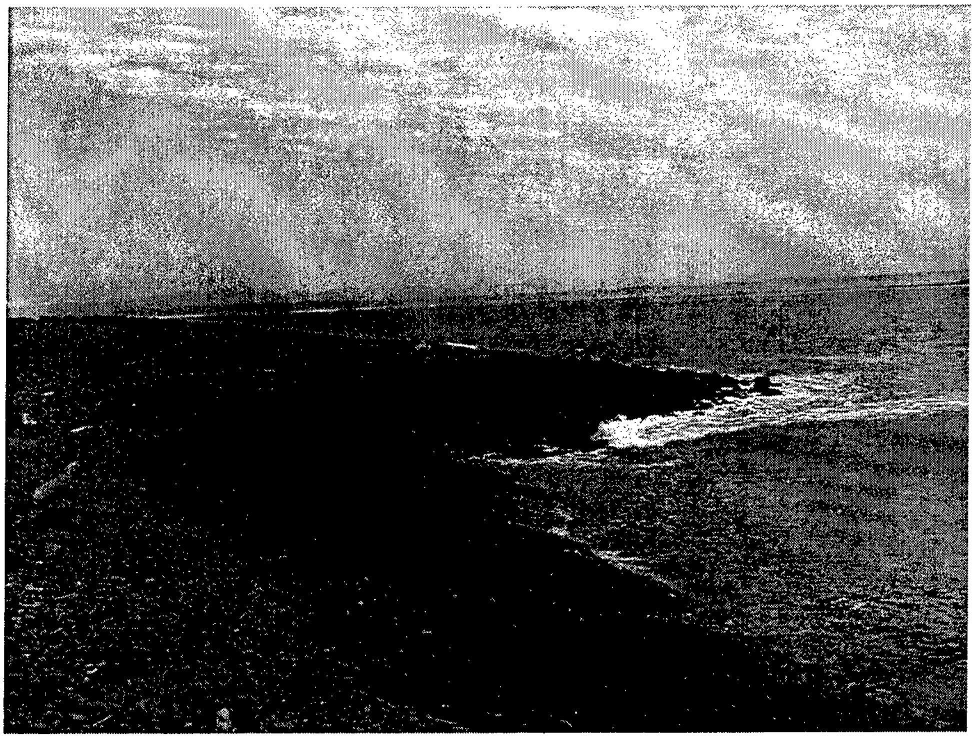

Figure A37. Wave diffraction mound, 6 March 2001

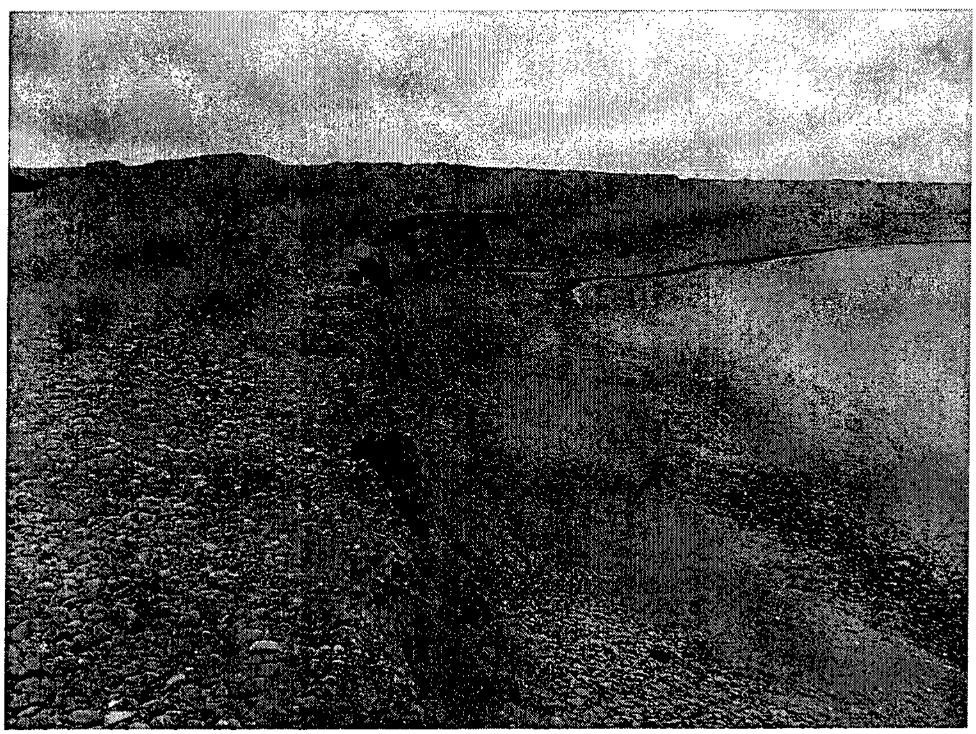

Figure A38. Half Moon Bay gravel transition zone and dune renourishment, 20 August 2002

