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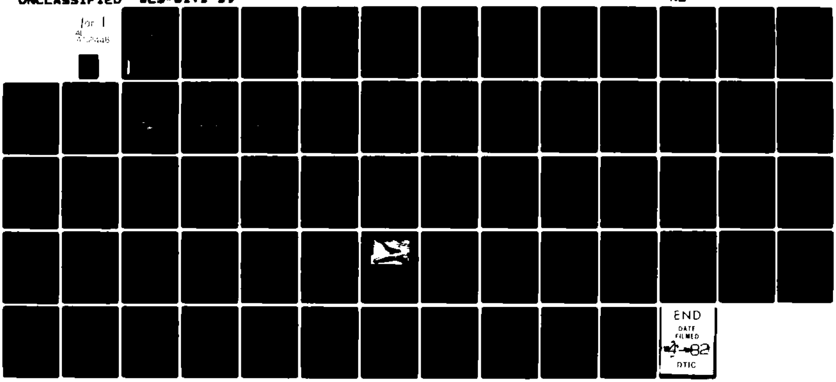

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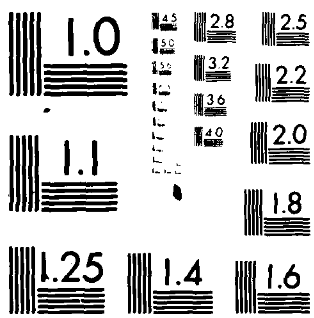

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Tidal Inlet Response to Jetty Construction

by

James M. Kieslich

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Cover Photo: Masonboro Inlet, North Carolina, July 1974

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Thirteen tidal inlets located on the Atlantic, gulf, and Pacific coasts of the continental United States were selected for a study of the response of inlet ocean entrances to manmade improvements. Inlet entrance behavior following jetty construction were evaluated and guidelines for the functional design of inlet entrance improvements are suggested. The inlets considered in the study were those where a single updrift or downdrift jetty was built first.

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The construction of single jetties at inlet entrances has resulted in migration of the channel thalweg toward the jetty regardless of the inlet-bay orientation, the jetty angle with the shoreline, the position of the jetty relative to the direction of net longshore sediment transport, the ratio of net-to-gross transport, or the gross transport. In some cases, this has caused undermining of the jetty.

For the inlets studied, the annual channel thalweg migration averaged 31 percent of the total distance available for migration following construction of a single updrift jetty, and 49 percent of the total distance available for migration following construction of a single downdrift jetty.

Accretion at the updrift shoreline and erosion at the downdrift shoreline usually followed construction of a single updrift jetty. Accretion rates at the updrift shoreline ranged up to about 800 feet (244 meters) per year. Data on erosion rates of the downdrift shoreline following construction of an updrift jetty were available for only a limited number of inlets. Sufficient information was not available to generalize the response of either adjacent shoreline following construction of a single downdrift jetty.

The channel cross-sectional area usually decreased following construction of a single updrift jetty; the decrease in area ranging up to 40 percent. Sufficient data were not available to quantify channel area response following construction of a single downdrift jetty.

FOREWORD

This report is one of a series of reports on the General Investigation of Tidal Inlets (GITI). The GITI research program is under the technical surveillance of the U.S. Army Coastal Engineering Research Center (CERC) and is conducted by CERC, WES, other government agencies, and by private organizations. This report presents results of a study to investigate the response of inlets and adjacent beaches to structural inlet improvements, with the aim of providing improved design guidelines for future inlet improvements.

The report was prepared by James M. Kieslich, formerly of CERC and currently at the U.S. Army Engineer District, Galveston. CERC technical direction was provided by C. Mason under the general supervision of R.M. Sorensen, Chief, Coastal Processes and Structures Branch. Dean M.P. O'Brien and Professor R.L. Wiegel, civilian members of the Coastal Engineering Research Board, reviewed the report.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

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Commander and Director
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PREFACE

1. The Corps of Engineers, through its Civil Works Program, has sponsored, over the past 23 years, research into the behavior and characteristics of tidal inlets. The Corps' interest in tidal inlet research stems from its responsibilities for navigation, beach erosion prevention and control, and flood control. Tasked with the creation and maintenance of navigable U.S. waterways, the Corps dredges millions of cubic yards of material each year from tidal inlets that connect the ocean with bays, estuaries, and lagoons. Design and construction of navigation improvements to existing tidal inlets are an important part of the work of many Corps' offices. In some cases, design and construction of new inlets are required. Development of information concernin, the hydraulic characteristics of inlets is important not only for navigation and inlet stability, but also because inlets, by allowing for the ingress of storm surges and egress of flood waters, play an important role in the flushing of bays and lagoons.

2. A research program, the General Investigation of Tidal Inlets (GITI), was developed to provide quantitative data for use in design of inlets and inlet improvements. It is designed to meet the following objectives:

> To determine the effects of wave action, tidal flow, and related phenomena on inlet stability and on the hydraulic, geometric, and sedimentary characteristics of tidal inlets; to develop the knowledge necessary to design effective navigation improvements, new inlets, and sand transfer systems at existing tidal inlets; to evaluate the water transfer and flushing capability of tidal inlets; and to define the processes controlling inlet stability.

3. The GITI is divided into three major study areas: (a) inlet classification, (b) inlet hydraulics, and (c) inlet dynamics.

a. Inlet Classification. The objectives of the inlet classification study are to classify inlets according to their geometry, hydraulics, and stability, and to determine the relationships that exist among the geometric and dynamic characteristics and the environmental factors that control these characteristics. The classification study keeps the general investigation closely related to real inlets and produces an important inlet data base useful in documenting the characteristics of inlets.

b. Inlet Hydraulics. The objectives of the inlet hydraulics study are to define tide-generated flow regime and water level fluctuations in the vicinity of coastal inlets and to develop techniques for predicting these phenomena. The inlet hydraulics study is divided into these areas: (1) idealized inlet model study, (2) evaluation of state-of-the-art physical and numerical models, and (3) prototype inlet hydraulics.

(1) The idealized Inlet Model. The objectives of this model study are to determine the effect of inlet configurations and structures on discharge, head loss, and velocity distribution for a number of realistic inlet shapes and tide conditions. An initial set of tests in a trapezoidal inlet was conducted between 1967 and 1970. However, in order that subsequent inlet models are more representative of real inlets, a number of "idealized" models representing various inlet morphological classes are being developed and tested. The effects of jetties and wave action on the hydraulics are included in the study.

(2) Evaluation of State-of-the-Art Modeling Techniques. The objectives of this part of the inlet hydraulics study are to determine the usefulness and reliability of existing physical and numerical modeling techniques in predicting the hydraulic characteristics of inlet-bay systems, and to determine whether simple tests, performed rapidly and economically, are useful in the evaluation of proposed inlet improvements. Masonboro Inlet, North Carolina, was selected as the prototype inlet which would be used along with hydraulic and numerical models in the evaluation of existing techniques. In September 1969 a complete set of hydraulic and bathymetric data was collected at Masonboro Inlet. Construction of the fixed-bed physical model was initiated in 1969, and extensive tests have been performed since then. In addition, three existing numerical models were applied to predict the inlet's hydraulics. Extensive field data were collected at Masonboro Inlet in August 1974 for use in evaluating the capabilities of the physical and numerical models.

(3) Prototype Inlet Hydraulics. Field studies at a number of inlets are providing information on prototype inlet-bay tidal hydraulic relationships and the effects of friction, waves, tides, and inlet morphology on these relationships.

c. Inlet Dynamics. The basic objective of the inlet dynamics study is to investigate the interactions of tidal flow, inlet configuration, and wave action at tidal inlets as a guide to improvement of inlet channels and nearby shore protection works. The study is subdivided into four specific areas: (1) model materials evaluation, (2) movable-bed modeling evaluation, (3) reanalysis of a previous inlet model study, and (4) prototype inlet studies.

(1) Model Materials Evaluation. This evaluation was initiated in 1969 to provide data on the response of movable-bed model materials to waves and flow to allow selection of the optimum bed materials for inlet models.

(2) Movable-Bed Model Evaluation. The objectives of this study is to evaluate the state-of-the-art of modeling techniques, in this case movable-bed inlet modeling. Since, in many cases, movable-bed modeling is the only tool available for predicting the response of an inlet to improvements, the capabilities and limitations of these models must be established.

(3) Reanalysis of an Earlier Inlet Model Study. In 1957, a report entitled, "Preliminary Report: Laboratory Study of the Effect of an Uncontrolled Inlet on the Adjacent Beaches," was published by the Beach Erosion Board (now CERC). A reanalysis of the original data is being performed to aid in planning of additional GITI efforts.

(4) Prototype Dynamics. Field and office studies of a number of inlets are providing information on the effects of physical forces and artificial improvements on inlet morphology. Of particular importance are studies to define the mechanisms of natural sand bypassing at inlets, the response of inlet navigation channels to dredging and natural forces, and the effects of inlets on adjacent beaches.

4. This report presents results of a study conducted as part of the prototype inlet dynamics effort (paragraph 3.c(4)). During the inlet model evaluation (paragraph 3.b(2)), a similarity in channel and beach response to jetty construction at Tillamook Bay, Oregon, and Masonboro Inlet, North Carolina, was noted. An effort was then undertaken to determine if the response pattern exhibited by these two inlets was typical of other inlets on U.S. coasts.

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.

To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

TIDAL INLET RESPONSE TO JETTY CONSTRUCTION

by
James M. Kieslich

I. INTRODUCTION

The term *tidal inlet*, as used in this study, refers to a narrow channel connecting the ocean to an estuary, bay, or river with flow in the channel generated predominantly by the tides. Functionally, inlets promote commercial and recreational navigation between sheltered waters and the open ocean, provide water exchange to enhance water quality, reduce flooding due to intense rainfall or surges generated by hurricanes and other severe storms, and permit fish migration, as well as serving other needs. These functional requirements have necessitated the improvement of many natural inlets. This is accomplished by either dredging the sediment deposited in the entrance by waves and tidal current action or stabilizing the entrance with structures that minimize the amount of sediment transported into the inlet and control tidal currents. Both methods are commonly needed to maintain viable channels at inlet entrances.

The objectives of this study were to investigate the behavior of inlet entrances controlled by structures and, from the investigation, expand functional design guidelines for inlet entrance improvements. Knowing how inlet entrances have responded, first to the construction of a single jetty and later to the addition of a second jetty, assists in developing the relationships between channel response and combinations of waves, longshore sediment transport (transport of sediment in the nearshore zone parallel to the shoreline), and jetty construction. These relationships will aid the coastal engineer in the design of future inlet improvements.

The need for this report became evident during an evaluation of physical and numerical models of Masonboro Inlet, North Carolina. Bathymetric surveys showed that after the construction of a single jetty in 1966, the seaward part of the Masonboro Inlet thalweg (the line connecting the deepest points of the channel) migrated toward the jetty, and by 1968 had reached a stable position immediately adjacent to the jetty. Since a similar response to the construction of a single jetty had occurred at Tillamook Bay entrance, Oregon, a study was initiated to determine if these two cases were unique or if they were part of a general trend in inlet response, a trend which would improve design guidelines for future inlet improvements.

The data compiled for this study included bathymetric surveys of inlet entrances; historical wind, wave, and longshore sediment transport summaries; jetty construction histories; and dredging records. The bathymetric surveys were used to prepare a time history of inlet thalwegs, and to determine inlet cross-sectional areas and adjacent shoreline positions for each inlet entrance. Wind, wave, and longshore sediment transport summaries provided insight into the causes of documented inlet entrance response. The separation of natural inlet response from manmade changes in channel conditions was determined from dredging records.

II. PRINCIPLES OF JETTIES AND SPECIFIC DESIGN THEORIES

No single publication details the principles of jetty layout and functional design. Much can be learned, however, from the past experiences of engineers who have designed inlet improvements. Symons (1893, 1896), Harts (1901), and Tower (1911) discussed the design theory of early Pacific coast inlet entrance improvements. Sweitzer (1898), Haupt (1888, 1891, 1899), and Ripley (1912, 1924) described early gulf coast inlet improvements. Eads (1878), Black (1983), Gillette (1904), Rayner (1964), and Magnuson (1967) discussed Atlantic coast inlet improvements. The most detailed case histories of U.S. tidal inlet improvements can be found in the Annual Reports of the Chief of Engineers on Corps of Engineers civil works activities, in Corps of Engineers District project design reports, and in the House of Representatives and Senate Documents.

This section summarizes the principles and design theories for the jetty systems discussed in this report. As used here, a *jetty* is defined as a structure built at the entrance of a tidal inlet to help deepen and stabilize the navigation channel and confine tidal flow.

1. Principles of Jetty Design.

A jetty system helps to deepen an inlet channel and reduce required dredging by concentrating and directing tidal currents to optimize scouring action. This is accomplished by confining discharge areas and making flow channels more hydraulically efficient, thereby promoting higher channel velocities. Jetties stabilize an inlet entrance by intercepting the littoral drift and preventing or minimizing deposition in the inlet channel. Jetties also minimize the effects of wave action and crosscurrents on vessels transiting an inlet.

2. Specific Design Theories.

Two basic jetty designs are discussed in this report: single jetties and twin jetties built one at a time. A single straight or curved jetty may be oriented perpendicular to the shoreline or may be placed at an angle with the shoreline, depending on the predominant wave direction, the channel alinement of the natural inlet, and the desired alinement of the improved inlet. The jetty may be located on either the updrift or downdrift side of the inlet entrance with respect to the net direction of longshore sediment transport.

A single updrift jetty is attached to the shore on the updrift side of the channel entrance to act as a barrier to the movement of littoral drift alongshore from the net transport direction. With the major influx of littoral drift minimized, the tidal current scouring action should be more effective (Coiner, 1932). Two variations to the basic single updrift jetty are discussed in this report--the weir jetty and the Haupt (or reaction) jetty. A weir jetty is placed on the updrift side of the inlet entrance and has a low section or weir having a crest elevation near mean sea level (MSL) at the shore end. Sediment is transported over the weir by waves and currents into a deposition basin that is periodically dredged. The elevation of the weir section is designed low enough to pass littoral drift, but high enough to control tidal currents (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977). With this design, the littoral drift from the updrift direction is trapped and localized in the basin before it reaches the navigation channel.

The basin provides a protected region for the dredge to operate. Figure 1 is an example of a weir-jetty system constructed at Masonboro Inlet, North Carolina.

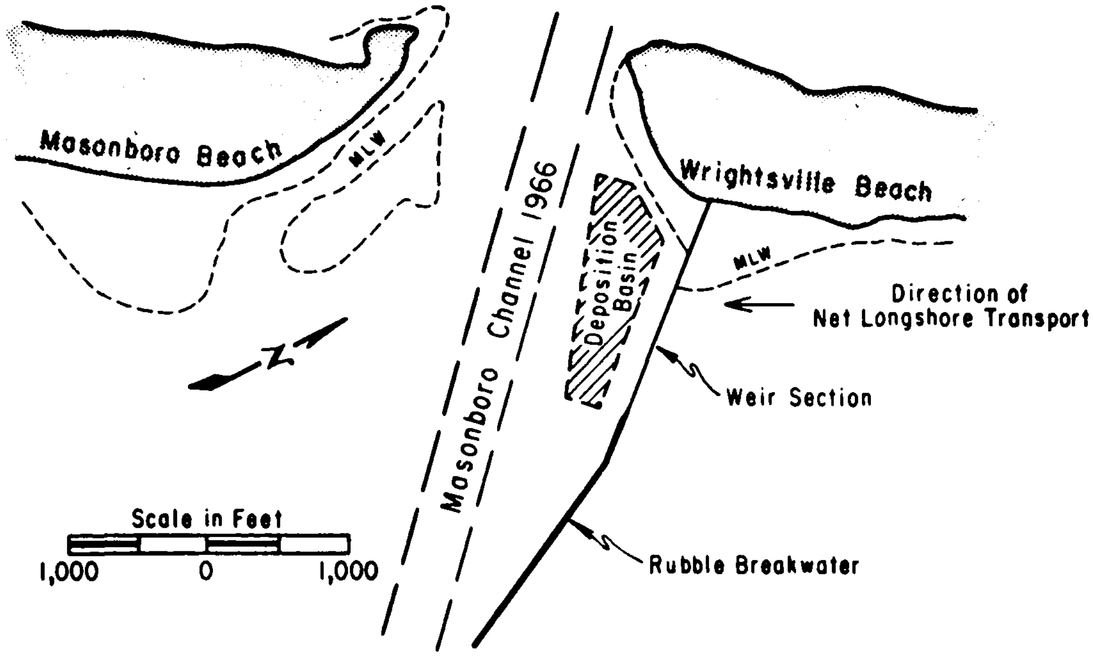

Figure 1. Masonboro Inlet, North Carolina (after U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977).

The Haupt (or reaction) jetty is a single curved jetty that is detached from the shoreline and located on the updrift side of an entrance channel. The jetty is concave to the main ebb tidal currents (Haupt, 1899) to force the ebb current against the jetty and scour a well-defined channel. The channel entrance at Aransas Pass, Texas, for example, was originally improved with a Haupt jetty (Fig. 2). Haupt (1899) proposed that this design would function as a single updrift jetty in trapping littoral drift. Being detached from shore, the system would readily admit flood tidal currents to increase the tidal prism and thus permit greater discharge through the channel during ebbtide. The curved design would promote self-maintenance of the channel.

The idealized local current pattern at a single updrift jetty is shown in Figure 3. The current pattern at an inlet results from interactions between tidal flow, wave-generated currents, inlet bathymetry, and the structures. Segregation of the flood and ebb currents results from the development of marginal flood channels at the entrance. Usually, the flood currents converge from a seaward direction, except where prevented by a jetty, and occur as a radial inflow at the entrance. The ebb flow, however, is more channelized upon leaving the throat and acts as a jet through the ebb tidal delta. The lateral mixing of this jet as it exits from the inlet throat may produce an eddy on each side of the main channel, causing a circulation back toward the entrance in the marginal flood channels (O'Brien, 1966).

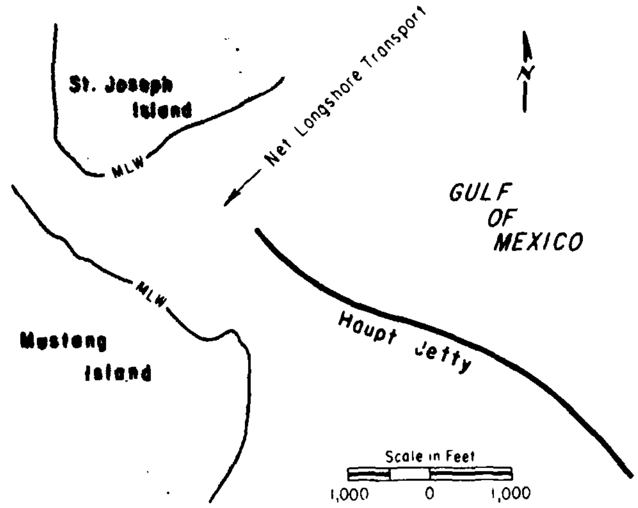

Figure 2. Aransas Pass, Texas (after U.S. Army, Corps of Engineers, 1908).

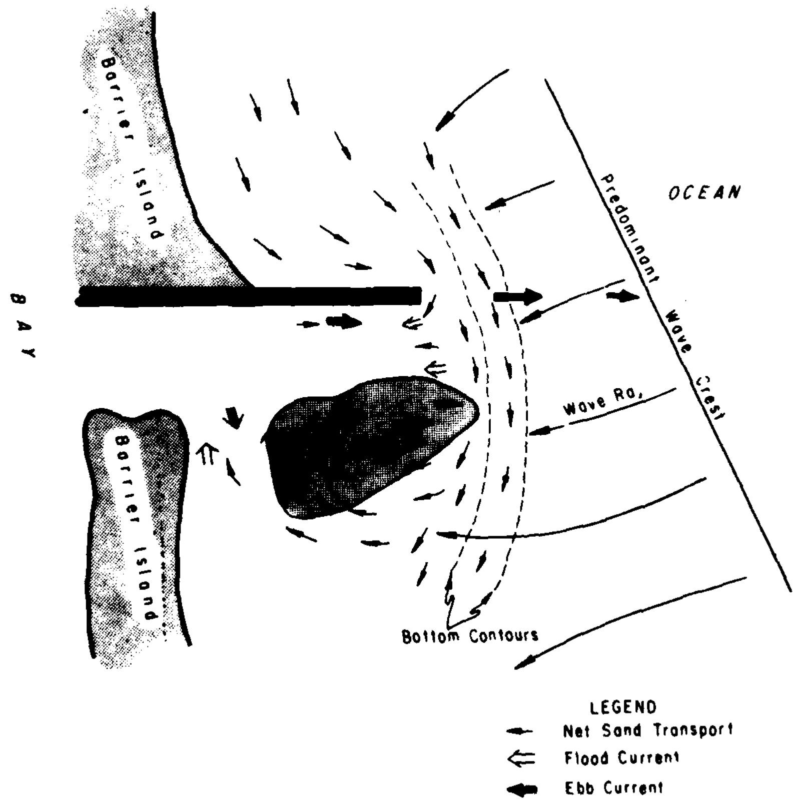

Figure 3. Current pattern at a single updrift jetty.