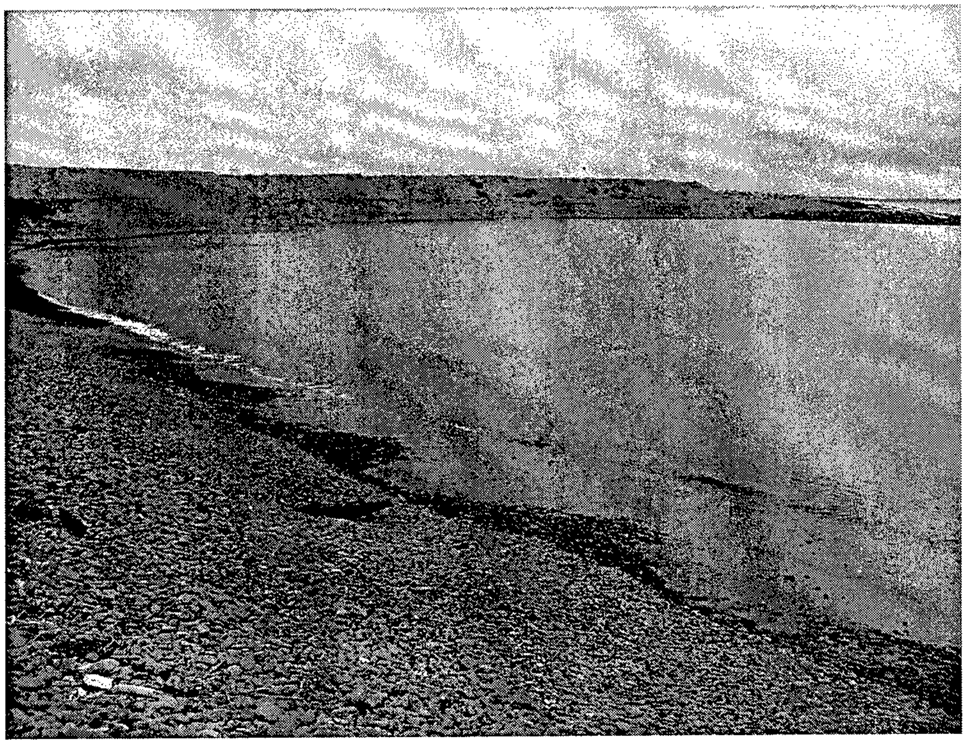

Figure A39. Half Moon Bay gravel transition zone and dune renourishment,
20 August 2002

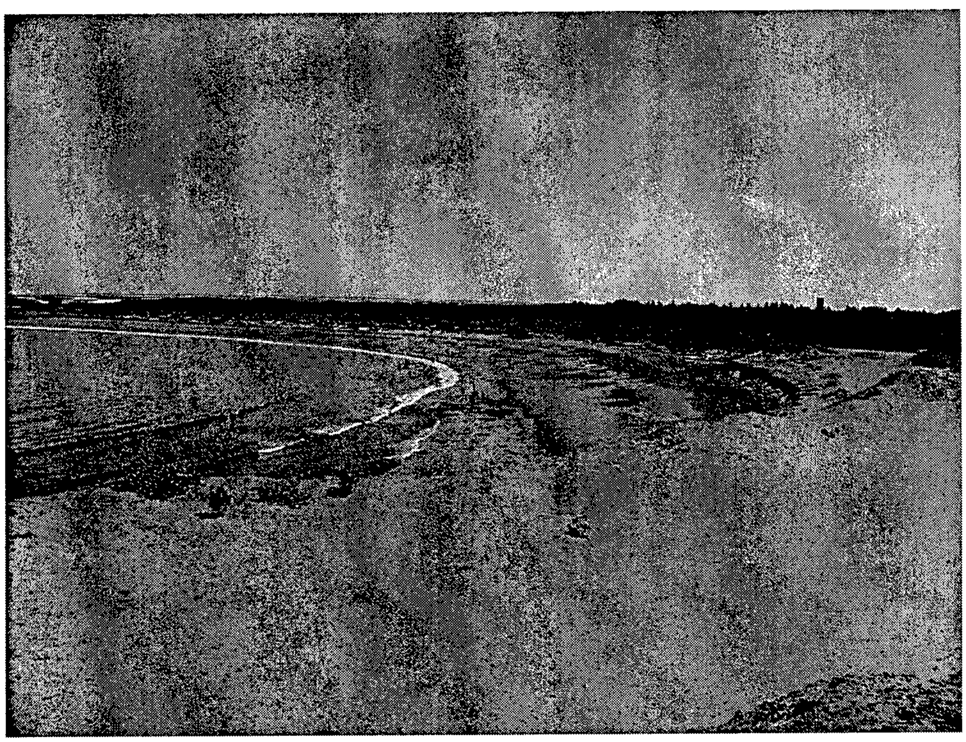

Figure A40. Half Moon Bay gravel transition zone and dune renourishment,
20 August 2002

Figure A41. Half Moon Bay, 1 February 2002

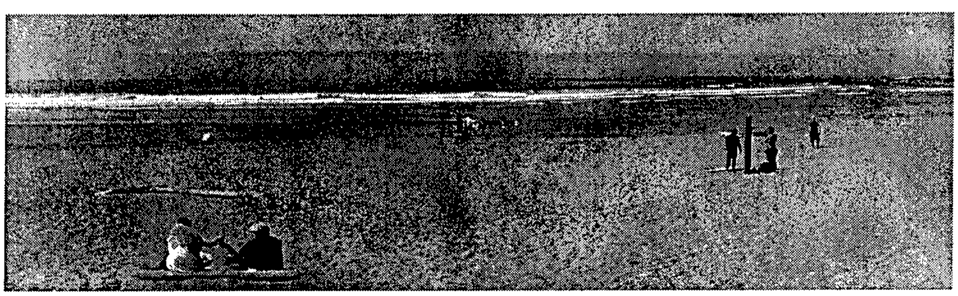

Figure A42. South Beach and south jetty; vertical pipe marks former location of park rest room, 24 August 1998

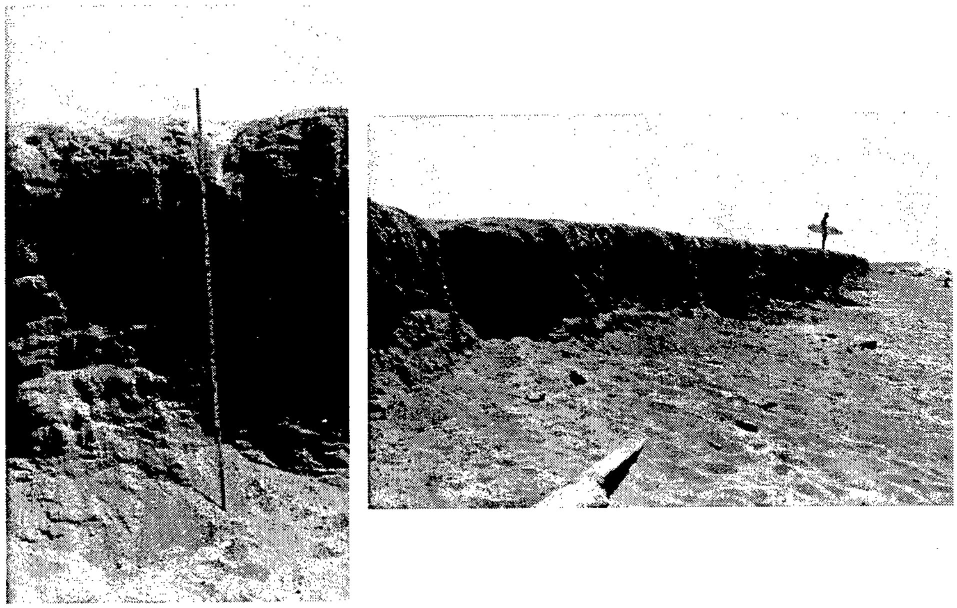

Figure A43. South Beach scarp near south jetty (scarp height is 5 ft), 24 August 1998

Figure A44. South Beach, 21 January 1999; pipe marks former location of park rest room

Figure A45. South Beach from dune renourishment, 20 August 2002; vertical pipe marks former location of park rest room