The effects of wave refraction caused by the crescent-shaped ebb tidal delta and the ebb tidal jet are also shown in Figure 3. A wave crest approaching an inlet refracts to become parallel to the bottom contours and thus bends around the ebb tidal delta to produce a convergence of sand transport toward the entrance, regardless of the wave direction.

The longshore sand transport arrows updrift from the jetty in Figure 3 indicate a net transport condition which may reverse direction if the direction of wave approach changes. An updrift jetty is designed to trap littoral drift from the net longshore transport or updrift direction. The longshore currents on the updrift side of a jetty deflect to form a current toward the seaward end of the jetty (Sato and Irie, 1970). Wave diffraction and reflection at the jetty would slightly contribute to the local current pattern and modify accordingly the pattern shown in Figure 3.

Single jetties located on the downdrift side of the inlet entrance permit the net longshore transport of sand from the updrift direction to force the channel against the jetty. This concentrates the ebb tidal currents and controls their scouring activity. The idealized local current pattern at a single downdrift jetty is shown in Figure 4.

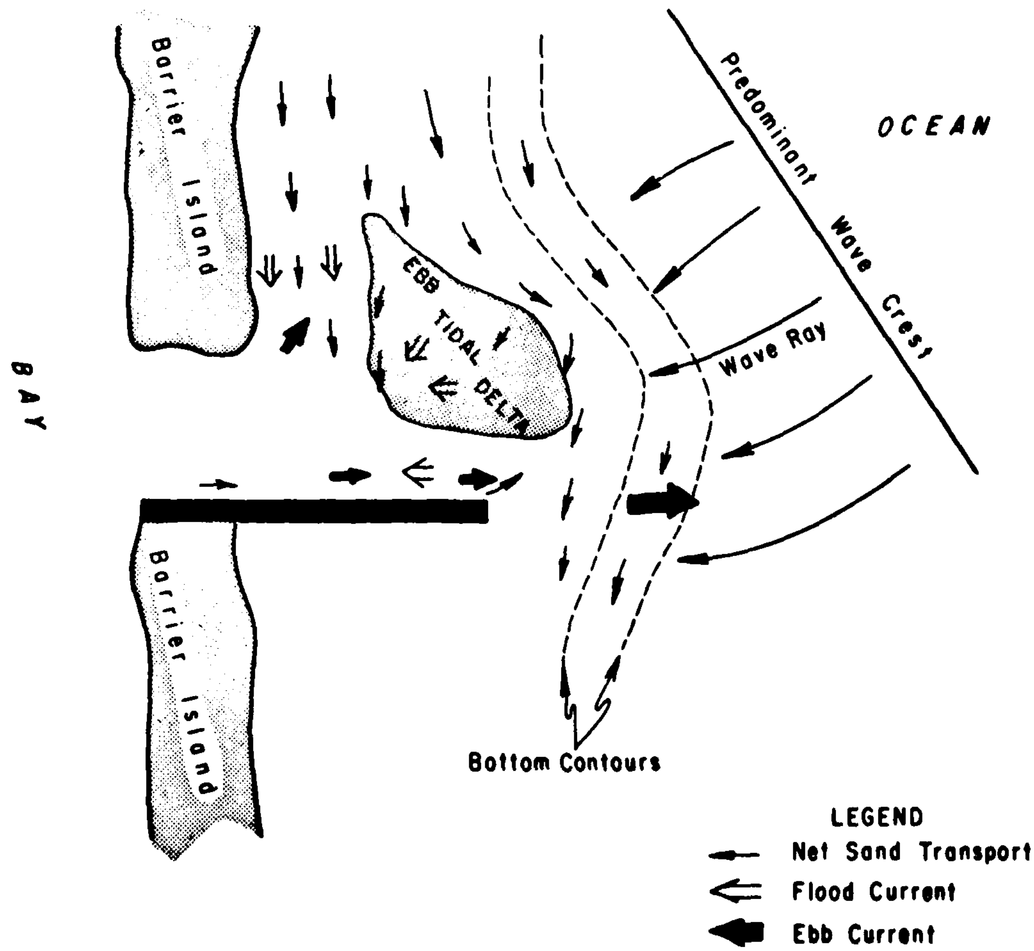

Figure 4. Current pattern at a single downdrift jetty.

Segregation of flood and ebb flow, lateral mixing of the ebb jet, and convergence of sand transport into the entrance by wave refraction produce a current pattern similar to Figure 3. Wave diffraction and reflection at the jetty would also affect the current pattern; however, the channel is more affected by longshore currents because the jetty is located on the downdrift side. This allows greater sand transport directly into the channel than at an entrance controlled with an updrift jetty.

A twin jetty system is usually either the original design or the later addition of a second jetty to a single-jettied entrance. In a twin jetty design the jetties may be placed perpendicular to or at an angle with the shoreline; curved or straight and converging, diverging, or parallel; and equal or unequal in length depending on the local conditions at the entrance. The idealized local current pattern at the typical twin jetty system shown in Figure 5 is produced by the same factors producing the current patterns in Figures 3 and 4.

Although flood and ebb tidal flows are segregated at a twin-jettied inlet, both flows are more channelized because the jetties constrict the entrance. Wave refraction also produces a convergence of sand transport at the entrance, but less sediment enters the channel.

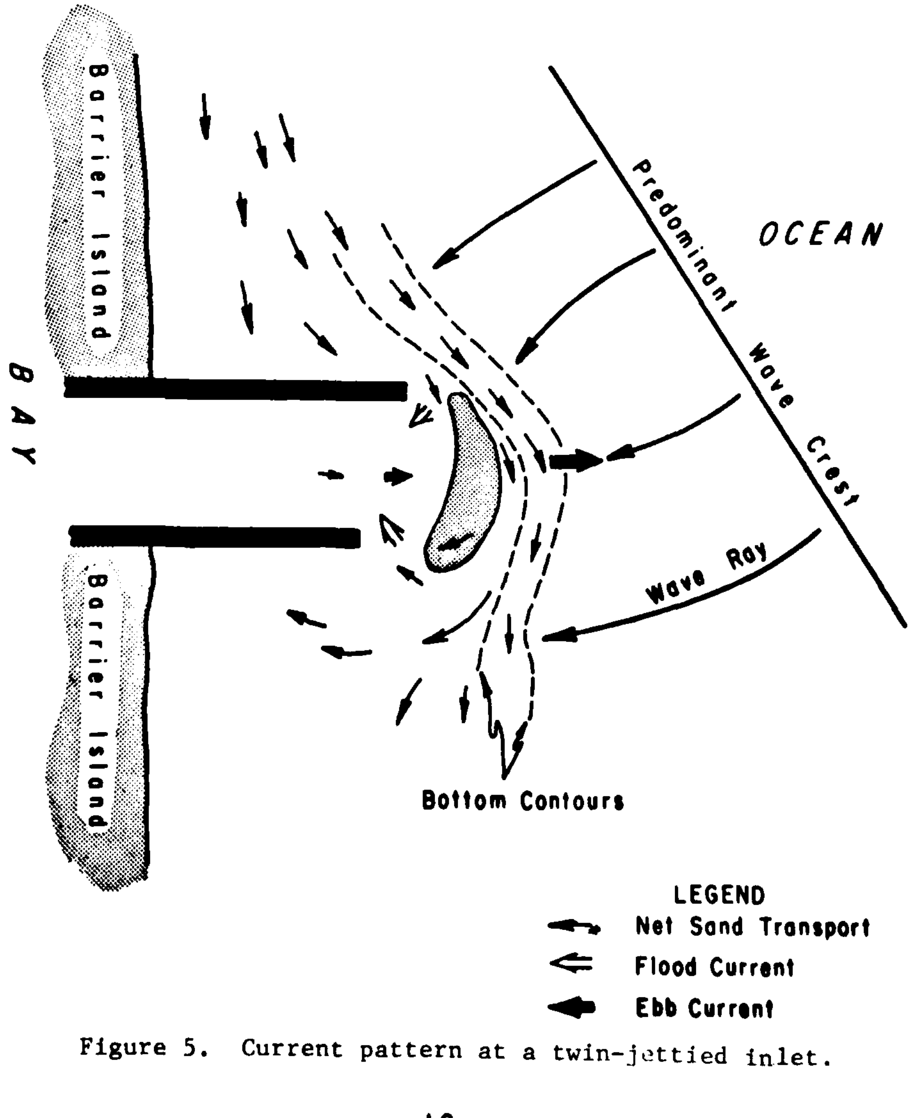

Figure 5. Current pattern at a twin-jettied inlet.

A variation of the twin jetty system uses two weir jetties. Twin weir jetties originally improved the harbor entrance to Charleston, South Carolina, but the improvements did not include a deposition basin. The weir sections were designed for a freer admittance of flood tidal currents to assure filling of the tidal basin during floodtide, increasing the dominance of discharges through the channel during ebbtide and enhancing the self-scouring capability of the channel (U.S. Army, Corps of Engineers, 1878).

Tidal flow, wave-generated currents, and sand transport at single- and twin-jettied inlets are discussed in detail in Section IV.

III. CASE HISTORIES

This section outlines the history of improvements of selected tidal inlets along the Atlantic, gulf, and Pacific coasts of the continental United States. These inlets were originally improved by the construction of single jetties with several adding a second jetty at a later date. Discussed first are the inlets originally improved with single updrift jetties, followed by those improved by single downdrift jetties: Grays Harbor, Washington; Tillamook Bay entrance and Umpqua River entrance, Oregon; Masonboro Inlet, North Carolina; Humboldt Bay entrance, California; Coquille River entrance, Oregon; Merrimack River entrance, Massachusetts; Newport Harbor entrance, California; Fernandina Harbor entrance and St. Johns River entrance, Florida; Coos Bay entrance, Oregon; Aransas Pass, Texas; and Manasquan Inlet, New Jersey.

The response of inlet entrances to jetty construction was documented from an analysis of bathymetric surveys made before and after the improvements. Since only the natural response was of interest, inlet behavior was not analyzed for the years where dredging occurred unless actual dredging locations were known and dredging effects on the channel were negligible. Inlet response is shown through time histories of channel thalwegs, shoreline positions adjacent to the inlets, and minimum channel cross-sectional areas. The factors which produced the observed responses are discussed in Section IV.

1. Grays Harbor Entrance, Washington.

a. Existing Project. Grays Harbor is a large shallow estuary located about 45 miles (72.4 kilometers) north of the Columbia River (Fig. 6). Two convergent jetties constrict the ocean entrance width to 6,500 feet (1,981.2 meters). The south and north jetties are 13,734 and 16,000 feet (4,186.1 and 4,876.8 meters) long, respectively. Both jetties have a design crest elevation of 16 feet (4.9 meters) above mean lower low water (MLLW). The authorized size of the entrance channel across the ebb tidal delta is 600 feet (182.9 meters) wide and 30 feet (9.1 meters) deep at MLLW.

b. Environmental Setting. The tides in the Grays Harbor area are mixed with a diurnal range of 9 feet (2.7 meters) at Point Chehalis. Maximum tidal currents in the entrance are 3.2 feet (0.98 meter) per second during floodtide and 4.7 feet (1.4 meters) per second during ebbtide (National Oceanic and Atmospheric Administration, 1980). The spring, summer, and fall winds are predominantly from the northwest; the winter winds are primarily from the east and southeast (Washington State University, 1955a). The predominant direction of sea waves is from the south; swell arrives predominantly from the west (National Marine Consultants, 1961).

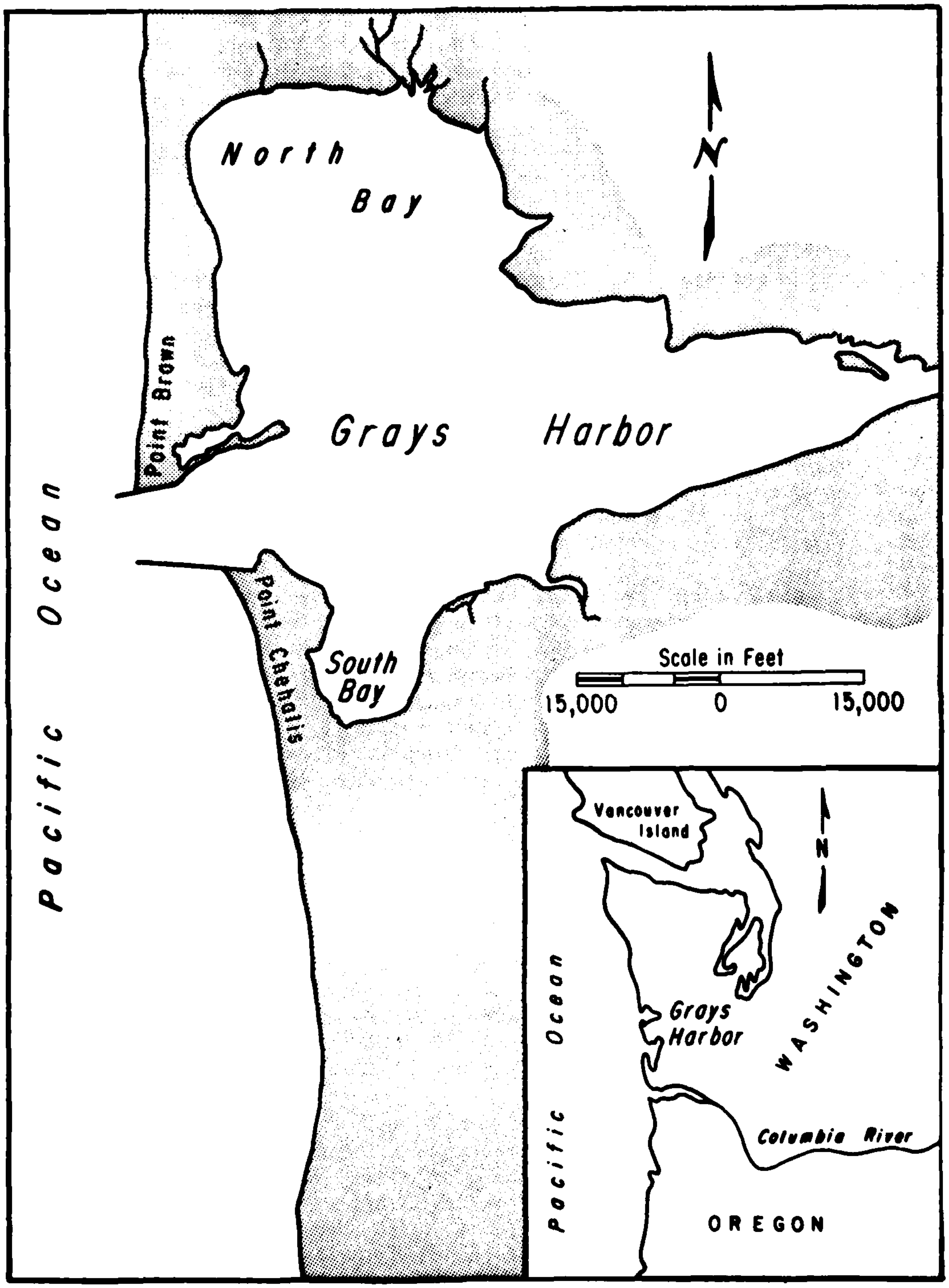

Figure 6. Grays Harbor, Washington (after a 1975 National Oceanic and Atmospheric Administration survey).

The longshore sediment transport rates at Grays Harbor were determined from wave energy flux calculations using hindcast data developed by National Marine Consultants (1961). The estimated north and south transport rates were 1,200,000 and 650,000 cubic yards (917,466 and 496,961 cubic meters) per year, respectively. Thus, the estimated net transport is 550,000 cubic yards (420, 505 cubic meters) per year to the north, and the gross transport is about 1,850,000 cubic yards (1,414,427 cubic meters) per year.

c. Preimprovement History. Figure 7 shows a time history of thalwegs for Grays Harbor from 1862 to 1909. The channel thalwegs indicate a major reorientation of the channel between 1862 and 1881, followed by a northward migration of the unjettied entrance channel in the direction of net longshore sediment transport from 1881 to 1900. This migration slowed when construction of a single updrift (south) jetty began in 1898. Channel depths decreased from 71 to 52 feet (21.6 to 15.8 meters) below MLLW along the thalweg as the channel migrated from the 1881 to the 1900 position. Maximum channel depths in 1862 and 1881 were essentially equal at 71 feet below MLLW.

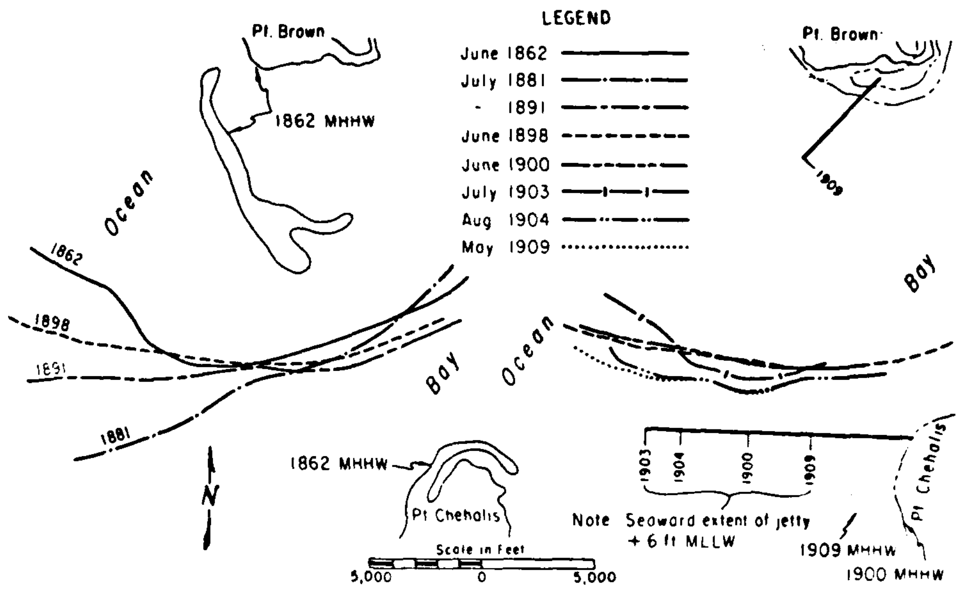

Figure 7. Time history of channel thalwegs, Grays Harbor, Washington, June 1862-May 1909 (after U.S. Army Engineer District, Seattle, surveys).

Between 1862 and 1898, the principal shoreline changes adjacent to the entrance were accretion at Point Chehalis and erosion at Point Brown (Blackman, 1938). By 1898, Point Chehalis had accreted seaward about 1 mile (1.6 kilometers); the small island off Point Brown (Fig. 7) had retreated about 2,000 feet (609.6 meters) at the north end (Blackman, 1938).

d. Inlet Entrance Response. Improvement of Grays Harbor began with the 1898 construction of the single updrift jetty (U.S. Army Engineer District, Seattle, 1965). By 1903, the south jetty had reached its design length of 13,748 feet (4,201.4 meters) (Blackman, 1938). It was assumed this single updrift jetty would effectively trap and retain the net northward longshore transport of sand as well as concentrate and direct ebb tidal currents to scour and maintain a channel suitable for navigation (Symons, 1896). However, the south jetty rapidly began to deteriorate owing to waving action. The seaward locations of the +6-foot (1.8 meters) MLLW jetty heights for 1904 and 1909 are shown in Figure 7. As work progressed on the south jetty between 1900 and 1903, the middle length of the channel migrated a maximum distance of 1,000 feet (304.8 meters) toward the jetty; the outer channel (beyond the seaward end of the south jetty) moved northward (note the outer part of 1903 thalweg in Fig. 7). The middle channel length continued to migrate and by 1904 had migrated a maximum of 500 feet (152.4 meters) farther southward. By 1904, the outer parts of the channel had migrated 2,000 feet closer to the jetty.