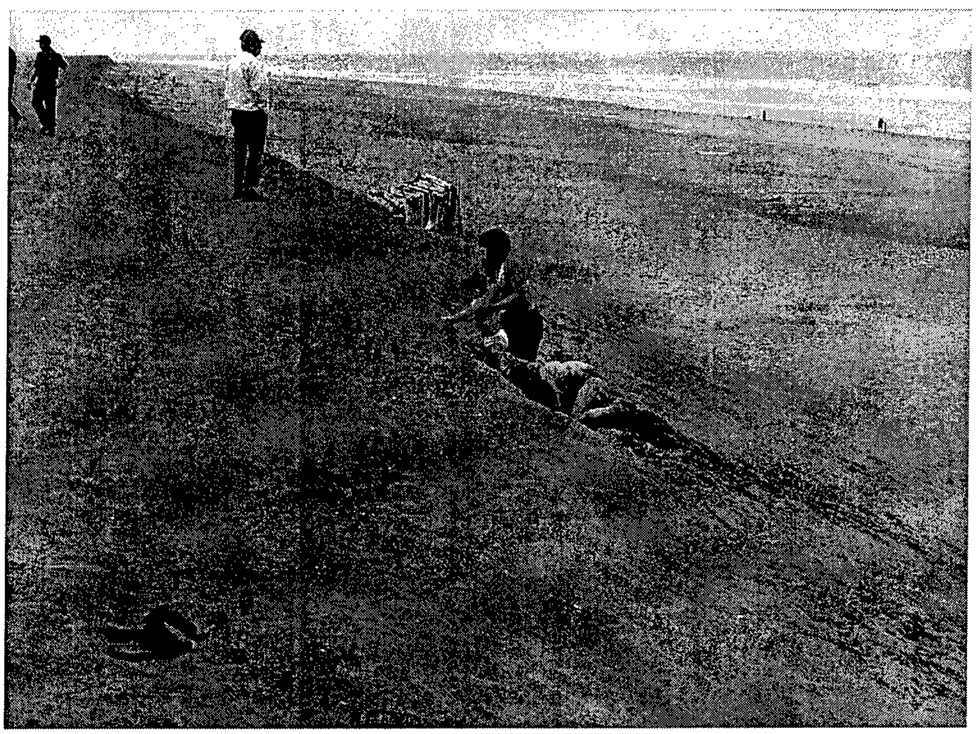

Figure A46. South Beach from dune renourishment, 20 August 2002

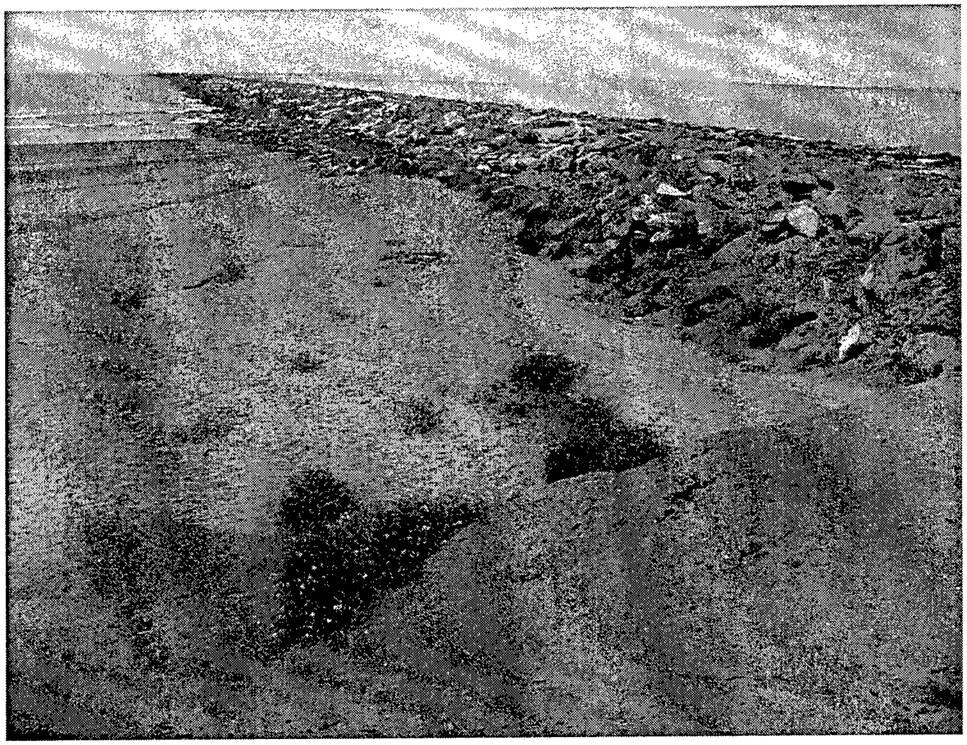

Figure A47. South jetty from dune renourishment, 20 August 2002

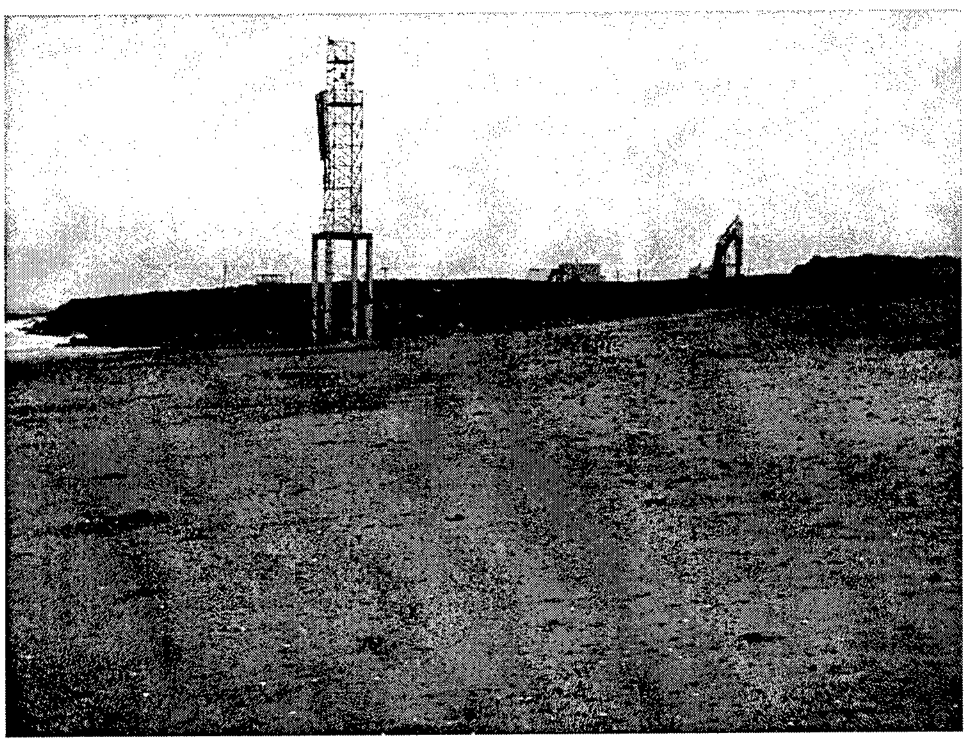

Figure A48. USCG Range tower seaward of Point Chehalis revetment,
21 January 1999

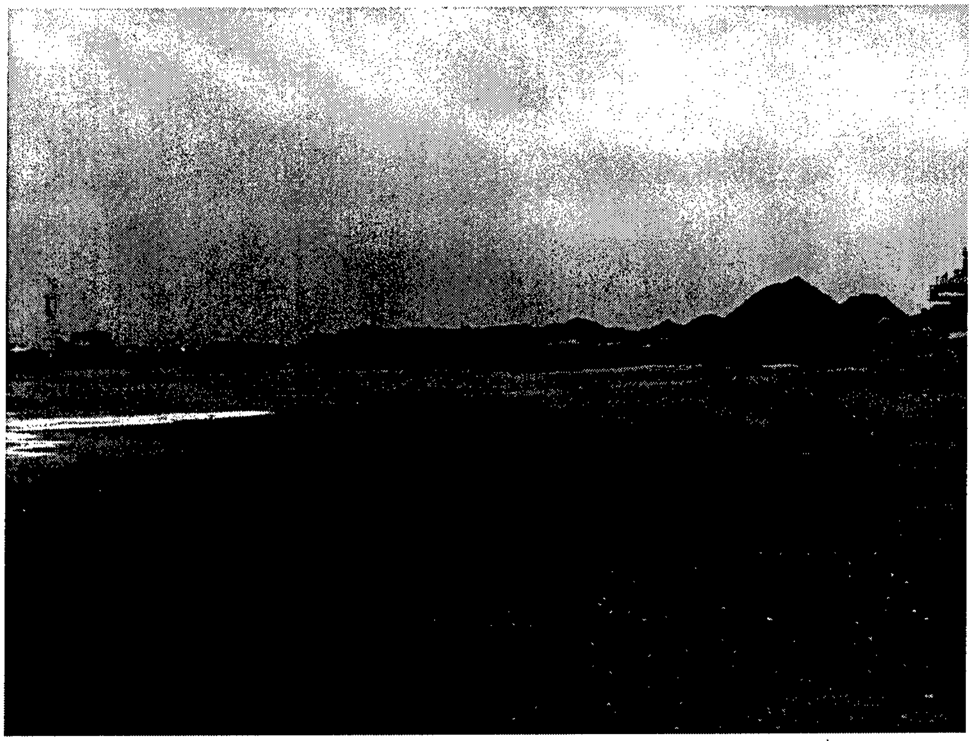

Figure A49. Point Chehalis revetment fill, 21 January 1999

Figure A50. Half Moon Bay shoreline and northwest of Point Chehalis revetment, 1 February 2002