From 1904 to 1909, the inner channel reaches showed little net movement as indicated by the coincidence of the 1904 and 1909 thalwegs in Figure 7. No work was done on the south jetty during this time (Blackman, 1938), and the jetty crown deteriorated over most of its length to below +6 feet MLLW (see Fig. 7). This probably reduced its sand-trapping ability. A controlling depth of only 12 feet (3.7 meters) below MLLW over the ebb tidal delta in the navigation channel in 1907 prompted the 1908 construction of the north jetty, 5 feet (1.5 meters) above MLLW with an overall length of 17,000 feet (5,181.6 meters) by 1913 (U.S. Army Engineer District, Seattle, 1973). However by 1916, reconstruction was necessary to raise the jetty to 8 feet (2.4 meters) above MLLW and also extend the jetty to a project length of 17,204 feet (5,243.8 meters) (U.S. Army Engineer District, Seattle, 1973). The channel migrated southward a maximum distance of about 500 feet between 1909 and 1915 (Fig. 8) but moved northward 1,000 feet from 1915 to

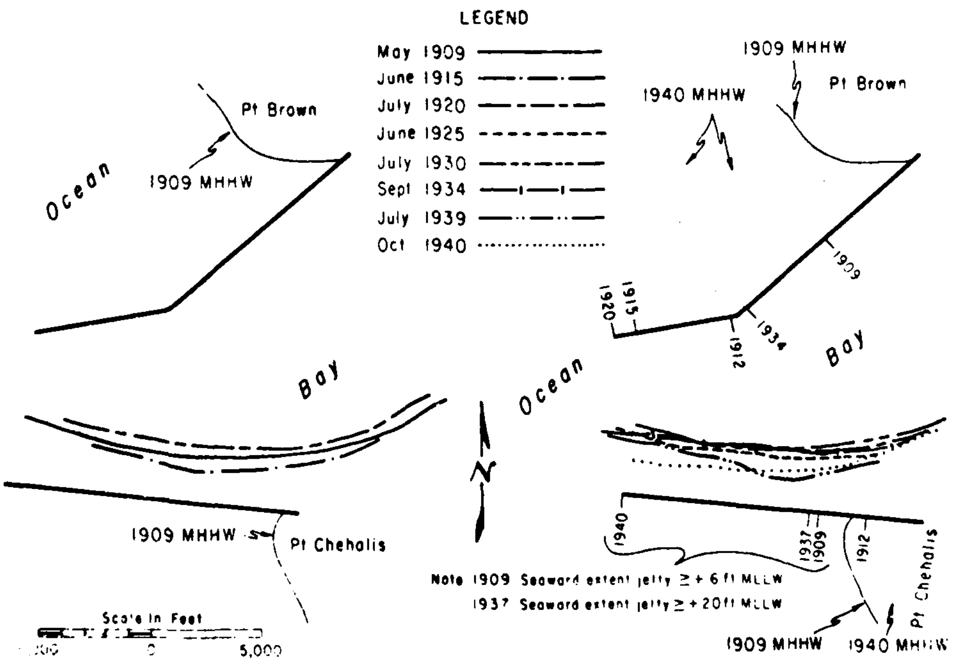

Figure 8. Time history of channel thalwegs, Grays Harbor, Washington, May 1909–October 1940 (after U.S. Army Engineer District, Seattle, surveys).

1920 possibly due to dredging or in response to north jetty construction. In 1916, it became necessary to dredge the channel across the ebb tidal delta and dredging continued annually until 1942 (U.S. Army Engineer District, Seattle, 1973). The channel showed little net movement between 1920 and 1935, and the south jetty had settled from only 2 feet (0.61 meter) at the shoreline to as much as 18 feet (5.5 meters) at the seaward end (U.S. Army Engineer District, Seattle, 1965).

From 1935 to 1939, the entire south jetty was reconstructed to an elevation of 20 feet (6.1 meters) above MLLW. Responding rapidly to the rehabilitation, the channel migrated southward about 2,000 feet by 1942, becoming immediately adjacent to the south jetty (Fig. 9), its present position. The outer reaches of the north jetty were less than 6 feet above MLLW from 1935 to 1939.

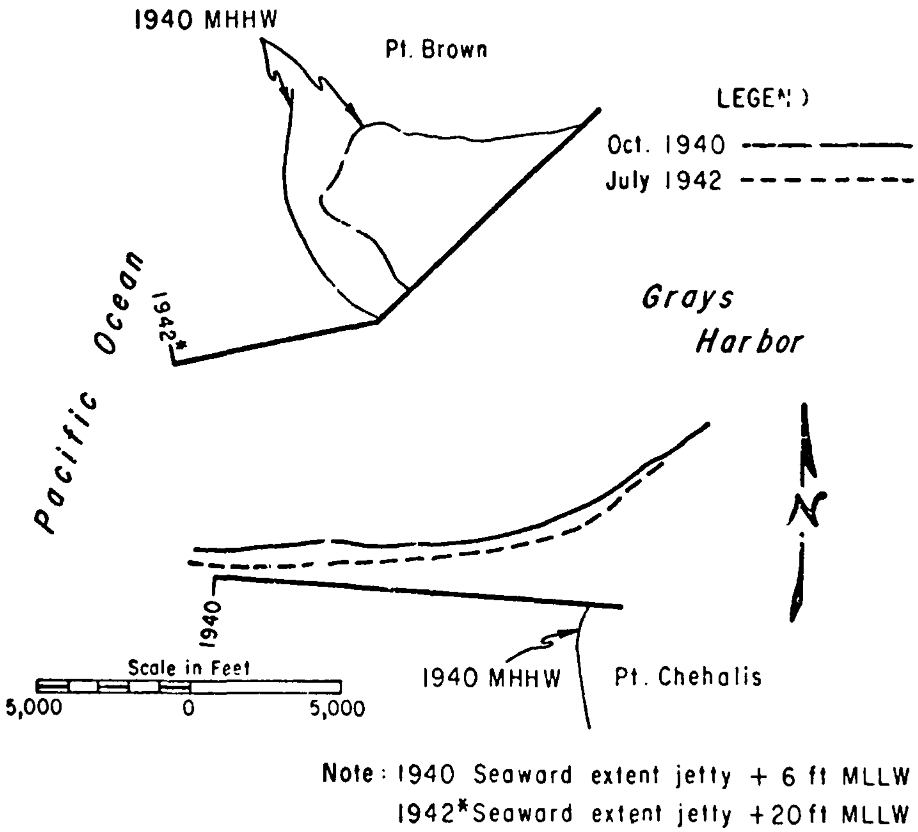

Figure 9. Time history of channel thalwegs, Grays Harbor, Washington, October 1940-July 1942 (after U.S. Army Engineer District, Seattle, surveys).

Detailed annual surveys immediately after construction of the south jetty are not available to accurately define changes in the channel cross-sectional area; however, the minimum channel depths along the thalweg between 1862 and 1908 (Table 1) give some indication of channel conditions.

Table 1. Summary of minimum thalweg depths, Grays Harbor, Washington, 1862-1908 (after O'Brien 1931a).

Minimum thalweg depth below MLLW (ft)	(m)	Year	Remarks
16	4.9	1862	
16	4.9	1881	
10	3.0	1883	
14	4.3	1891	
15	4.6	1898	South jetty started
16	4.9	1900	
18	5.5	1901	
20	6.1	1902	
14	4.3	1903	
17	5.2	1904	
13	4.0	1906	
12	3.7	1907	
17	5.2	1908	North jetty started

Table 1 shows a 25-percent increase in minimum channel thalweg depths from 1898 to 1902; minimum thalweg depths then decreased in 1907 to 12 feet below MLLW. The average width of the channel remained relatively constant (Blackman, 1938). During construction of the south jetty from 1898 to 1909, the ebb tidal delta off the end of the jetty moved seaward about 1,000 feet. More frequent surveys after 1910 provided a detailed time history of the channel cross-sectional area (Fig. 10). Following initiation of the north jetty construction in 1908, the minimum channel area below MSL increased by 7 percent by 1911. After this slight increase, the channel area steadily decreased as both jetties deteriorated.

Immediately after reconstruction of both the north jetty in 1916 and the south jetty in 1939, the minimum channel area increased; decreases occurred after a few years. The ebb tidal delta moved seaward about ,500 feet (1,371.6 meters) from 1909 to 1940; 76 percent of this movement occurred between 1935 and 1940. Between 1899 and 1908, the high water shoreline at Point Chehalis advanced seaward about 2,500 feet (762 meters) at the south side of the jetty with the advance tapering to 1,000 feet at a distance of 10,000 feet (3,048 meters) south of the jetty (Blackman, 1938). The north side eroded at an unspecified rate during this period (Blackman, 1938).

The net changes in the north and south high water shorelines adjacent to the jetties from 1909 to 1940 included about 10,000 feet of accretion and 1,750 feet (533.4 meters) of erosion, respectively.

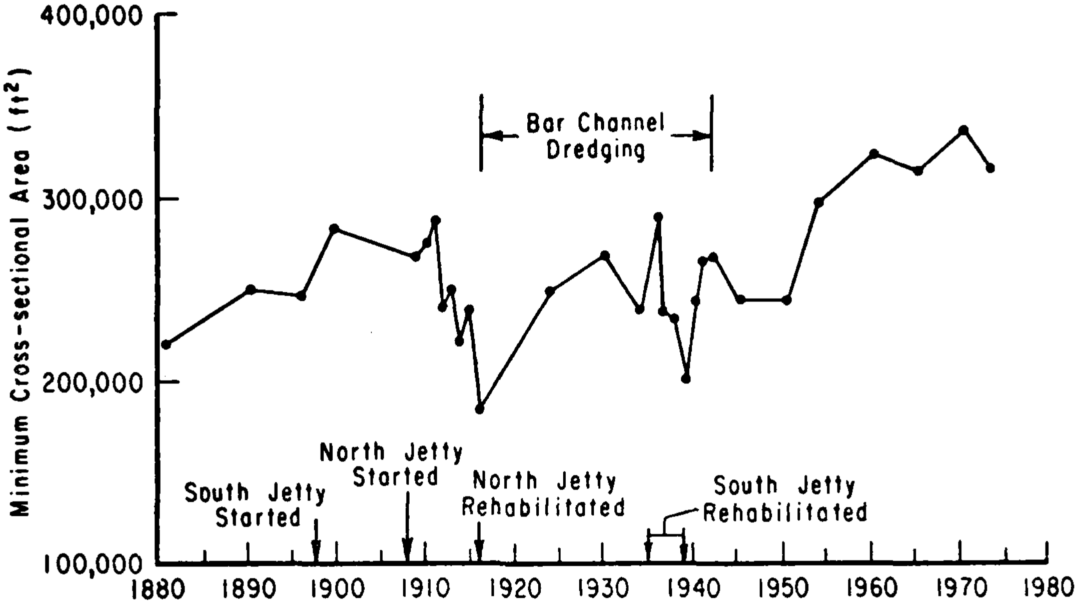

Figure 10. Time history of minimum channel area below MSL, Grays Harbor, Washington.

e. Summary. In the 7-year period before jetty construction, the Grays Harbor entrance channel migrated in the direction of net longshore sediment transport. As work progressed on the south jetty, the channel migrated toward the jetty, continuing updrift through construction of the second jetty on the downdrift side of the channel. Minimum channel thalweg depths increased after construction of the single updrift jetty, while the channel width remained constant. However, channel improvements were only temporary; within 4 years, a second jetty was necessary.

Immediately after construction of the north jetty, the minimum charnel area increased 7 percent. After this initial period of increase, the chann[illegible] area decreased as the jetty deteriorated from wave action. Immediately after reconstruction of the north (1916) and south (1939) jetties, the minimum channel area increased 31 and 26 percent, respectively, but the increase that followed each rehabilitation was not permanent.

2. Tillamook Bay Entrance, Oregon.

a. Existing Projects. Tillamook Bay (Fig. 11) is about 50 miles (80.5 kilometers) south of the Columbia River entrance. Improvements to Tillamook Bay entrance include a north jetty 5,700 feet (1,737.4 meters) long, built in 1917, and a south jetty 6,525 feet (1,988.8 meters) long built in 1974. The authorized channel dimensions through the ebb tidal delta are 18 feet deep at MLLW and 200 feet (61 meters) wide.

b. Environmental Setting. The tides at the ocean entrance are mixed with a diurnal range of 7.5 feet (2.3 meters) (National Oceanic and Atmospheric Administration, 1977). Maximum velocities in the entrance averaged over three tidal cycles were 5.8 feet (1.8 meters) per second during floodtide and 4.1 feet (1.2 meters) per second during ebbtide (U.S. Army Committee on Tidal Hydraulics, 1970). The summer winds are generally from the north to northwest;

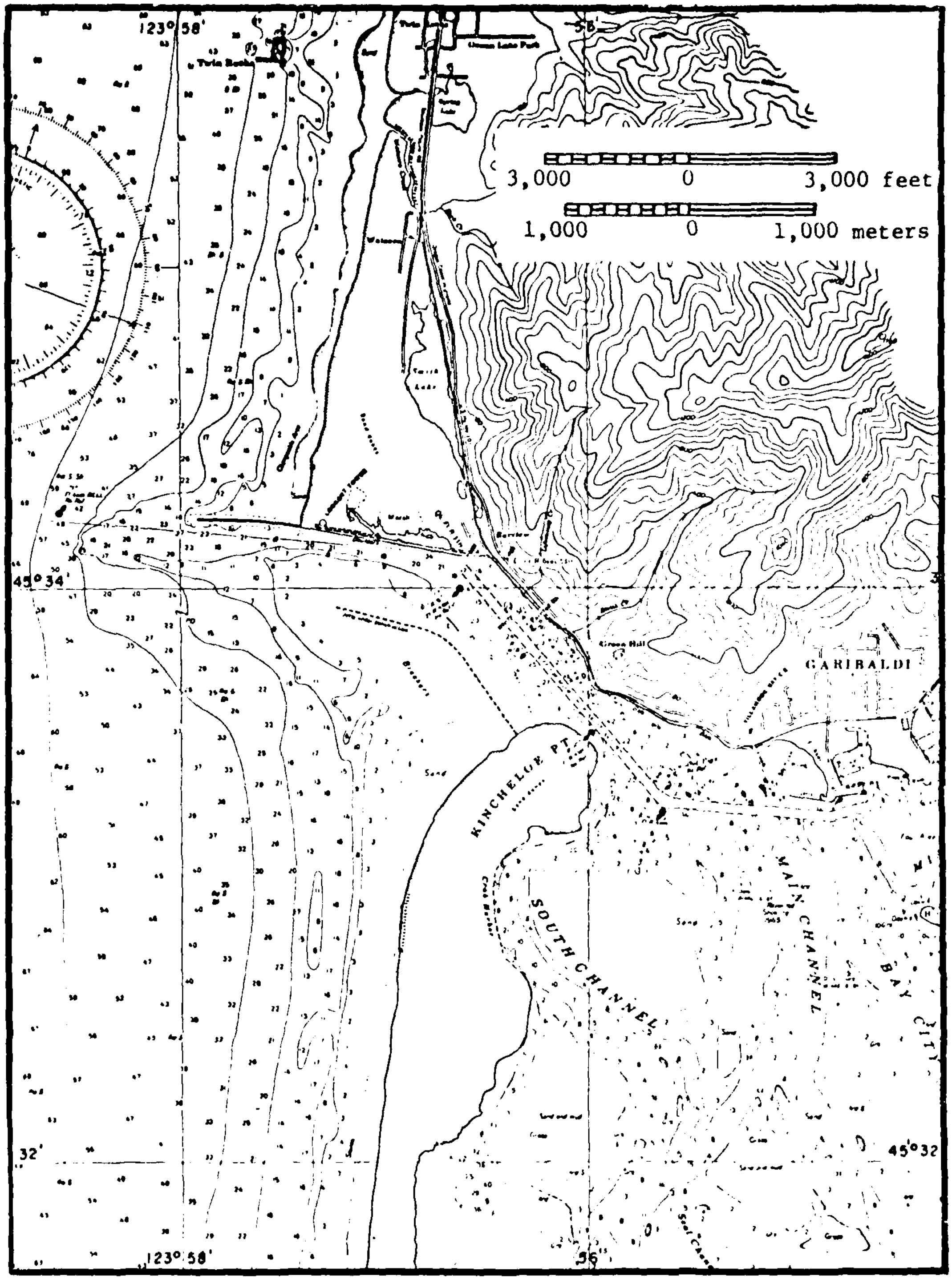

Figure 11. Tillamook Bay, Oregon, in 1973 (from National Ocean Survey chart 6112).

the winter winds are mostly from the south (Cooper, 1958). The predominant direction of sea waves is from the northwest; swell arrives predominantly from the west (National Marine Consultants, 1961).

An estimated 800,000 cubic yards (611,644 cubic meters) per year of sediment moves southward, based on the amount of sediment trapped in the fillet of the north jetty from 1915 to 1925 (U.S. Army Committee on Tidal Hydraulics, 1970). Terich and Komar (1973) stated that the southward and northward longshore sediment transport rates are approximately balanced, based on deposition and erosion patterns around the south jetty. Thus, the net longshore sediment transport rate at the Tillamook Bay entrance is approximately zero, and the gross annual rate is about 1,600,000 cubic yards (1,223,288 cubic meters) per year or higher.

c. Preimprovement History. Before jetty construction, the inlet throat was about 750 feet (228.6 meters) wide (Blackman, 1938). Surveys taken between 1891 and 1914 showed the thalweg on the north side of the throat.

d. Inlet Entrance Response. Figure 12 shows channel thalweg locations at Tillamook Bay entrance from June 1914 to May 1918. Construction of the north jetty began in March 1914 and was completed in October 1917. The north jetty had a design length of 5,400 feet (1,645.9 meters) and a crest elevation of 12 feet above MLLW.

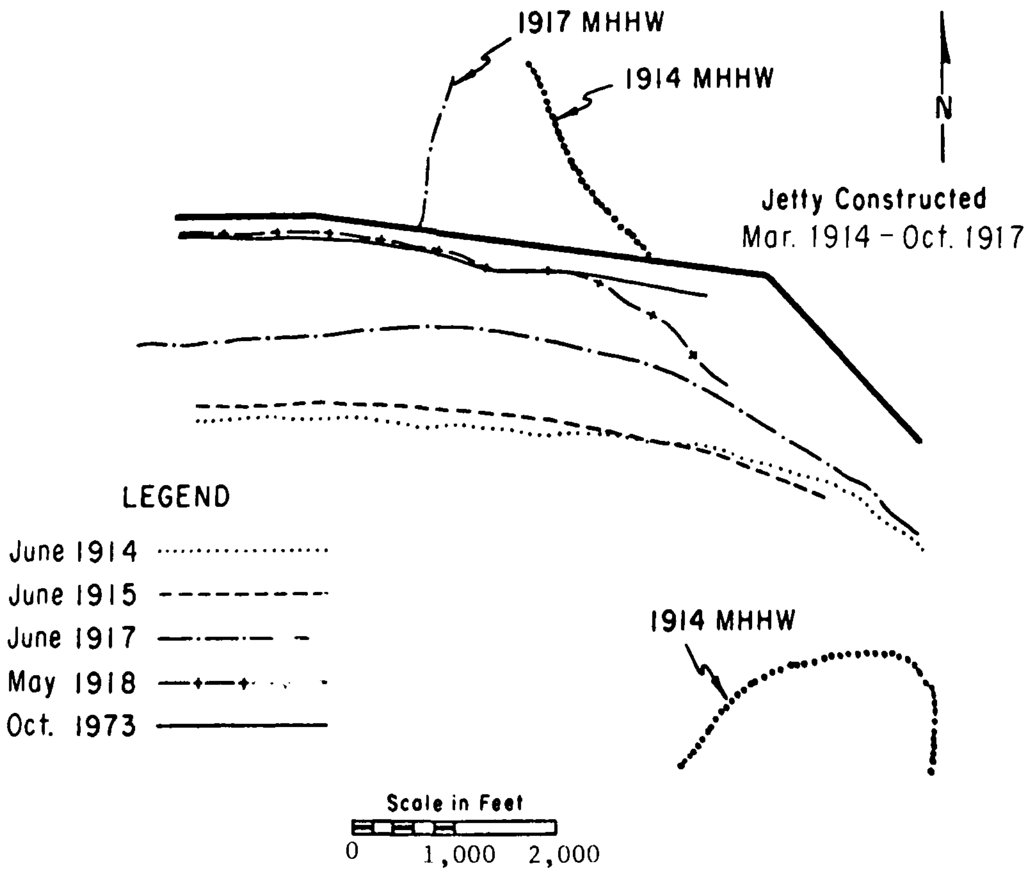

Figure 12. Time history of channel thalwegs, Tillamook Bay, Oregon, June 1914-May 1918 (after U.S. Army Engineer District, Portland, surveys).

During construction of the north jetty, the channel migrated toward the jetty, and by May 1918 had migrated about 2,000 feet from the June 1914 position (Fig. 12). The channel immediately adjacent to the jetty was from 22 to 35 feet (6.7 to 10.7 meters) deep at MLLW and 400 feet (121.9 meters) wide (Blackman, 1938). During the 3-year construction of the north jetty, the adjacent beach accreted 2,500 feet seaward (U.S. Army Committee on Tidal Hydraulics, 1970); the south beach receded at an unspecified rate (Blackman, 1938).