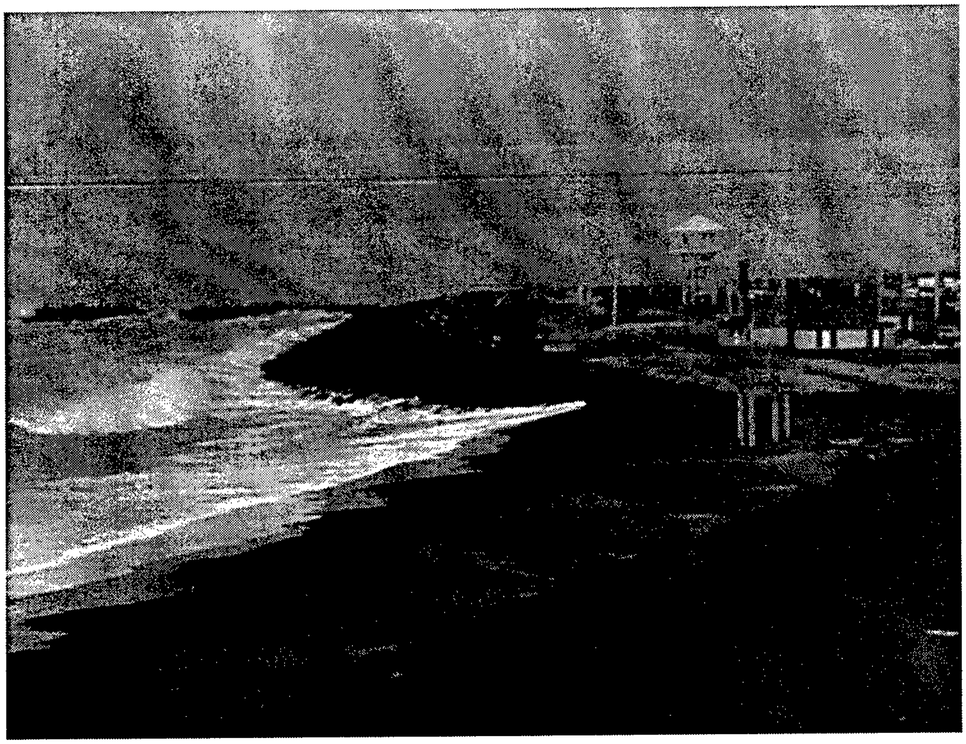

Figure A51. Half Moon Bay shoreline and northwest of Point Chehalis revetment, 1 February 2002

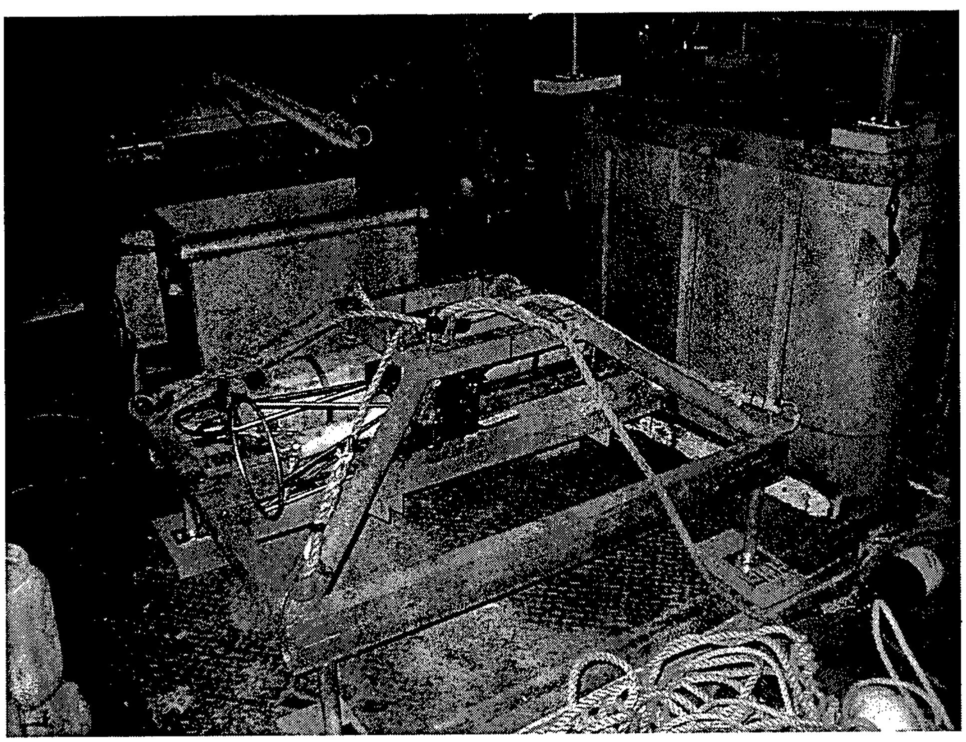

Figure A52. Wave gauge deployed in Half Moon Bay, 6 March 2002

Figure A53. Wave gauge recovery Half Moon Bay, 30 April 2002

# Appendix B
# Bathymetry Surveys for Morphological Change Analysis

This appendix lists the Seattle District surveys and corresponding filenames used to create the bathymetric surfaces for the morphological change analysis documented in Chapter 4.