Figure 13 shows that during construction of the north jetty the minimum channel cross-sectional area below MSL increased by about 20 percent due to dredging. By 1918, the ebb tidal delta had migrated seaward 1,000 feet from the seaward end of the jetty (Blackman, 1938).

Shortly after completion of the north jetty, both the north and south beach shorelines receded as the jetty deteriorated and became less of a littoral barrier (Terich and Komar, 1973). This deterioration also caused increased shoaling in the channel. Dredging has been necessary since 1920 (Blackman, 1938) to maintain navigable depths in the channel. The channel has remained adjacent to the north jetty, even with the addition of a south jetty at the entrance during 1973 and 1974. Sand is currently trapped adjacent to both jetties, causing the shorelines to accrete. Based on 1975 and 1976 surveys, deposition in the entrance channel has decreased about 50 percent since construction of the south jetty (G. Hartman, U.S. Army Engineer District, Portland, personal communication, 1976).

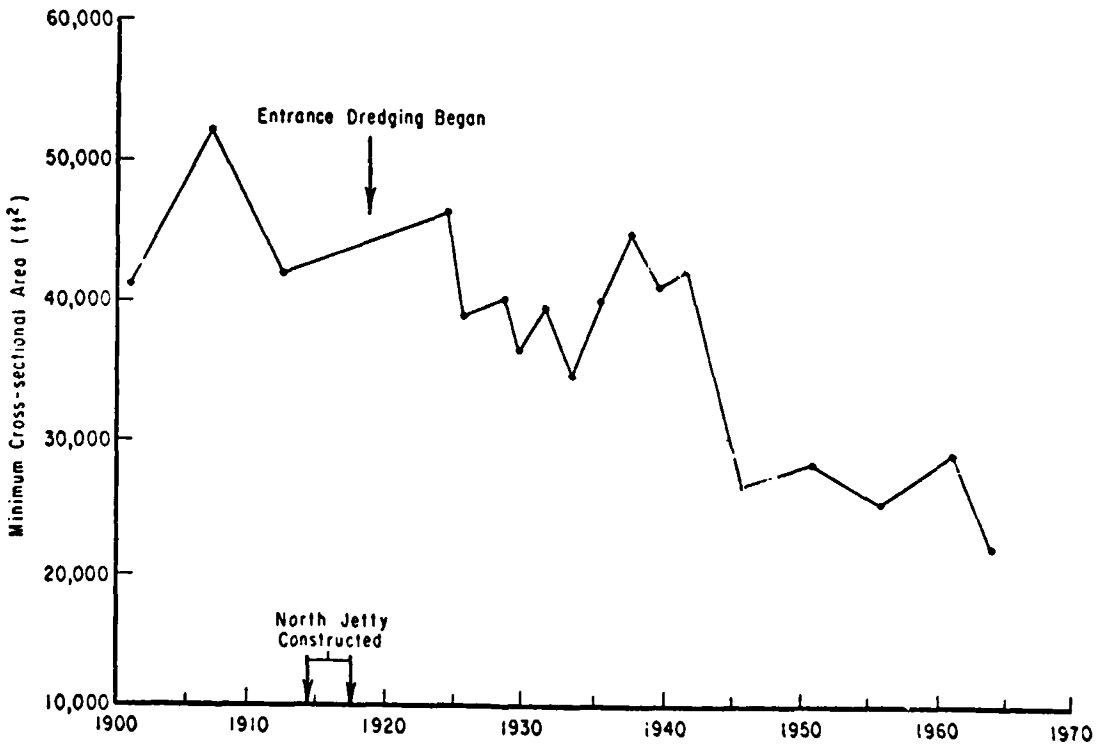

Figure 13. Time history of minimum channel area below MSL, Tillamook Bay, Oregon.

e. Summary. During construction of an updrift (north) jetty, the channel migrated 2,000 feet toward the jetty and remained immediately adjacent to the jetty even during construction of a downdrift jetty at a much later date. The updrift beach accreted seaward 2,500 feet during the 3 years of construction of the updrift jetty. After jetty construction, the minimum channel cross-sectional area increased about 20 percent due to dredging. Thereafter, the minimum area decreased to about 50 percent of the unimproved area.

3. Umpqua River Entrance, Oregon.

a. Existing Projects. The ocean entrance to the Umpqua River (Fig. 14) is about 180 miles (289.7 kilometers) south of the Columbia River. Improvements at the entrance include a north jetty 8,000 feet (2,438.4 meters) long, a south jetty 4,700 feet (1,432.6 meters) long and a 5,500-foot-long (1,676.4 meters) training jetty inside the entrance on the south side of the channel. The authorized entrance channel dimensions are 26 feet (7.9 meters) below MLLW and 400 feet wide.

The north jetty was constructed to a length of 3,390 feet (1,033 meters) in 1917-19 and extended to its present length in 1924-31. A short south jetty, constructed in 1933-34, was extended to the present length in 1937-38.

b. Environmental Setting. Tides at the ocean entrance are mixed with a diurnal tidal range of 6.9 feet (2.1 meters). Maximum tidal currents are 1.7 feet (0.52 meter) per second during ebbtide and 1.4 feet (0.43 meter) per second during floodtide (National Oceanic and Atmospheric Administration, 1977). The major onshore winds at Umpqua River are from the northwest and southwest. The prevailing winds are from the northwest. There are no wave statistics available for the Umpqua River entrance. The mean annual wave height determined from visual observations is 3.3 feet (1 meter) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977).

The net longshore sediment transport at the entrance is to the south at a rate of 100,000 cubic yards (76,456 cubic meters) per year, and the gross transport is 900,000 cubic yards (688,100 cubic meters) per year. The figures are based on sediment accumulation rates measured adjacent to the north and south jetties which indicate that the minimum southward rate is 500,000 cubic yards (382,278 cubic meters) per year and the minimum northward transport is 400,000 cubic yards (305,822 cubic meters) per year (U.S. Army Committee on Tidal Hydraulics, 1975).

c. Preimprovement History. Before jetty construction the Umpqua River channel width at MLLW was about 900 feet (204.3 meters), and depths in the channel through the ebb tidal delta varied from 7 to 16 feet (2.1 to 4.9 meters), but were seldom less than 13 feet (4.0 meters). Surveys from 1886 until jetty construction show the thalweg located on the south side of the throat.

d. Inlet Entrance Response. Figure 15 is a time history of channel thalwegs at Umpqua River entrance from 1886 to 1927. Construction of the updrift north jetty was started in 1917 and completed in 1926. As indicated by the thalwegs locations in Figure 15, the channel migrated a maximum of almost 1,500 feet (457.2 meters) toward the jetty from 1917 to 1927 by which time it was immediately adjacent to the jetty. Significant sand transport into the channel

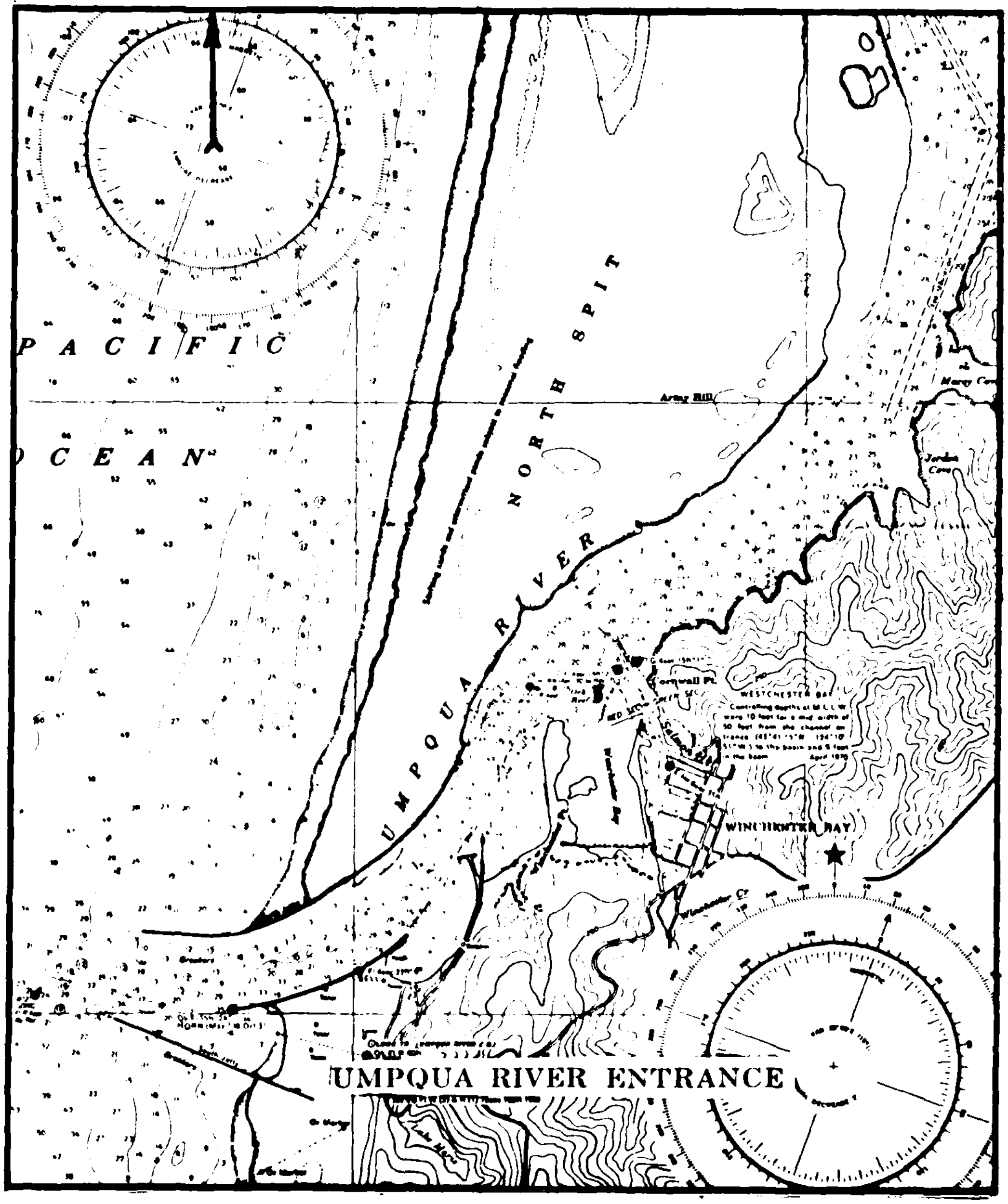

Figure 14. Umpqua River, Oregon, in 1970 (from National Ocean Survey chart 6004).

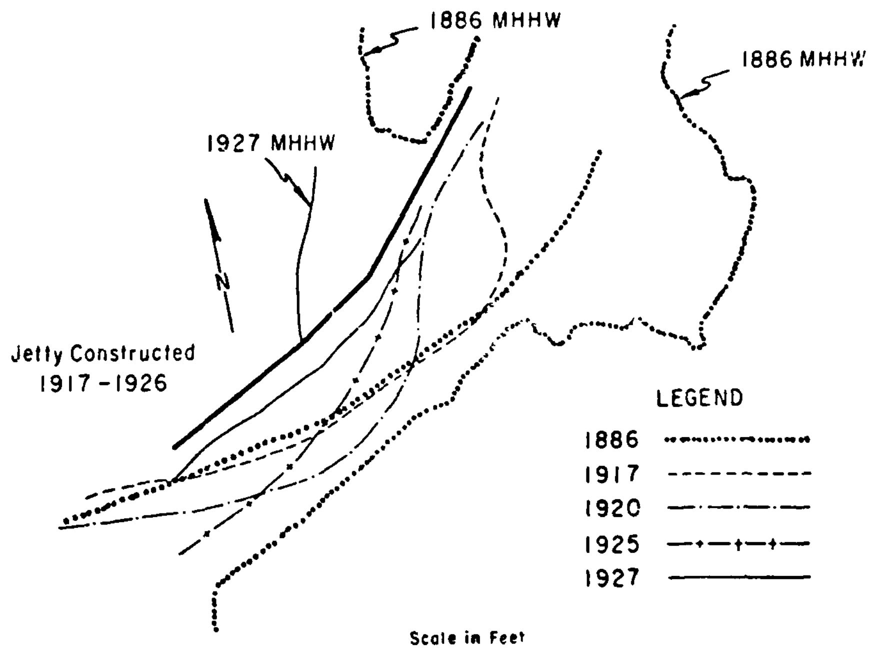

Figure 15. Time history of channel thalwegs 1886-1927, Umpqua River, Oregon (after U.S. Army Engineer District, Portland, surveys).

is indicated by the rapid decrease in channel area following the start of jetty construction (Fig. 16). The minimum channel cross section decreased 40 percent by 1926. From 1917 to 1926, the north beach adjacent to the jetty migrated seaward approximately 2,400 feet (731.5 meters). Surveys of the unjettied south beach were not available during the north jetty construction.

Maintenance dredging of the ocean entrance began immediately after completion of the jetty. Although a channel developed adjacent to the structure after construction of the training jetty, 200,000 cubic yards (152,911 cubic meters) of sediment continues to be dredged annually from the outer reach of the channel to achieve project dimensions (U.S. Army Committee on Tidal Hydraulics, 1975).

e. Summary. The channel migrated 1,500 feet toward the updrift north jetty during construction from 1917 to 1927. The updrift adjacent shoreline accreted seaward 2,400 feet during jetty construction, while the minimum cross-sectional area decreased by 40 percent.

4. Masonboro Inlet, North Carolina.

a. Existing Project. Masonboro Inlet (see Fig. 1) is about 25 miles (40.2 kilometers) northeast of Cape Fear, North Carolina. The inlet was modified in June 1966 by construction of a weir-jetty system. The authorized channel is 14 feet (4.3 meters) deep at MLLW and 400 feet wide across the ebb tidal delta.

b. Environmental Setting. Tides at Masonboro Inlet are semidiurnal with a spring range of 4.7 feet (1.4 meter) (U.S. Army Engineer District, Wilmington, 1970). Maximum velocities of 3.2 feet per second during floodtide and 4.9 feet

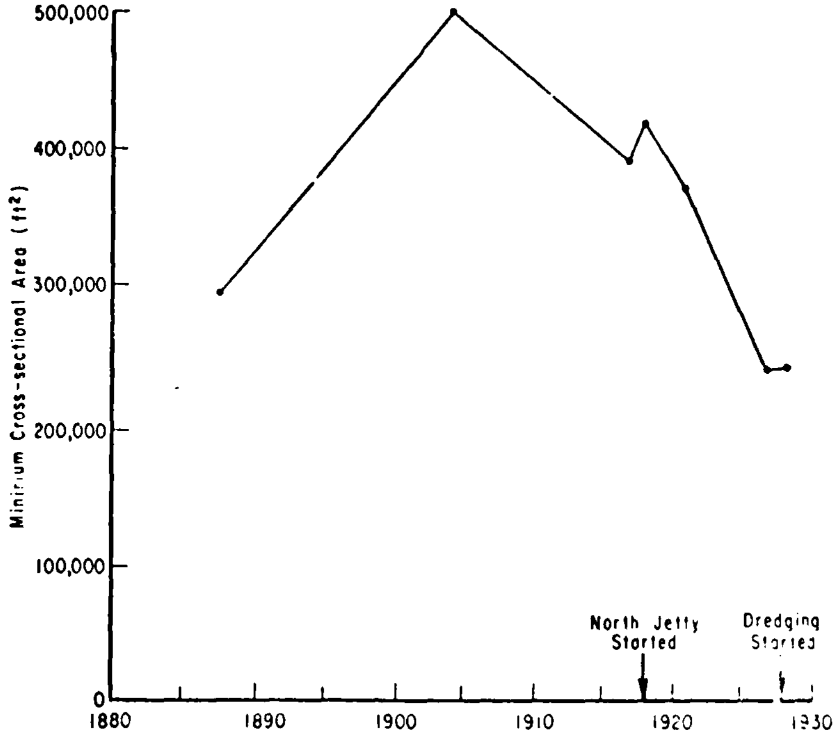

Figure 16. Time history of minimum channel area below MSL, Umpqua River, Oregon.

(1.5 meters) per second during ebbtide on a mean tidal range have been measured at the ocean entrance (U.S. Army Engineer District, Wilmington, 1970). Winds at Masonboro Inlet blow onshore annually about 39 percent of the time and offshore 50 percent of the time; predominant onshore winds are from the northeast and east (U.S. Army Engineer District, Wilmington, 1970). During fall and winter months, most waves approach Masonboro Inlet from the northeast and east. During the spring, wave direction varies with almost an equal frequency of wave occurrence from all offshore directions. In summer, waves generally approach from the southeast and south. On an annual basis (for energy supplied on the coast), the predominant wave direction is from the northeast and east (U.S. Army Engineer District, Wilmington, 1970). An analysis of wave data collected from September 1971 to August 1972 at a wave gage near Masonboro Inlet yielded an average significant wave height of 2.6 feet (0.8 meter) and an average significant wave period of 7.7 seconds (E. Thompson, Hydraulic Engineer, Coastal Engineering Research Center, personal communication, 1975).

Using both visual wave observations and wave gage data to compute wave energy flux, the northward and southward transport rates are estimated at 500,000 and 750,000 cubic yards (382,278 and 573,416 cubic meters) per year, respectively (J. Jarrett, U.S. Army Engineer District, Wilmington, personal communication, 1975). Thus, the net longshore sediment transport at Masonboro Inlet is southward at 250,000 cubic yards (191,139 cubic meters) per year, and the gross transport is 1,250,000 cubic yards (955,694 cubic meters) per year (Jarrett, personal communication, 1975).

c. Preimprovement History. In its natural state, Masonboro Inlet remained in the same geographic area throughout recorded history, although the channel migrated both upcoast and downcoast during the past 100 years. Recession was the general trend for the adjacent beaches (Magnuson, 1967).

d. Inlet Entrance Response. The north jetty at Masonboro Inlet, which extends seaward 3,650 feet (112.5 meters), was constructed between July 1965 and June 1966. The jetty consists of a sheet-pile weir section about 1,750 feet long with a top elevation at MSL. The seaward part is a rubble-mound section 1,900 feet (579.1 meters) long with an elevation of 3 to 6 feet (0.91 to 1.8 meters).

The December 1966 thalweg (Fig. 17) shows the location of the navigation channel, dredged just after jetty construction. Between December 1966 and June 1967, 151,000 cubic yards (115,448 cubic meters) of material was deposited throughout the channel (U.S. Army Engineer District, Wilmington, 1970); the channel migrated slightly to the south (Fig. 17). Following this initial movement to the south, the seaward part of the channel migrated rapidly more than 1,000 feet northward and, by July 1968, was immediately adjacent to the outer part of the jetty. By 1973 the channel closely paralleled almost the entire jetty length, causing undermining of the rubble section which required toe protection for the structure.

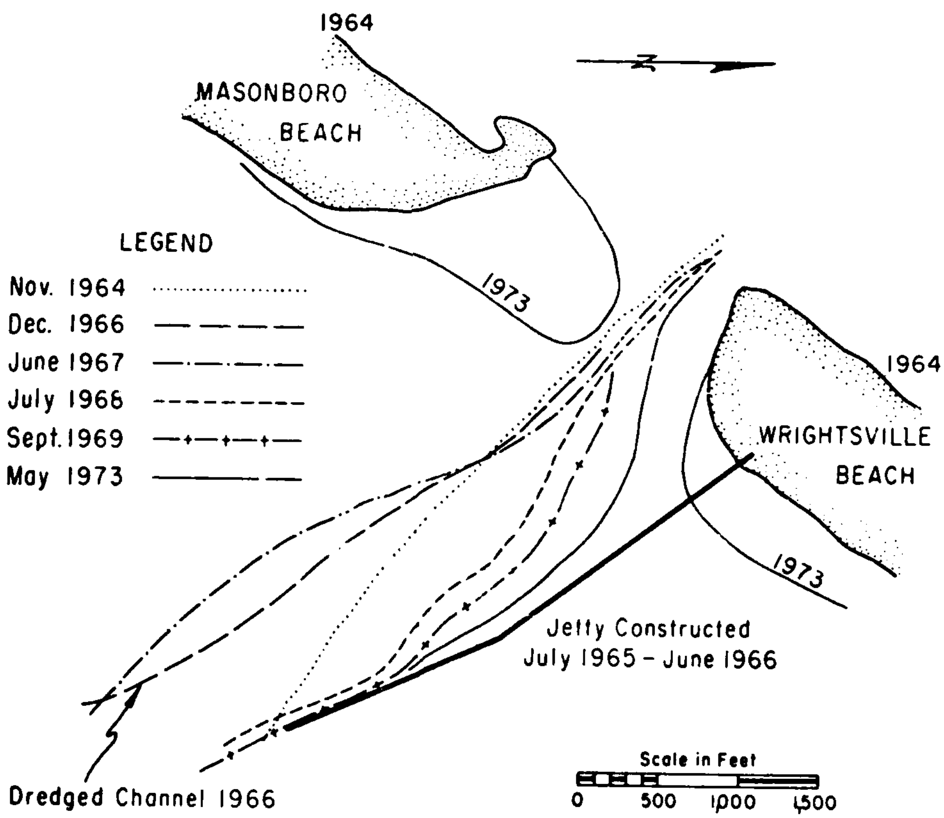

Figure 17. Time history of channel thalwegs, Masonboro Inlet, North Carolina, November 1964-May 1973 (after U.S. Army Engineer District, Wilmington, surveys).

A time history of the minimum channel area below MSL for Masonboro Inlet is shown in Figure 18. Some shoaling in the throat between 1964 and 1966 is indicated. The larger channel area in 1967 was primarily due to dredging. During October and November 1968, 105,600 cubic yards (80,737 cubic meters) of material was dredged from the channel (U.S. Army Engineer District, Wilmington, 1970). Following the 1968 dredging, the minimum channel area decreased slightly; however, the area has remained relatively constant since 1966. Between 1964 and 1973, the inlet throat width was reduced 1,200 feet (365.8 meters) because of the northeastward growth of Masonboro Beach (Fig. 17). During the same period, Wrightsville Beach accreted approximately 350 feet (106.7 meters) seaward, adjacent to the jetty.

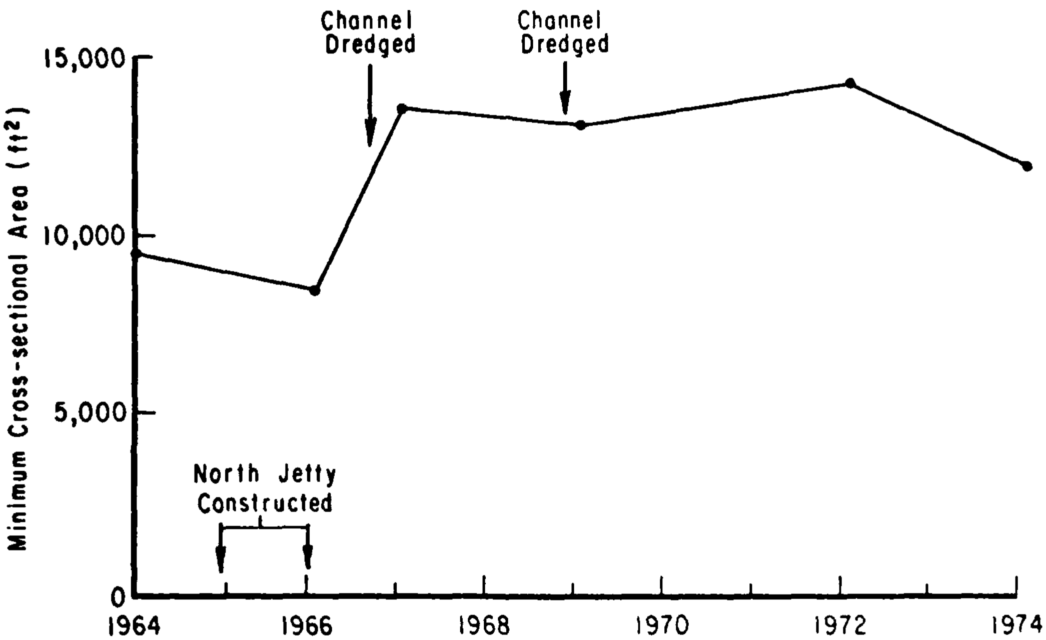

Figure 18. Time history of minimum channel area below MSL, Masonboro Inlet, North Carolina.

A south jetty is planned for Masonboro Inlet. Hydraulic model investigations have provided a jetty design that would concentrate tidal flow in the center of the jetties. The design would maintain the existing channel cross section and probably increase tidal current velocities along the south bank of the existing channel, causing the channel to aline midway between the jetties (Seabergh, 1976). The south jetty is expected to trap sediment at the landward end, causing shoreline accretion to form a fillet, which will keep sediment out of the channel by trapping northerly transport; however, the shoreline is not expected to advance to the seaward end of the jetty (Seabergh, 1976).

e. Summary. The channel at Masonboro Inlet migrated about 1,100 feet (335.3 meters) northward to a position immediately adjacent to the seaward part of the updrift jetty soon after its construction. The updrift adjacent shoreline accreted seaward only slightly due to the weir.

5. Humboldt Bay Entrance, California.

a. Existing Project. Humboldt Bay (Fig. 19) is located about 280 miles (450.6 kilometers) north of San Francisco, California, and about 80 miles (128.7 kilometers) south of Crescent City. Humboldt Bay entrance is presently stabilized by two parallel jetties 2,100 feet (640.1 meters) apart. The north jetty is about 7,500 feet (2,286 meters) long. The channel across the ebb tidal delta at the end of the jetties has a 40-foot (12.2 meters) design depth at MLLW, and a 1,600-foot (287.7 meters) design width at the bottom.

b. Environmental Setting. Tides at the ocean entrance are mixed with a diurnal range of 6.4 feet (2.0 meters). Maximum velocities during floodtide and ebbtide in the entrance are 3.4 and 6.8 feet (1.0 and 2.1 meters) per second, respectively (National Oceanic and Atmospheric Administration, 1977). The prevailing winds at Humboldt Bay are from the north and northwest during the summer and from the southeast and southwest during the winter (Washington State University, 1955b). The predominant direction of sea waves is from the northwest; swell arrives predominantly from the west (National Marine Consultants, 1960).

Based on wave energy flux calculations, the northward and southward longshore transport rates are 164,000 and 837,000 cubic yards (125,387 and 639,933 cubic meters) per year, respectively (R. Ecker, U.S. Army Engineer District, San Francisco, personal communication, 1976). This yields a net transport of 673,000 cubic yards (514,546 cubic meters) per year southward and a gross transport of about 1,000,000 cubic yards (765,320 cubic meters) per year.

c. Preimprovement History. Before jetty construction, the ocean entrance channel shifted sporadically over the ebb tidal delta. A time history of channel thalwegs for Humboldt Bay entrance from 1851 to 1882 (Fig. 20) shows the inlet channel changing from the northwest to southwest orientation and back again. The 1882 position of the thalweg suggests the possibility that this change in orientation resulted from channel bifurcation. During this period, both north and south spits retreated, and the entrance widened.

d. Inlet Entrance Response. Improvements to the Humboldt Bay entrance began in 1889 with construction of a downdrift south jetty having a crest elevation of 10 feet (3.0 meters) above MLLW. Construction on the north jetty, also to a crest elevation of 10 feet above MLLW, began in 1891. The seaward extent of each jetty through 1898 is shown in Figure 21, along with the channel thalweg locations from 1883 to 1898.

The channel responded to construction by migrating toward the south jetty (see 1894 thalweg, Fig. 21). However, as the north jetty extended seaward beyond the south jetty, the channel migrated approximately 500 feet toward the north jetty (see 1894-98 thalwegs, Fig. 21). By 1903, waves had deteriorated the outer one-third of both jetties to or below MLLW (O'Brien, 1931b). In 1916, both jetties were reconstructed to 18 feet above MLLW; the north jetty was rebuilt to within 500 feet of its original seaward extent. The north jetty was completed to its original length in 1925 (Noble, 1971).

Figure 22 shows that as the south jetty was extended seaward between 1898 and 1899, the channel migrated southward a maximum of 750 feet. From 1899 to 1907 the outer end of the channel migrated northward a maximum of about 1,300 feet (396.2 meters). Between 1898 and 1905 the north beach

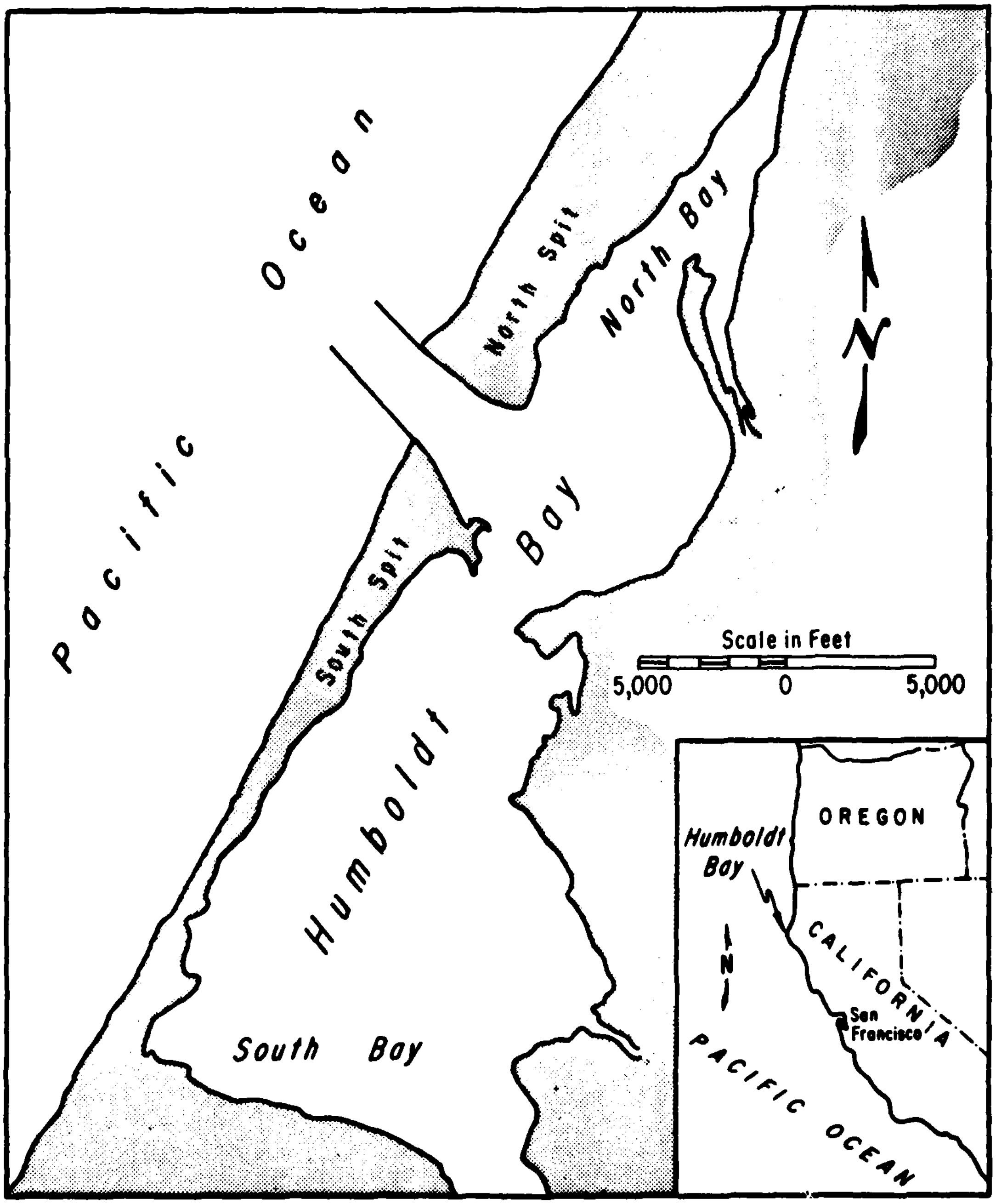

Figure 19. Humboldt Bay, California, in 1975 (after National Ocean Survey chart No. 5832).

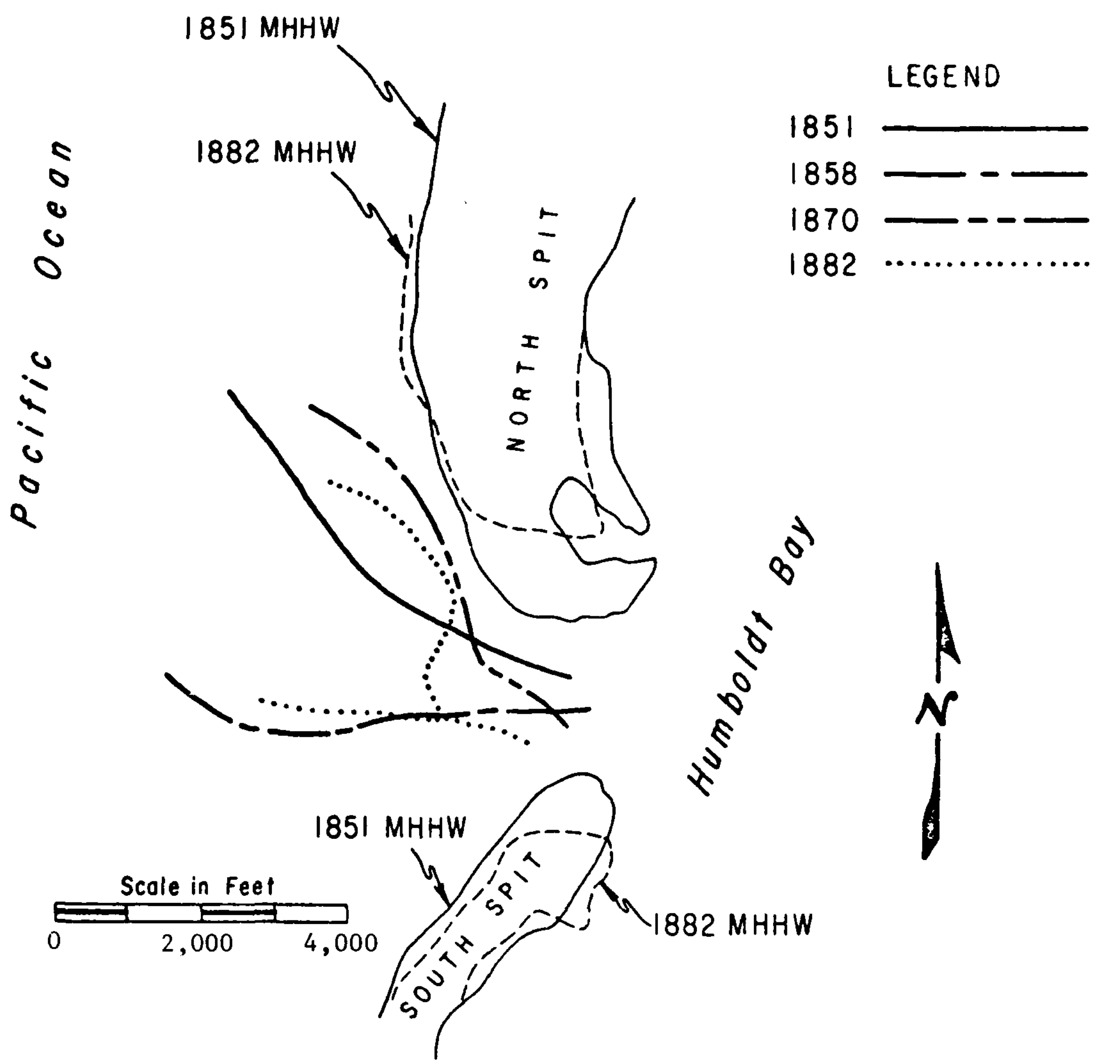

Figure 20. Time history of channel thalwegs, Humboldt Bay, California, 1851-82 (after U.S. Army Engineer District, San Francisco, surveys).

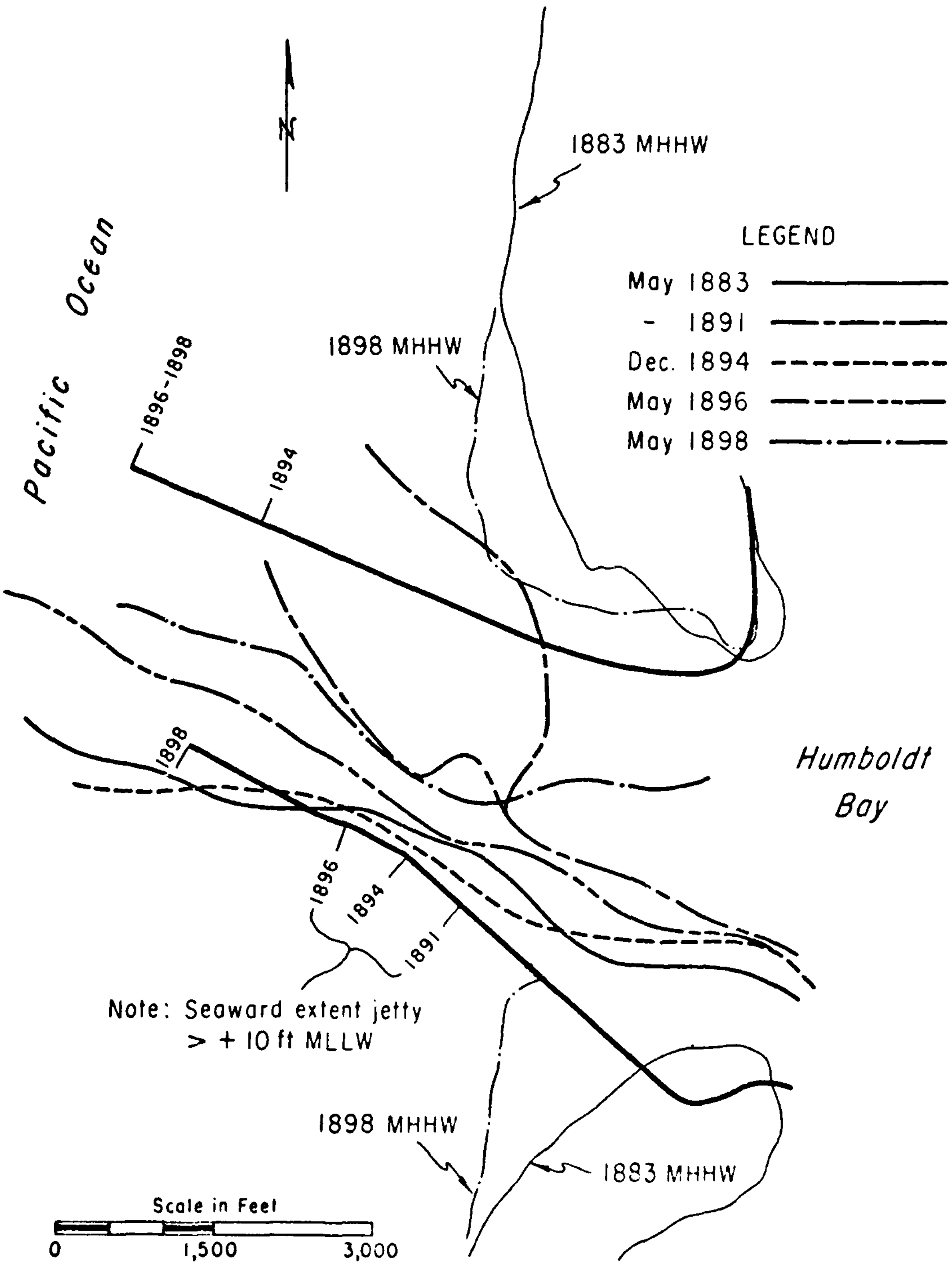

Figure 21. Time history of channel thalwegs, Humboldt Bay, California, May 1883-May 1898 (after U.S. Army Engineer District, San Francisco, surveys).