| PI Engineering Summary Bathymetry | Seattle District Survey File | Survey Date | Seattle District Project Name | Seattle District Survey Type |
|---|---|---|---|---|
| | 2002gr038 | 07 Feb 02 | Grays Harbor, South Channel | Condition |
| blowout_02-26-02 | 2002gr039a | 12 Feb 02 | Grays Harbor, Blow out, Cross Sections | Condition |
| | 2002gr039b | 13 Feb 02 | Grays Harbor, Blow out, Cross Sections | Condition |
| | 2002gr039c | 12 Feb 02 | Grays Harbor, Blow out, Cross Sections | Condition |
| | 2002gr039d | 12 Feb 02 | Grays Harbor, Blow out, range lines | Condition |
| | 2002gr039e | 25 Feb 02 | Grays Harbor, Rock Dock for the Blow out | Condition |
| | 2002gr040 | 26 Feb 02 | Grays Harbor, Entrance Channel | Condition |
| blowout_09-25-01 | 2001gr050a | 24 Sep 01 | Grays Harbor, Blowout, Cross Sections | Condition |
| | 2001gr050b | 25 Sep 01 | Grays Harbor, Blowout, Cross Sections | Condition |
| | 2001gr038a | 05 Jun 01 | Grays Harbor, Entrance Channel, blow out, Cross Sections | After Dredge |
| blowout_06-05-01 | 2001gr038b | 05 Jun 01 | Grays Harbor, Entrance Channel, blow out, Cross Sections | After Dredge |
| | 2001gr038c | 05 Jun 01 | Grays Harbor, Entrance Channel, blow out, Cross Sections | After Dredge |
| | 2001gr021a | 12 Feb 01 | Grays harbor, Entrance Channel, Cross sections | Condition |
| blowout_02-21-01 | 2001gr021b | 21 Feb 01 | Grays harbor, Pt. Chehalis Reach, Cross sections | Condition |
| | 2001gr021c | 15 Feb 01 | Grays harbor, Pt. Chehalis Reach, Cross sections | Condition |

(Sheet 1 of 4)

| PI Engineering Summary Bathymetry | Seattle District Survey File | Survey Date | Seattle District Project Name | Seattle District Survey Type |
|---|---|---|---|---|
| | 2000gr052a | 06 Sep 00 | Grays harbor, blowout/Pt Chehalis Reach, Cross sections | Condition |
| blowout_09-06-00 | 2000gr052b | 05 Sep 00 | Grays harbor, blowout/Pt Chehalis Reach, Cross sections | Condition |
| | 2000gr052c | 06 Sep 00 | Grays harbor, blowout/entrance channel, Cross sections | Condition |
| | 2000gr044a | 06 Jun 00 | Grays harbor, Blow out-Entrance Channel, Cross sections | After Dredge |
| blowout_06-08-00 | 2000gr044b | 07 Jun 00 | Grays harbor, Blow out-Entrance Channel, Cross sections | After Dredge |
| | 2000gr044c | 08 Jun 00 | Grays harbor, Blow out-Entrance Channel, Cross sections | After Dredge |
| | 2000gr021a | 03 Apr 00 | Grays Harbor,Washington, Entrance Channel, Cross sections | Condition |
| blowout_04-05-00 | 2000gr021b | 03 Apr 00 | Grays Harbor,Washington, Entrance Channel, Cross sections | Condition |
| | 2000gr021c | 03 Apr 00 | Grays Harbor,Washington, Entrance Channel, Cross sections | Condition |
| blowout_02-07-00 | 2000gr007a | 03 Feb 00 | Grays Harbor, Blowout | Condition |
| | 2000gr007b | 07 Feb 00 | Grays Harbor, Entrance Channel, cross sections | Condition |