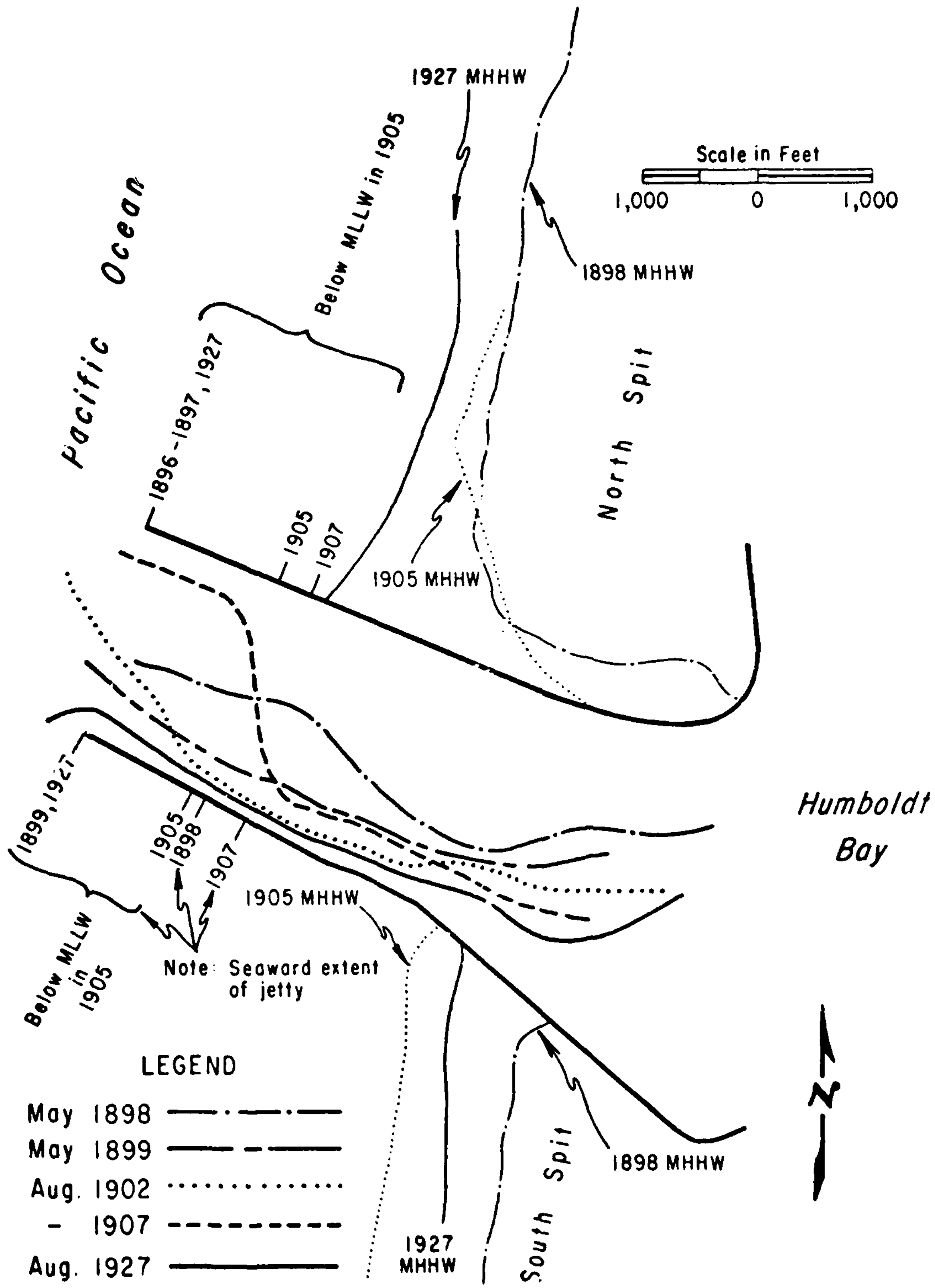

Figure 22. Time history of channel thalwegs, Humboldt Bay, California, May 1898-August 1927 (after U.S. Army Engineer District, San Francisco, surveys).

migrated seaward 900 feet, and the south beach immediately adjacent to the jetties migrated 1,275 feet (388.6 meters) seaward. Between 1907 and 1927, the outer end of the channel once again migrated southward about 1,500 feet, adjacent to the south jetty. Accretion of the north beach from 1905 to 1927 with erosion of the south beach implies the net transport was to the south.

Between 1927 and 1954 little movement of the channel occurred (Fig. 23). The adjacent shoreline surveys show a net accretion of about 150 feet (45.7 meters) on the north beach and a net recession of about 300 feet (91.4 meters) on the south beach, with most of the shoreline change occurring early in this period.

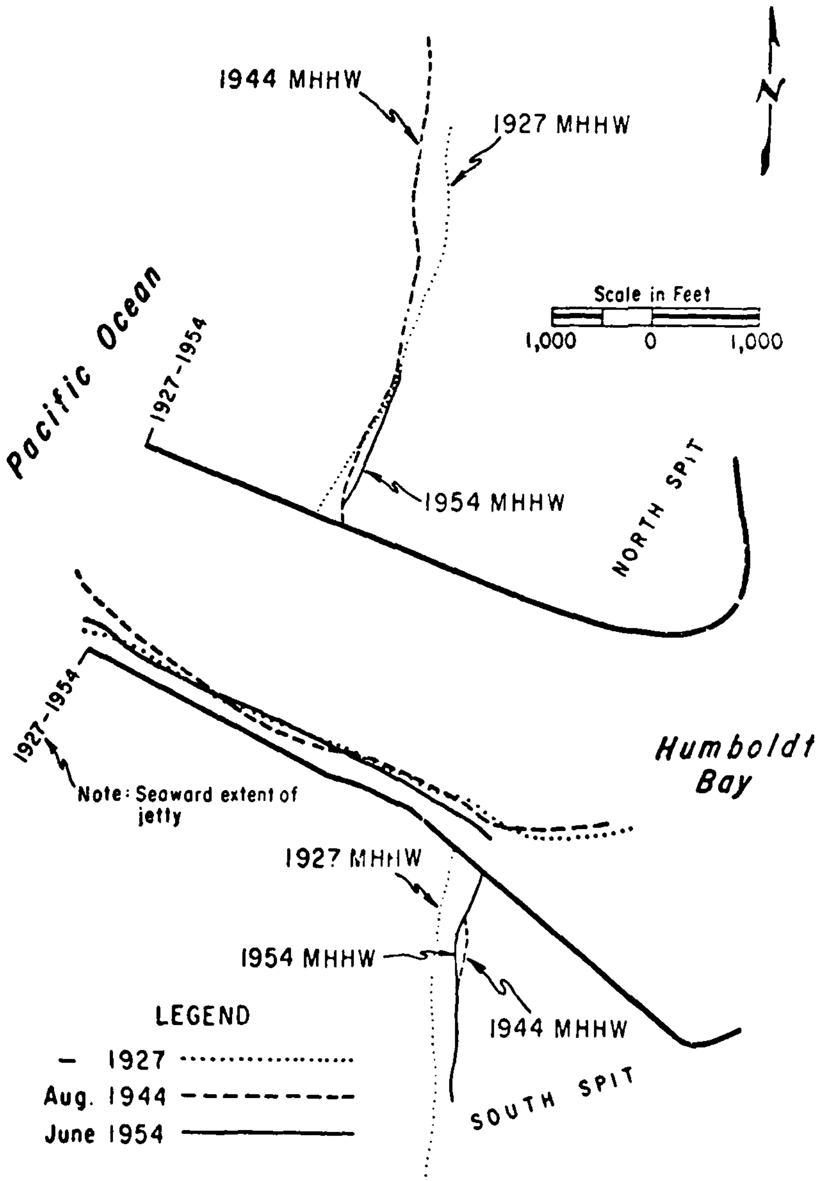

Figure 23. Time history of channel thalwegs, Humboldt Bay, California, 1927-June 1954 (after U.S. Army Engineer District, San Francisco, surveys).

In 1934, a channel 35 feet deep MLLW and 500 feet wide was dredged across the ebb tidal delta (U.S. Army, Corps of Engineers, 1934). By 1940, the channel had shoaled almost completely and the ebb tidal delta began migrating toward the south jetty (Noble, 1971).

Figure 24 is a time history of the minimum channel area below MSL from 185ι to 1971, although, unfortunately, detailed surveys were not available immediately after initial jetty construction. In general, the channel area increased after later jetty repairs and then decreased as the jetties deteriorated. However, the effects of storms and high rainfall periods may also be reflected in the data. Annual dredging of about 500,000 cubic yards has been necessary since 1954.

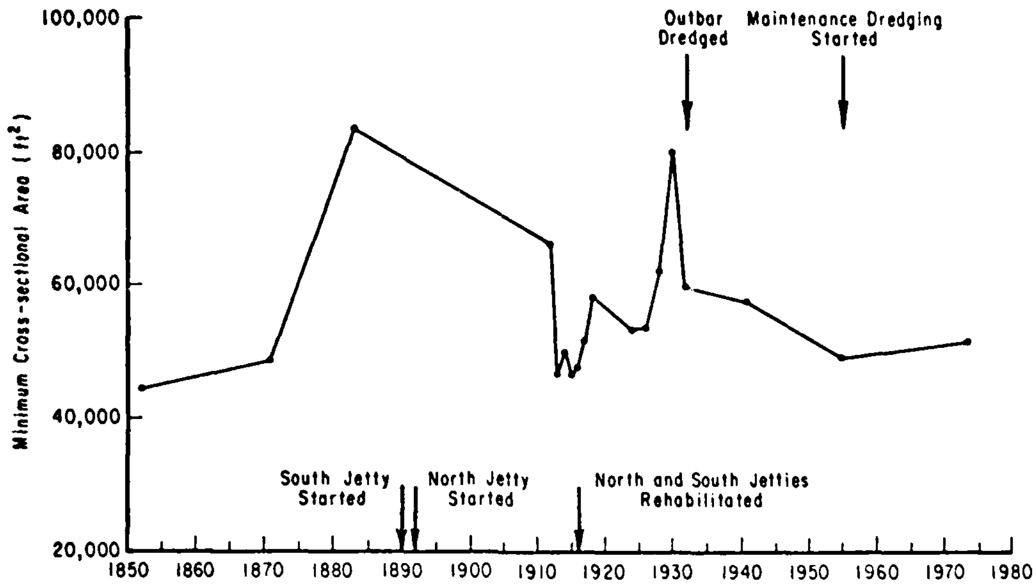

Figure 24. Time history of minimum channel area below MSL Humboldt Bay, California.

e. Summary. Before jetty construction, the entrance channel to Humboldt Bay did not maintain a stable orientation across the ebb tidal delta. With construction of a single downdrift (south) jetty, the channel migrated rapidly toward the jetty and remained there until a second jetty was constructed on the updrift (north) side of the channel. As the updrift jetty extended seaward beyond the downdrift one, the channel migrated toward it remaining there until the jetty had deteriorated to the point that the channel once more began to move downdrift.

6. Coquille River Entrance.

a. Existing Project. The Coquille River (Fig. 25) is about 225 miles (362 kilometers) south of the Columbia River. Improvements include a north jetty 3,450 feet (1,051.6 meters) long and a south jetty 2,700 feet (823 meters) long. The design channel depth at MLLW is 13 feet.

b. Environmental Setting. Tides in the Coquille River entrance area are mixed with a diurnal range of 6.8 feet at the ocean entrance. Maximum currents in the entrance during floodtide and ebbtide are 2.4 and 2.0 feet (0.73 and 0.61 meter) per second, respectively (National Oceanic and Atmospheric Administration, 1977). The prevailing winds at the Coquille River entrance are from

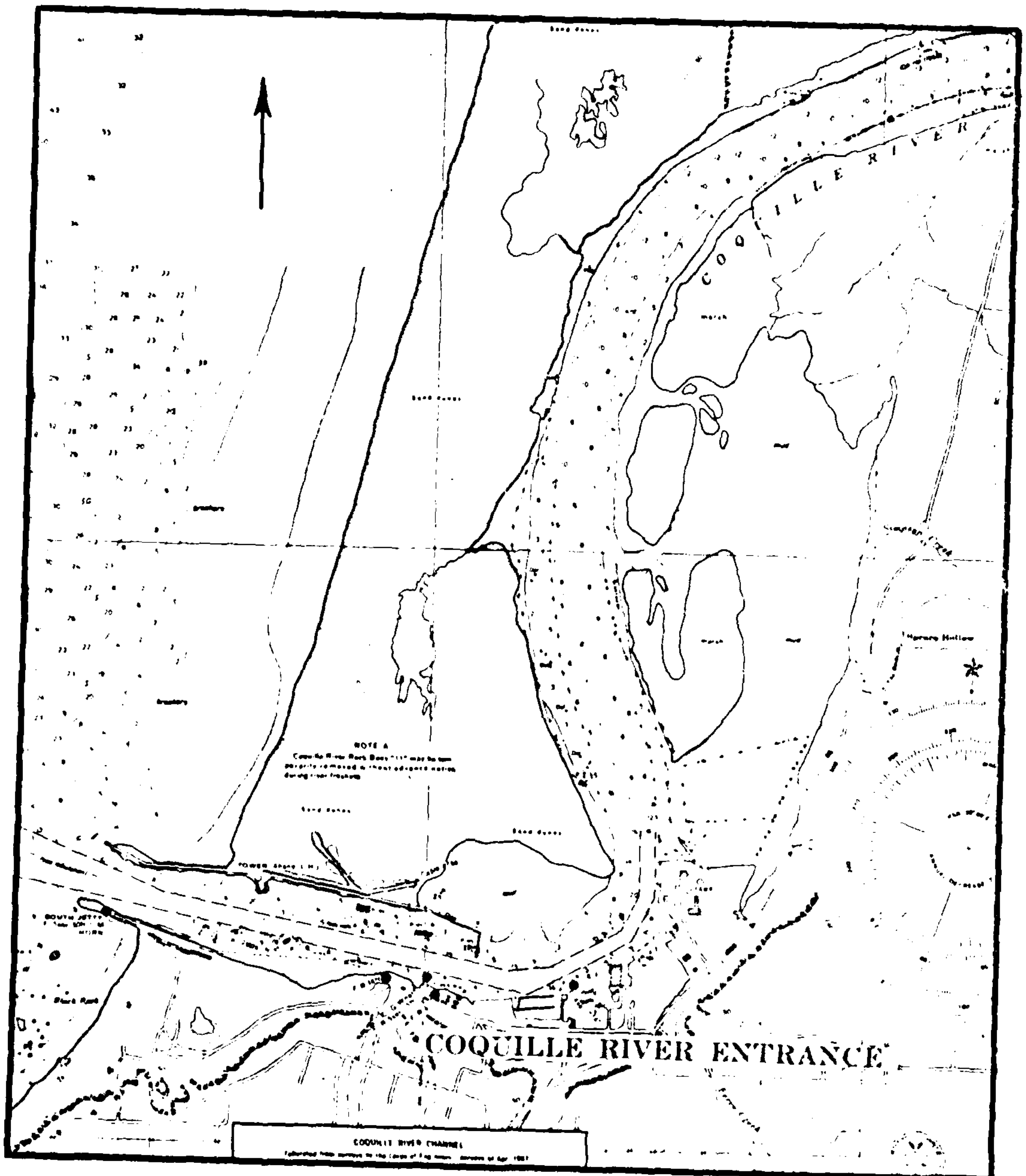

Figure 25. Coquille River, Oregon, in 1975 (after National Ocean Survey chart 5971).

the northwest 75 percent of the time and from the southwest 25 percent of the time; winds from the southwest occur mainly during December, January, and February (O'Brien, 1931b). There are no available wave records for Coquille River entrance. However, conditions are probably similar to those at the previously discussed Oregon inlets.

There are no quantitative estimates for longshore sediment transport rates in the vicinity of the Coquille River entrance. The net longshore sediment transport is assumed to be southward, based on the southward growth of the north spit at the ocean entrance (O'Brien, 1931b), but could be near zero (Lizarraga-Arciniega and Komar, 1975).

c. Preimprovement History. In 1880, the north spit overlapped the south spit, creating a bend in the channel which was difficult to navigate (see Fig. 26). Parkers jetty (Fig. 26) was built in 1881 to deflect the channel directly across the north spit, eliminating the bend in the ocean entrance (O'Brien, 1931b). A channel was opened through the north spit by 1882, but the improvements were only temporary due to the structural failure of Parkers jetty (U.S. Army, Corps of Engineers, 1888).

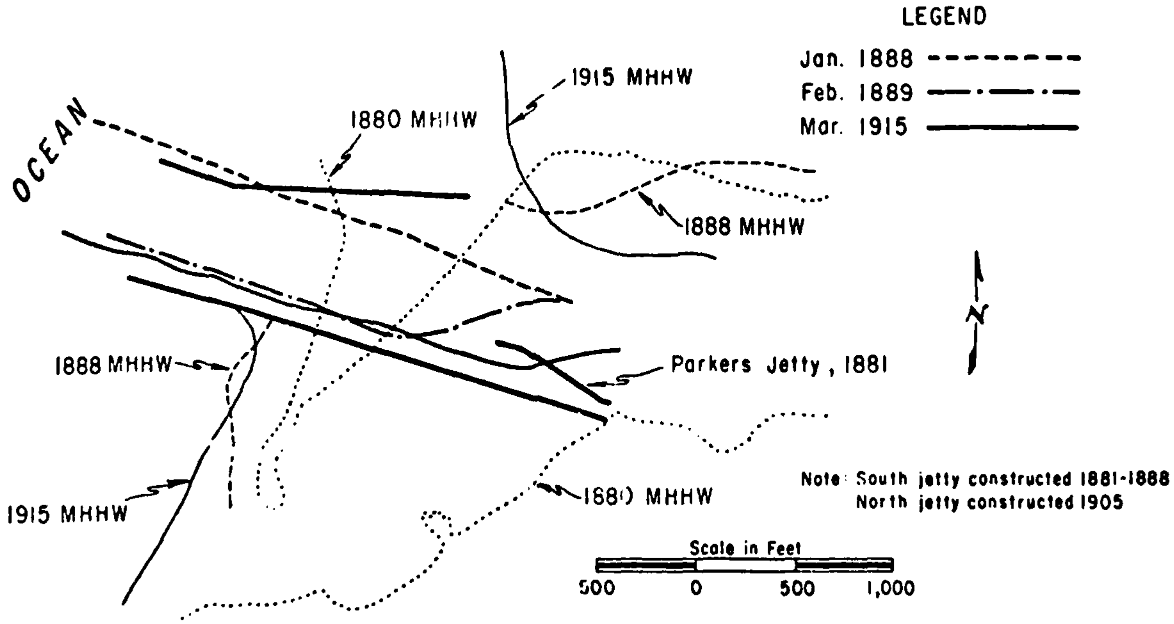

Figure 26. Time history of channel thalwegs, Coquille River, Oregon, 1888-1915 (U.S. Army Engineer District, Portland, surveys).

d. Inlet Entrance Response. The longer downdrift south jetty, constructed from 1884 to 1900 with a crest elevation of 10 feet above MLLW, was added to stabilize the channel. During construction the channel migrated 450 feet (137.2 meters) southward to a position adjacent to the jetty as shown by the February 1889 thalweg (Fig. 26). The north jetty, constructed from 1900 to 1916, also had a crest elevation of 10 feet above MLLW (O'Brien, 1931b). The channel remained adjacent to the south jetty through construction of the north jetty, as shown in Figure 26 by the 1889 to 1915 thalwegs.

Detailed surveys are not available to accurately define changes in the minimum channel area after construction of the jetties. Since 1916, annual dredging has been required between the jetties to maintain the channel design depth.

e. Summary. During construction of a downdrift (south) jetty, the channel migrated 450 feet southward to a position adjacent to the jetty. During construction of the updrift (north) jetty, the channel remained adjacent to the downdrift jetty. The net effect of jetty construction on the adjacent shorelines was accretion of the shoreline on both sides of the channel, with the largest shoreline advance on the south or downdrift side due to a larger impoundment area formed by the south jetty (Lizarraga-Arciniega and Komar, 1975).

7. Other Inlets.

Response to jetty construction at the Merrimack River entrance, Massachusetts; Newport Harbor entrance, California; Fernandina Harbor and St. Johns River entrances, Florida; Coos Bay entrance, Oregon; Aransas Pass, Texas; and Manasquan Inlet, New Jersey (Fig. 27) is briefly discussed either because of a limited amount of data or because of a simple response to jetty construction.

a. Merrimack River Entrance, Massachusetts. Figure 28 is a time history of channel thalwegs at Merrimack Inlet. Both the north (updrift) jetty, started in 1881, and the south jetty, started in 1883, have a crest elevation of 12 feet above MLLW. The seaward extent of the jetties through 1915 is shown in Figure 28.

Following the initial construction of the north jetty, the seaward part of the channel shifted southward, as shown by the 1883 thalweg. However, after this southward movement, the interior part of the channel migrated a maximum of 1,300 feet northward as shown by the 1883-1915 thalwegs. Construction from 1905 to 1915 completed the north jetty to the length shown in Figure 29; however, no work was done on the south jetty during this time. In 1916, the channel re-formed approximately in the 1885 position and, by 1938, migrated adjacent to the north jetty. Channel dredging began in 1938 (U.S. Congress, 1953).

After the start of the construction of the north jetty and before construction of the south jetty, the north beach accreted approximately 325 feet (99.1 meters) by June 1883; the south beach eroded (U.S. Congress, 1953). The south beach then accreted seaward with construction of the south jetty.

b. Newport Harbor Entrance, California. Improvements to the entrance to Newport Harbor began in 1917 with the construction of an updrift (northwest) jetty with a crest elevation of 10 feet above MLLW (O'Brien, 1931b). Bathymetric surveys with enough detail to define channel thalwegs were not available; however, it is evident from Figure 29 that the channel migrated to the updrift jetty after jetty construction. Figure 30 is a photo of the entrance in 1928, showing the proximity of the channel to the jetty. Constructing the east jetty began in 1928, added to serve as a littoral barrier to the westward longshore sediment transport; however, dredging in the entrance became necessary by 1930 (O'Brien, 1931b).

After construction of the west jetty, both the west and east beaches eroded. The west beach eroded 200 feet by 1921 and a landward extension of the west jetty became necessary to prevent flanking (O'Brien, 1931b). The east beach retreated continuously until the east jetty was constructed and a fillet developed.