**(Sheet 2 of 4)**

| PI Engineering Summary Bathymetry | Seattle District Survey File | Survey Date | Seattle District Project Name | Seattle District Survey Type |
|---|---|---|---|---|
| blowout_11-02-99 | 2000gr001 | 02 Nov 99 | Grays Harbor, Blow Out Survey, Entrance Channel, Cross sections | Condition |
| blowout_06-09-99 | 1999gr043a | 04 Jun 99 | Grays Harbor, Blowout | After Dredge |
| | 1999gr043b | 09 Jun 99 | Grays Harbor, Blowout | After Dredge |
| | 1999gr043c | 09 Jun 99 | Grays Harbor, Blowout | After Dredge |
| | 1999gr043d | 09 Jun 99 | Grays Harbor, Blowout | After Dredge |
| blowout_05-17-99 | 1999gr036a | 17 May 99 | Grays Harbor, entrance Channel, Blowout | Progress |
| | 1999gr036b | 17 May 99 | Grays Harbor, PT Chehalis, Blowout | Progress |
| blowout_10-01-98 | 1999gr001a | 01 Oct 98 | Grays Harbor, Entrance channel, Blowout | Condition |
| | 1999gr001b | 01 Oct 98 | Grays Harbor, Entrance channel, Blowout | Condition |
| | 1999gr001c | 01 Oct 98 | Grays Harbor, Entrance channel, Blowout | Condition |
| blowout_06-05-98 | 1998gr040a | 03 Jun 98 | Grays Harbor, Blowout Survey | Condition |
| | 1998gr040b | 04 Jun 98 | Grays Harbor, Blowout Survey | Condition |
| | 1998gr040c | 05 Jun 98 | Grays Harbor, Blowout Survey | Condition |
| blowout_05-07-98 | 1998gr027a | 04 May 98 | Grays Harbor, Blowout Survey | Condition |
| | 1998gr027b | 05 May 98 | Grays Harbor, Blowout survey | Condition |
| | 1998gr027c | 07 May 98 | Grays Harbor, Blowout Survey | Condition |

(Sheet 3 of 4)

| PI Engineering Summary Bathymetry | Seattle District Survey File | Survey Date | Seattle District Project Name | Seattle District Survey Type |
|---|---|---|---|---|
| blowout_03-02-98 | 1998gr013 | 02 Mar 98 | Blowout | Condition |
| blowout_02-10-98 | 1998gr010a | 05 Feb 98 | Blowout | Condition |
| | 1998gr010b | 10 Feb 98 | Blowout | Condition |
| blowout_10-28-97 | 1998gr002 | 28 Oct 97 | Blowout | Condition |
| blowout_07-02-97 | 1997gr037 | 02 Jul 97 | Entrance Channel | Condition |
| blowout_09-30-96 | 1996gr068a | 30 Sep 96 | Blowout | Condition |
| | 1996gr068b | 30 Sep 96 | Blowout | Condition |
| blowout_08-27-96 | 1996gr059a | 27 Aug 96 | Blowout | Condition |
| | 1996gr059b | 27 Aug 96 | Blowout | Condition |
| blowout_06-07-96 | 1996gr051a | 25-28 May 96 | Grays Harbor Annual 1996 | Annual |
| | 1996gr051b | 29 May 96 | Grays Harbor Annual 1996 | Annual |
| | 1996gr051c | 4,6,7 Jun 96 | Grays Harbor Annual 1996 | Annual |

(Sheet 4 of 4)

# REPORT DOCUMENTATION PAGE

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**5c. PROGRAM ELEMENT NUMBER**

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Philip D. Osborne, Ty V. Wamsley, Hiram T. Arden

With assistance by
Zeki Demirbilek, Nicholas C. Kraus, Robert M. Parry, William C. Seabergh, Vladimir Shepsis, and David P. Simpson

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**14. ABSTRACT**

Grays Harbor is located on the southwest Washington coast at the mouth of the Chehalis River, about 45 miles north of the Columbia River mouth. The harbor is 13 miles wide at its broadest point and 15 miles long from Aberdeen, WA, on the east to the entrance o the west. Two convergent rock jetties, a north jetty and a south jetty, are part of the Grays Harbor navigation project, which is a federally constructed and maintained navigation channel. Development of the channels and facilities at Grays Harbor has been a continuing process since the Rivers and Harbors Act of June 1896 authorized the construction of the south jetty. Maintenance dredging has been required after the 1990 Grays Harbor navigation improvement project was completed.

The U.S. Army Engineer District, Seattle requested a study to evaluate the engineering features and maintenance measures in the vicinity of the south jetty. The south jetty sediment processes study was developed and keyed to elements of a plan of action. The purpose of the study is to evaluate the performance of engineering and maintenance measures that have been implemented to control breaching next

(Continued)

**15. SUBJECT TERMS**

| | | |
|---|---|---|
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| Channel Jetty | Navigation | Washington |
| Deep Draft | Sediment Transport | Waves |

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to the south jetty, and to reduce shoreline erosion in Half Moon Bay and placement of dredged material to alleviate erosion. Another study in a series on the south jetty is in progress to document the analysis of a breached condition and assess the risk of future breaching.

This report documents the history of the south jetty and related engineering structures, and reviews previous studies relevant to the acting coastal processes. It includes reviews of dredging and disposal activities associated with maintenance and new work dredging, analysis of the wave diffraction mound performance, analysis of upland and intertidal topography and nearshore bathymetry surveys, analysis of shoreline position change, identification of sediment pathways, and a sediment budget. The performance of the engineering and maintenance measures is then evaluated based on these results. The role of continued periodic nourishment activities is also assessed.