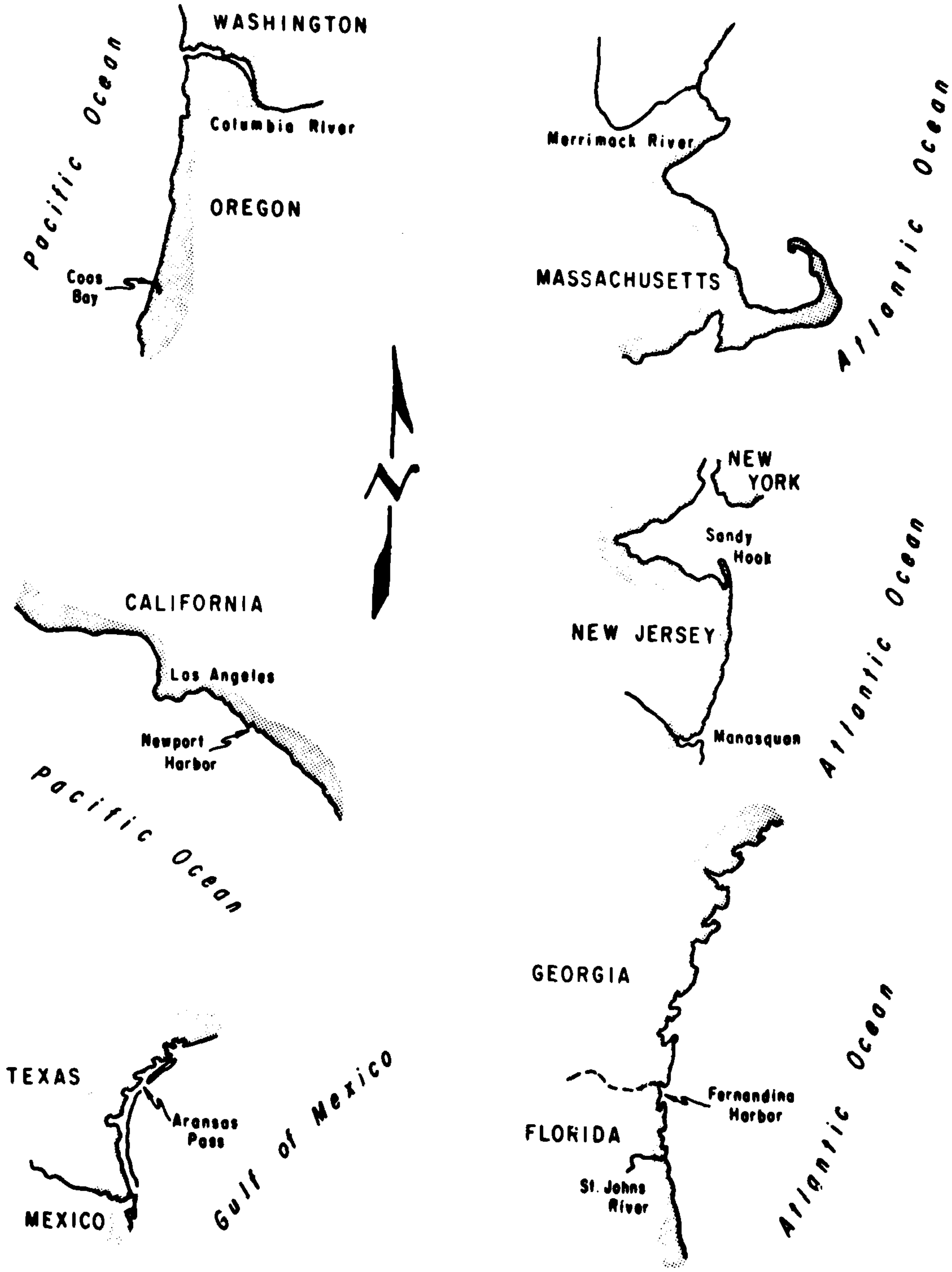

Figure 27. Inlet locations.

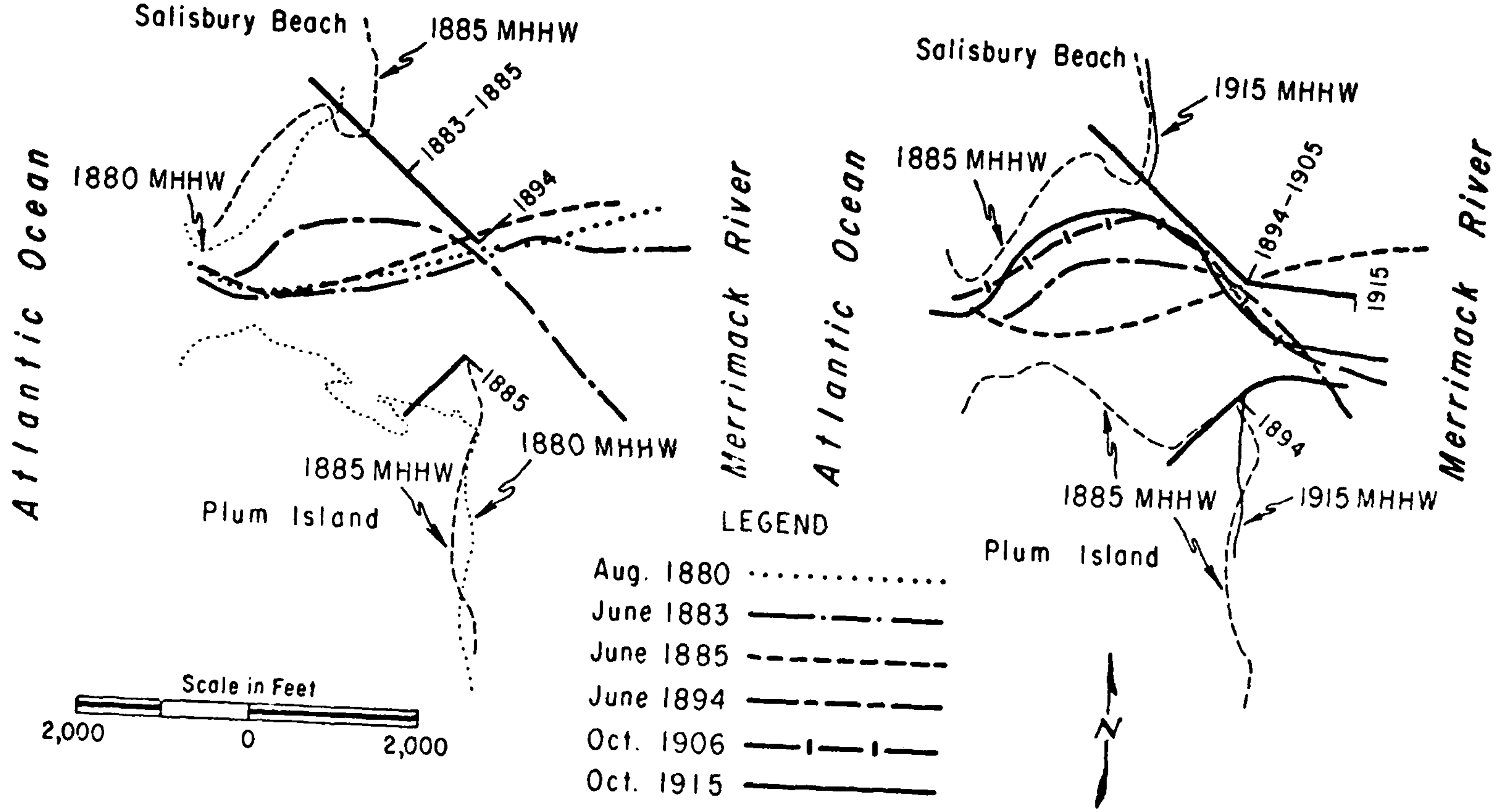

Figure 28. Time history of channel thalwegs, Merrimack River, Massachusetts, August 1880–October 1915 (after U.S. Army Engineer Division, New England, surveys).

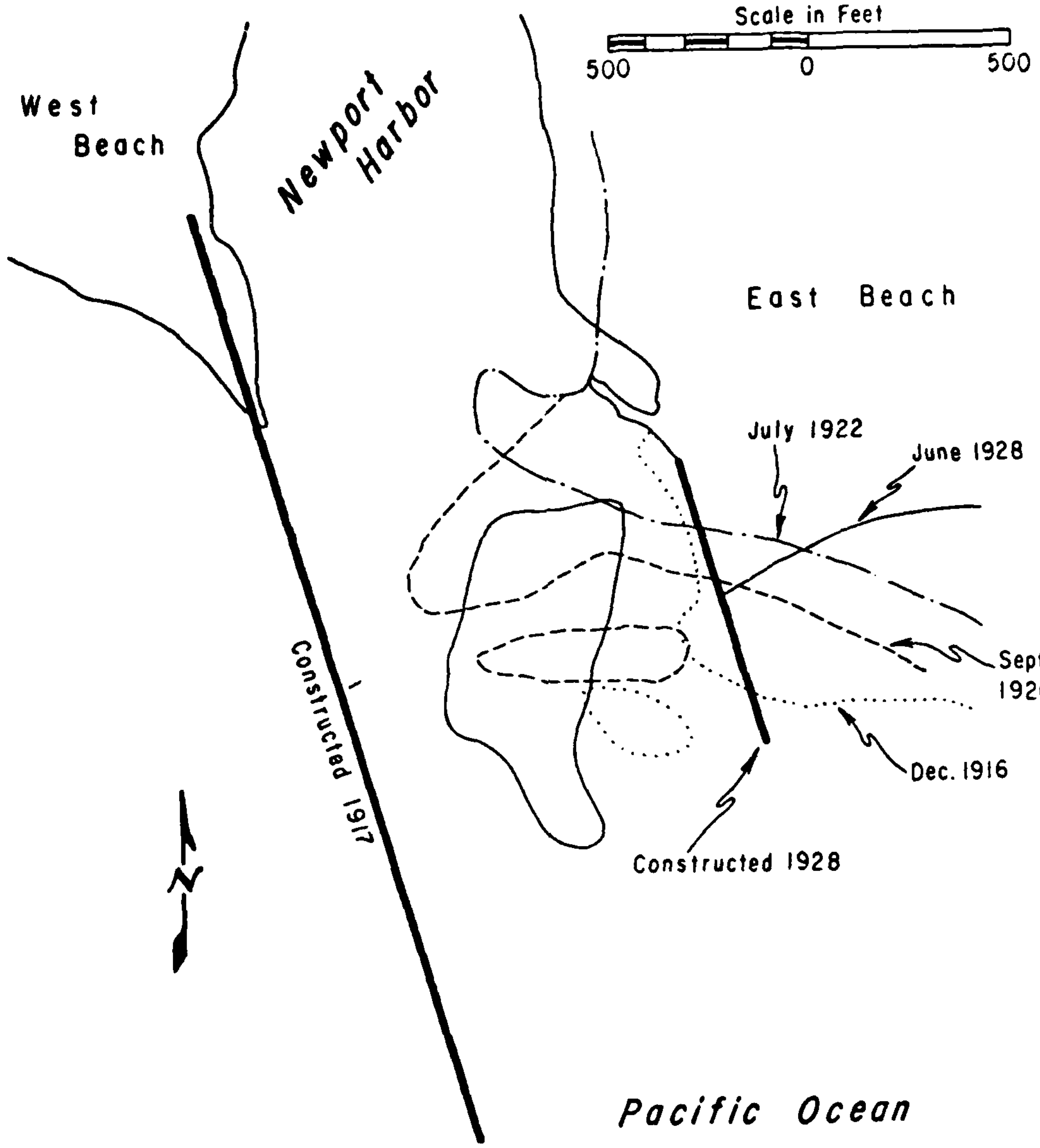

Figure 29. Entrance to Newport Harbor, California (after a 1928 map by the Newport city engineer).

Figure 30. Newport Harbor, California, in 1928 (after O'Brien, 1931b).

c. Fernandina Harbor Entrance, Florida. During the 1881-1903 construction of the jetties at Fernandina Harbor entrance, the downdrift jetty was extended seaward ahead of the updrift jetty (Blackman, 1938). Both were low tide jetties, and the influx of sand across the updrift jetty formed a shoal in the channel. The growth of this shoal forced the channel against the downdrift jetty (Blackman, 1938) so extension of the updrift jetty and dredging of the entrance channel became necessary.

d. St. Johns River Entrance, Florida. The channel through the ebb tidal delta of St. Johns River entrance was dredged in 1852, 1868, and 1870 to 1873, but there was little or no permanent improvement to the channel (U.S. Army Engineer District, Jacksonville, 1964). Construction of a downdrift jetty immediately adjacent to the existing channel was begun in 1880, but this still did not improve channel conditions. A second jetty on the updrift side of the channel was constructed in 1882 to improve depths over the ebb tidal delta. The channel remained adjacent to the downdrift jetty, through construction of the second jetty, until 1902 when the channel position was maintained between the jetties by dredging.

e. Coos Bay Entrance, Oregon. The entrance to Coos Bay was improved by a single updrift (north) jetty constructed from 1891 to 1895 immediately adjacent to the channel (O'Brien, 1931b). The channel migrated toward the jetty, but depths in the channel were not navigable; channel dredging was initiated in 1917 (Reynolds, 1951). A second jetty was added between 1924 and 1928 (O'Brien, 1931b). Shoreline changes after jetty construction are discussed by Lizarraga-Arciniega and Komar (1975).

f. Aransas Pass, Texas. After two earlier unsuccessful attempts to improve the entrance with single jetties, which were destroyed by storms, a Haupt jetty was constructed between 1895 and 1906 on the north side of the inlet close to the existing channel. The navigation channel steadily decreased in depth following construction of the Haupt jetty and moved closer to the jetty; a second channel began to develop in the gap between the Haupt jetty and the shore. By 1908, it became necessary to connect the Haupt jetty to the shoreline and construct a south jetty. Dredging in the entrance began in 1916 (Reynolds, 1951).

g. Manasquan Inlet, New Jersey. Dikes were constructed between 1881 and 1886 on the north and south sides of the entrance channel (Blackman, 1938); however, the dikes were not successful in stabilizing the entrance and the inlet closed completely in 1920. The inlet was reopened in 1922, improved by a Haupt jetty constructed on the south side of the channel. The jetty completely failed to stabilize the channel so the inlet closed again in 1925 (Blackman, 1938). Twin jetties were constructed at the entrance in 1931, and dredging was begun to keep the inlet open.

IV. INLET PROCESSES

This section discusses the factors that produced the inlet thalweg, adjacent shoreline, cross-sectional area, and ebb tidal delta responses to jetty construction observed at the 13 inlet entrances described in Section III. The inlet entrance responses are assumed to result from one or a combination of the following factors:

(a) Tidal currents, whose magnitude and horizontal distribution affect sediment scour and deposition patterns;

(b) riverflow and density currents which also affect sediment scour and deposition patterns;

(c) wave-generated longshore currents and sediment transport processes which transport material to the inlet entrance and affect the deposition and erosion of material on the ebb tidal delta, inlet channel, and bay shoals;

(d) jetty structure factors to include jetty length, shape, orientation, spacing, crest-elevation, and permeability.

The current regime at any inlet is affected primarily by the tidal characteristics; the inlet channel geometry; the relative position, orientation, and size of the inlet with respect to the bay; and the bay size and plan geometry. The wave processes depend primarily on the wave characteristics (height, period, and direction), as well as wave refraction over the local bathymetry and wave-current interactions. As the wave characteristics change, the direction and rate of longshore sediment transport change. The jetty structure factors control the amount of wave action and sediment entering the entrance and thus affect depositional patterns in the inlet.

1. Inlet Thalweg Response.

At Grays Harbor, where the net longshore transport is to the north, most of the ebb tidal flow is from the main drainage area north of the inlet (see Fig. 6), causing ebb currents to deflect against the south side of the inlet throat. The migration of the thalweg after construction of the south jetty was probably predictable since these currents would be expected to scour the outside of the channel bend, resulting in channel migration toward the jetty. However, only that reach of the channel within the jetty's length (1903 thalweg in Fig. 7) migrated, where sand transport from the south was minimized by the jetty, allowing the southward migration. The southward migration was due to the choking effect of wave-transported material deposited along the north side of the channel and to the jetty minimizing sand transport from the south. Scour of the south side of the channel was caused by tidal currents attempting to maintain an equilibrium cross-sectional area.

The importance of longshore sediment transport in influencing channel migration is substantiated by the cyclic downdrift (northward) migration of the prejetty channel entrance and the small net movement of the channel during deterioration of the south jetty between 1904 and 1915. The updrift migration of the channel slowed when the permeability and crown elevation of the south jetty no longer prevented sand from entering the channel from the south. As the south jetty's sand-trapping capability was decreased further and the north jetty was extended seaward, sand transport into the channel from the north became limited. The channel then migrated to the north in opposition to the current regime (1915-20 thalweg) and, because of the choking effect of wave-transported material, deposition occurred along the south side of the channel.

During bar dredging, the thalweg position remained relatively stable. Following the 1935-39 reconstruction of the south jetty, however, the channel migrated rapidly southward. The outer reaches of the north jetty deteriorated during this period and allowed sand to enter the channel from the north, further encouraging the migration.

It is concluded that the major factors producing changes in channel location at Grays Harbor are longshore sediment transport and tidal currents. When there were no jetties, the channel migrated in the same direction as the net longshore transport; however, after improvement, the condition of the north and south jetties controlled sediment influx to the channel and the resulting thalweg shift. Also, wave refraction around the ebb tidal delta probably influenced channel migration by affecting the direction of sediment transport. Refraction of waves from the south of west around the ebb tidal produces a convergence of longshore sediment transport at the entrance, although the net transport is northward (U.S. Army Engineer District, Seattle, 1965). This, combined with the reversals in transport direction due to waves from the north of west, produced enough sediment transport southward to produce channel migration. This is evident by the extensive shoreline accretion adjacent to the north jetty (see Fig. 8).

At Tillamook Bay entrance, where the net transport is near zero, most of the ebb tidal prism flows from the main drainage area south of the inlet (see Fig. 11). This causes the ebb jet to deflect against the north side of the inlet throat where the thalweg had historically remained before jetty construction. Initially, the north jetty provided an effective littoral barrier and trapped a large part of the longshore transport which rapidly accreted against the jetty. With sediment transport from the north minimized, the channel, due to sediment transport from the south, migrated toward the jetty, which resulted in the growth of a large ebb tidal delta near the end of Kinchloe Point (Terich and Komar, 1973). As the ebb tidal delta grew due to this extensive deposition on the south side, the channel was pushed toward the jetty. The material deposited on the bar was transported toward the channel by a combination of flood tidal currents and wave-induced circulation developed in the lee of jetties and breakwaters, documented by Seabergh and Sager (1980) and Sato and Irie (1970).

The Umpqua River estuary lies north of the ocean entrance (see Fig. 14); before jetty construction the thalweg was located on the south side of the throat, a position that was probably somewhat reinforced by the net southern longshore transport. With construction of the updrift jetty, the thalweg migrated northward as the jetty was extended seaward, in direct opposition to the ebb jet direction, which indicates wave-transported sediment produced the migration.

The geometry of Masonboro Inlet (see Fig. 1) indicates that Shinn Creek is oriented such that flow from the creek, if unaffected by converging flows of Masonboro and Banks Channels, would be directed toward the seaward tip of the jetty, approximating the alinement of the present thalweg. However, flow measurements taken in 1969 showed that the distribution of ebb flow through the sound channels was 38 percent from Shinn Creek, 21 percent from Masonboro Channel, and 41 percent from Banks Channel. Thus, the ebb flow from Shinn Creek is primarily affected by flow from Banks Channel, and a southward shift of the channel based on the hydraulics alone, might be expected. In fact, during the first 6 months (December to June) after the completion of the navigation channel, the channel shifted slightly to the south. The predominant waves during this period are generally from the northeast, so relatively little material is transported to the inlet from the south, allowing southward migration of the channel. Subsequent major reversals of the transport during summer months caused the channel to migrate rapidly toward the jetty where it has remained. It is concluded that the channel response was primarily due to wave processes similar to those affecting the previously discussed entrances.

The entrance channel to Humboldt Bay responded directly to reversals in longshore sediment transport by migrating in the same direction as the net transport, as shown by the 1898-1899, 1899-1907, and 1907-1927 thalweg positions in Figure 22. The condition of the north and south jetties controlled the migration in the same manner as the jetties at Grays Harbor. From 1927 to 1954, when the annual dredging at the entrance began, the channel showed little net movement. The jetties remained intact and prevented significant amounts of sand from entering the channel, thus substantiating the fact that wave-induced sediment transport was the primary factor producing channel migration at Humboldt Bay entrance.

Before jetty construction, the flow at the Coquille River estuary, which lies north of the entrance, was directed toward the south side of the inlet throat. The first jetty was constructed on the downdrift (south) side of the inlet, and the channel migration to the jetty was more uniform (the channel shifted an equal distance over the entire reach within the jetty's length) than the migration at most of the previously discussed entrances improved by updrift jetties. Therefore, it appears that either waves were allowed to penetrate more deeply into the estuary or the combination of currents and waves from the updrift direction produced a more rapid and uniform response.

Although the Merrimack River entrance channel generally behaved as other inlets initially improved with single updrift jetties, the channel migrated to a position adjacent to the updrift twice between 1883 and 1938. Following the initial migration toward the jetty, the channel developed a large bend at the entrance (1915 thalweg in Fig. 28). It is assumed that the subsequent reorientation of the channel in a more downdrift and less curved position was due to a combination of ebb tidal and river currents seeking a more hydraulically efficient path. The second migration of the channel adjacent to the updrift (north) jetty (1916 to 1938) indicates the south jetty was not functioning as a littoral barrier. The predominant wave approach direction at the entrance is northeast; however, refraction around the ocean bar produces a local reversal in transport direction contributing to channel migration toward the updrift (north) (Hayes, Goldsmith, and Hobbs, 1970).

The migration of the channel at Newport Harbor also resulted from wave processes. Longshore sediment transport formed an extensive shoal downdrift of the jetty, similar to that at Tillamook Bay entrance (Fig. 29). As the shoal developed, the channel was pushed against the jetty.

The entrance channel to Fernandina Harbor migrated to a position adjacent to the downdrift jetty due to extensive sediment deposited in the entrance by longshore currents. Sediment transported into the entrances to Coos Bay, Aransas Pass, and Manasquan Inlet by longshore currents caused these single jetty improvements to fail.

Migration of the channel toward a net *updrift* jetty is caused primarily by littoral drift approaching from the downdrift side of the inlet entrance. This is evident from the fact that in several instances the channel migrated in opposition to the ebb jet direction. Wave refraction around the ebb tidal delta also contributes to channel migration by increasing the amount of sediment transported into the channel from the downdrift direction. The elevation of the updrift jetty crown and the soundness of the jetty also influence channel migration. If the updrift jetty deteriorates, sand will move through and over the jetty, decreasing the channel migration rate toward the jetty. If the jetty crown is low and sand movement over the jetty is significant, the channel may migrate away from the jetty as at Gray's Harbor and Humboldt Bay.

The channel migration is proportional to longshore sediment transport. The unavailability of detailed longshore transport summaries or wave records during the migration period for the inlets discussed limits a quantitative analysis or correlation of the observed channel migration. However, the ratio of the maximum migration in 1 year to the distance from the prejetty thalweg location to the updrift jetty (potential migration distance), given in Table 2, allows a comparison between individual migration rates.

Table 2. Annual maximum channel migration ratios for inlets improved by a single updrift jetty.

Inlet	Estimated updrift longshore transport (yd^3/yr)	Direction	Annual maximum migration rate/distance to jetty from prejetty Thalweg (ft)	Ratio
Gray's Harbor, Wash.	650,000	Southerly	2,000/4,500	0.44
Tillamook Bay, Oreg.	800,000	Southerly	510/1,900	0.27
Umpqua River, Oreg.	400,000	Northerly	510/1,800	0.28
Masonboro Inlet, N.C.	500,000	Northerly	800/1,080	0.74
Merrimack River, Mass.	Not available		70/2,000	0.04
			AVERAGE	0.31

The maximum channel migration rates usually occurred near the seaward end of the jetty with the amount of channel migration decreasing toward the bay. This could account for some of the large variation in the rates in Table 2. The maximum rates at Gray's Harbor, Tillamook Bay, and Masonboro Inlet occurred near the seaward end of the jetty; the maximum migration at Umpqua River and Merrimack River occurred nearer the bay end of the jetty. Jetty construction progressed at a slower rate at the Umpqua River and Merrimack, which would also account for some of the variation in rates. It was noted that the maximum migration generally occurred shortly after jetty construction. If the construction of the updrift jetty was fast, the channel responded quickly by migrating toward it. Similarly, when jetty construction was slow, channel migration was also slower.

Table 2 indicates the highest relative thalweg migration rate occurred at Masonboro Inlet, where in 1 year the thalweg migrated 74 percent of the total distance available to migrate, i.e., the distance from the prejetty thalweg location to the jetty. On the average, the channel thalwegs migrated an annual maximum of 31 percent of the total distance available to migrate following construction of an updrift jetty. Migration of the channel toward a downdrift jetty is caused primarily by longshore sediment transport from the updrift side of the inlet entrance. As stated in Section II, in most cases the single downdrift jetty was designed to allow sand transport from the updrift side of the channel to force the channel against the jetty. It was believed this would confine the entrance discharge area by concentrating ebb tidal currents and increasing their scour capability. Although detailed surveys were not available to confirm this, it seems understandable that the construction of a downdrift jetty would result in a temporary improvement in channel area by concentrating ebb tidal currents. However, during periods of reversals in transport direction, the tidal prism would not be confined in the main channel by sand transport from the unjettied side of the channel. The channel would shoal due to sand transported around the jetty and the inability of weaker ebb tidal currents flowing over a larger area to remove the sediment. The channel would also shoal if the longshore sediment transport from the updrift direction greatly exceeded the ability of the ebb tidal currents to remove material deposited in the entrance.

Although data from only two inlets (Humboldt Bay and Coquille River) are available (Table 3), the average ratio between annual migration rate and

Table 3. Annual maximum channel migration ratios for inlets improved by a single downdrift jetty.

Inlet	Estimated updrift longshore transport (yd^3/yr)	Direction	Annual maximum migration rate/distance to prejetty (ft)	Ratio
Humboldt Bay, Calif.	837,000	Southerly	268/900	0.30
Coquille River, Oreg.	Not available		417/611	0.68
			AVERAGE	0.49

potential migration distance (49 percent) is significantly greater for downdrift jettied inlets than for updrift jetties (31 percent), even when construction proceeded slowly. Thus, wave processes appeared to have a more direct influence on these entrances.

A discussion of channel thalweg response following the addition of a second jetty to inlets initially improved by single jetties is limited because, in most cases, dredging was performed in the entrances soon after jetty construction and only natural response was of interest in this study. Discussions of channel thalweg response at Grays Harbor and Humboldt Bay have indicated how the permeability and crown elevation of both jetties may control channel migration. It was also shown that when the jetties were relatively impermeable and the crown elevation was high enough to prevent sand transport over the jetty, the channel position remained relatively stable. The thalweg remained adjacent to the jetty where it had migrated after construction of the second jetty. This migration occurred at Grays Harbor, Tillamook Bay, Humboldt Bay, Coquille River, Newport Harbor, Fernandina Harbor, St. Johns, Coos Bay, and Aransas Pass. Dredging has been necessary to relocate the channel away from the jetty; this was done at St. Johns River.

2. Adjacent Shoreline Response.

To minimize the amount of littoral drift entering the inlet entrance, jetties are generally constructed to extend from the shoreline to seaward of the breaker zone where longshore sediment transport is minimal. Accretion of the updrift shoreline and erosion of the downdrift shoreline usually follow jetty construction at rates proportional to the longshore transport (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977). The quantity of material trapped by a jetty depends on the jetty length and orientation (angle with the shoreline). More material will be trapped by a structure which forms an angle greater than 90° with the updrift shoreline than one forming an acute angle with this shoreline.

The updrift area of a jetty design does not have an unlimited storage capacity for sediment; some sediment will move around the jetty end and either deposit in the inlet-bay system or bypass downdrift of the entrance. Table 4 summarizes the response of the updrift shoreline-jetty intercept during construction.

Table 4. Summary of adjacent updrift shoreline accretion during construction of a single updrift jetty.

Inlet	Jetty construction (yr)	Accretion rate (ft/yr)	Downdrift longshore transport (yd^3/yr)	Direction
Grays Harbor Wash.	1899-1908	278	1,200,000	Northerly
Tillamook Bay, Oreg.	1914-1917	833	800,000	Northerly
Umpqua River, Oreg.	1917-1926	267	500,000	Southerly
Masonboro Inlet, N.C.	1965-1966			

[1]Small change due to weir design.

The distance along the shoreline where the accretion occurred varied. The advance was greatest at the jetty and decreased with increasing distance from the jetty. Construction of the jetties at both Grays Harbor and Umpqua River took about 9 years, and the accretion rates were almost equal. The jetty at each entrance was at an obtuse angle with the shoreline. The jetty at Tillamook Bay was constructed in 3 years and placed perpendicular to the shoreline. The accretion rate of the shoreline at Tillamook Bay was about three times faster than the rate at Grays Harbor or Umpqua River. Since the transport rate at Tillamook Bay is less than at Grays Harbor, the angle of the jetty with the shoreline is assumed to be the sole factor causing differences in accretion rates.

The length of jetty construction time is probably a factor in the development of an adjacent shoreline fillet. If jetty construction is slow, the development of the fillet adjacent to the jetty is limited by jetty length due to sediment bypassing around the jetty. Sufficient surveys of the downdrift or unjettied shoreline during construction of an updrift jetty were not available to quantify erosion rates. Erosion of the downdrift shoreline usually occurred, as seen in the case histories of Section III.

3. Cross-Sectional Area Response.

With the exception of Grays Harbor, where the minimum channel cross-sectional area below MSL temporarily increased, construction of a single updrift jetty resulted in a decrease in the minimum channel area. This decrease in area ranged up to 40 percent at the Umpqua River, indicating that construction of a single updrift will result in only a temporary improvement in channel cross-sectional area. Data were not available to determine changes in channel cross-sectional area immediately following construction of a single downdrift jetty.

Stability of an inlet channel results when there is a balance between the tidal prism, which tends to increase the channel cross-sectional area, and the amount of sediment transported to the inlet by waves and currents, which tends to reduce the inlet cross-sectional area. O'Brien (1931a, 1967) found that when an inlet was stable (in equilibrium with its hydraulic environment) the cross-sectional area of the throat was related to the tidal prism by

$$A = 4.7 \times 10^{-4} P^{0.85} \qquad (1)$$

where A is minimum flow area below MSL (in square feet), P the tidal prism for a spring or diurnal range (in cubic feet).

Most of the data from the 28 inlets used by O'Brien in developing equation (1) were for Pacific coast inlets which were controlled by two jetties. Jarret (1976) used data from 108 inlets to develop equations (2) and (3) for inlets controlled with single jetties on the Pacific and Atlantic coasts, respectively

$$A = 1.91 \times 10^{-6} P^{1.10} \quad (2)$$

$$A = 5.37 \times 10^{-6} P^{1.07} \quad (3)$$

Table 5 gives the actual channel cross-sectional areas at Grays Harbor, Tillamook Bay, Umpqua River, Masonboro Inlet, and Humboldt Bay at or close to the time of initial single jetty construction. The data were taken from Figures 10, 13, 16, 18, and 24; tidal prism data were taken from Jarrett (1976). The equilibrium areas for each inlet as predicted from equation (2) or (3), and the ratios of actual areas to equilibrium areas are also given in Table 5. With the exception of Grays Harbor and Masonboro Inlet, the areas at the time of single jetty construction were larger than the equilibrium area predicted from equation (2) or (3) (ratios larger than 1); thus, it appears that the areas at the time of single jetty construction were too large to be maintained by the tidal prism of each inlet, which resulted in the deposition.

Table 5. Summary of actual areas, tidal prisms, and equilibrium areas at single-jettied inlets,

Inlet	Actual area (ft^2)	Tidal prism (ft^3)	Equilibrium area (ft^2)	Actual area/ equilibrium area
Grays Harbor, Wash.	247,000	1.70×10^{10}	342,000	0.72
Tillamook Bay, Oreg.	41,800	2.11×10^{9}	34,000	1.23
Umpqua River, Oreg.	38,800	1.59×10^{9}	25,000	1.55
Masonboro Inlet, N.C.	14,000	8.55×10^{8}	19,000	0.74
Humboldt Bay, Calif.	82,000	3.51×10^{9}	60,000	1.37

Figures 10 and 18, the time histories of the channel cross-sectional areas for Grays Harbor and Masonboro Inlet show, as predicted from equations (2) and (3), that a larger area than the area at the time of single jetty construction would occur at each inlet. The cross-sectional area of 267,000 square feet (24,805.1 square meters) was greater than the equilibrium area of 233,300 square feet (21,674 square meters) predicted by equation (1) (by 13 percent) when the second jetty was added at Grays Harbor, and thus was too large to be maintained by the tidal prism. The channel area decreased 36 percent shortly after the jetty was constructed.

Dredging in the entrance channel at the other inlets in Table 5 precluded an analysis of the natural channel response to the addition of a second jetty.

4. Ebb Tidal Delta Response.

The effects of single jetty construction on the ebb tidal delta were quantitatively documented at only two inlets, Grays Harbor and Tillamook Bay. During jetty construction the delta at these two inlets moved seaward at the rate of 111 and 333 feet (33.8 and 101.5 meters) per year, respectively, as the jetties were extended seaward. Noble (1971) stated the ebb tidal delta at Humboldt Bay also moved seaward at an unspecified rate during jetty construction.

V. SUMMARY AND CONCLUSIONS

The construction of single jetties at the inlet entrances discussed in Section III produced similar channel thalweg, adjacent shoreline, cross-sectional area and ebb tidal delta responses. The channel thalwegs migrated toward the jetty and remained there, regardless of the inlet-bay orientation, the jetty angle with the shoreline, the position of the jetty relative to the direction of net longshore sediment transport, the ratio of net-to-gross transport, or the gross transport. On the average, the channel thalwegs migrated an annual maximum distance of 31 percent of the total distance available for migration following construction of a single updrift jetty and 49 percent of the total distance available for migration following construction of a single downdrift jetty.

Idealized models based on the case histories in Section III are shown in Figures 31 and 32. Figure 31 models channel migration toward a single updrift jetty and is representative of the response to jetty construction documented for the following inlets:

(a) Grays Harbor, Washington

(b) Tillamook Bay entrance, Oregon

(c) Umpqua River entrance, Oregon

(d) Masonboro Inlet, North Carolina

(e) Merrimack River entrance, Massachusetts

(f) Newport Harbor, California

Figure 32 models channel migration toward a single downdrift jetty and is representative of the response to jetty construction documented for the following inlets:

(a) Humboldt Bay entrance, California

(b) Coquille River entrance, Oregon

(c) Fernandina Harbor, Florida

The observed changes in channel thalweg orientation resulted from one or both of two primary factors: (a) wave-induced longshore sediment transport and (b) the inlet current regime. Migration of the channel thalwegs at Umpqua

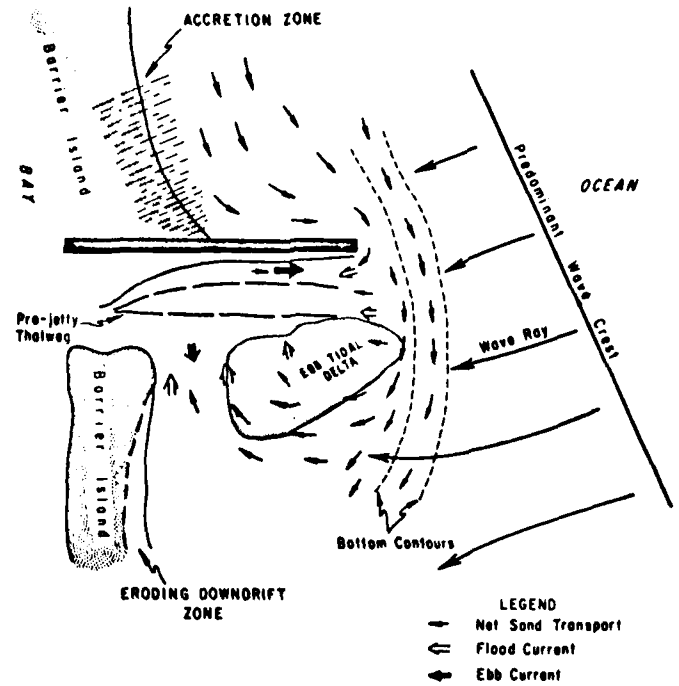

Figure 31. Idealized model of channel migration and shoreline response subsequent to construction of a single updrift jetty.

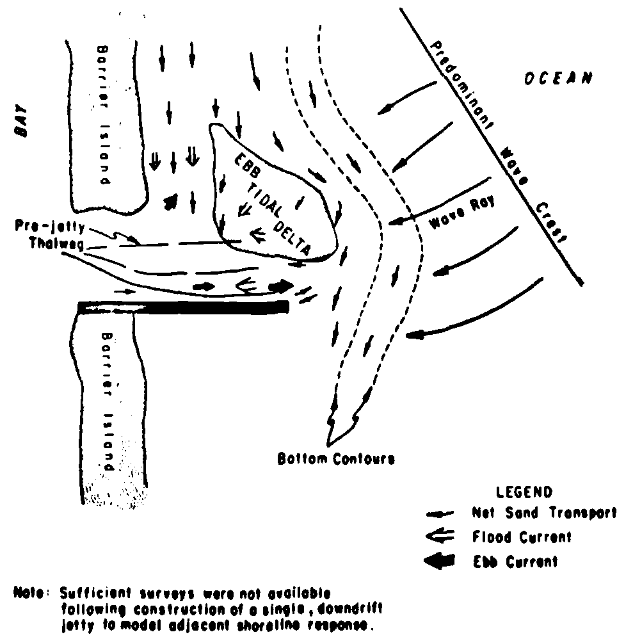

Figure 32. Idealized model of channel migration and shoreline response subsequent to construction of a single downdrift jetty.

River, Masonboro Inlet, Grays Harbor, for a period of time and Humboldt Bay was in opposition to the tidal current regime of each inlet. Therefore, channel migration results primarily from longshore sediment transport entering the entrance from the natural side of the channel, when waves are approaching from deep water on that side, and also when wave refraction around the ebb tidal delta produces localized transport toward the inlet. This is evident from the growth of large shoals on the natural side of the channel at the entrances to Tillamook Bay, Masonboro Inlet, Newport Bay, and Fernandina Harbor. The current regime contributes to channel migration by scouring the jetty side of the channel to maintain an equilibrium cross-sectional area which results in migration of the thalweg. The current regime alone may be sufficient to cause channel reorientation as shown by the improvements at the Merrimack River. The river discharge at this entrance sometimes exceeds the tidal prism, and it is not known whether tidal currents alone caused channel reorientation.

The permeability and the elevation of the single jetty protecting the entrance influence channel migration by establishing the effectiveness of the jetty as a littoral barrier. The channel will not migrate toward a single jetty if there is significant sand movement through the jetty, as indicated by one stage of the channel response at Grays Harbor. It is also noted that the channel will migrate away from a deteriorated jetty at a twin-jettied entrance, as indicated by the response at Humboldt Bay and Fernandina Harbor. If both jetties are relatively impermeable and the crown elevations are high enough to prevent sand transport over the jetty, the channel position should remain stable.

The updrift and downdrift longshore transport rates at each of the inlets discussed were sufficient to produce channel migration. A case of a single jetty being constructed at an inlet where the longshore transport was nearly unidirectional (net-to-gross transport ratio is close to one) was not available. If the net-to-gross longshore transport ratio was close to one, the small amount of transport from one direction including the effects of wave refraction, may not be sufficient to drive a channel against the jetty.

Accretion of the updrift shoreline and erosion of the downdrift shoreline at rates assumed proportional to the longshore transport usually followed construction of a single updrift jetty (see Fig. 31). Accretion rates ranged up to 800 feet per year with maximum rates occurring near the jetty and decreasing with greater distance from the jetty. The quantity of material trapped by a jetty depends on the jetty length, angle with the shoreline, crown elevation, and permeability, and length of jetty construction time.

A decrease in channel cross-sectional area ranging up to 40 percent usually followed construction of a single updrift jetty. Channel area response after construction of a single downdrift jetty could not be determined due to insufficient data. This instability resulted because the areas at jetty construction times were too large to be maintained by the tidal prism or each inlet. Dredging in the inlet entrance channels precluded an analysis of the natural channel response when a second jetty was added.

Based on a limited amount of data, the ebb tidal delta advanced seaward as the single jetties were extended seaward. The ebb tidal delta re-forms farther seaward as the jetty is extended seaward. The seaward migration is assumed in proportion to the length of the jetty moving seaward at some rate proportional to the rate at which the jetty was extended seaward.

It has been documented that single jetty construction has not prevented shoaling in the entrance channel or stabilized the thalweg position except immediately adjacent to the jetty. The construction of single jetties does not appear to be a practical engineering solution to improving an inlet ocean entrance. In fact, as indicated by several of the case histories, even when two jetties are constructed at the entrance, the jetties should be extended seaward at the same time if the channel is to naturally remain midway between them.

It is concluded that construction of a single jetty, whether on the updrift or downdrift side of the channel, will not deepen the inlet entrance. If the jetty is not built immediately adjacent to the channel, the channel will migrate to a position adjacent to the jetty due mainly to sand transported into the inlet from the natural side of the channel by waves and flood tidal currents.

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