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March 1993

US Army Corps of Engineers
Waterways Experiment Station

Coastal Engineering Research Program

Scour Hole Problems Experienced by the Corps of Engineers; Data Presentation and Summary

by W. Jeff Lillycrop, Steven A. Hughes
Coastal Engineering Research Center

Prepared for Headquarters, U.S. Army Corps of Engineers

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U.S. Army Corps of Engineers
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3909 Halls Ferry Road
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Final report

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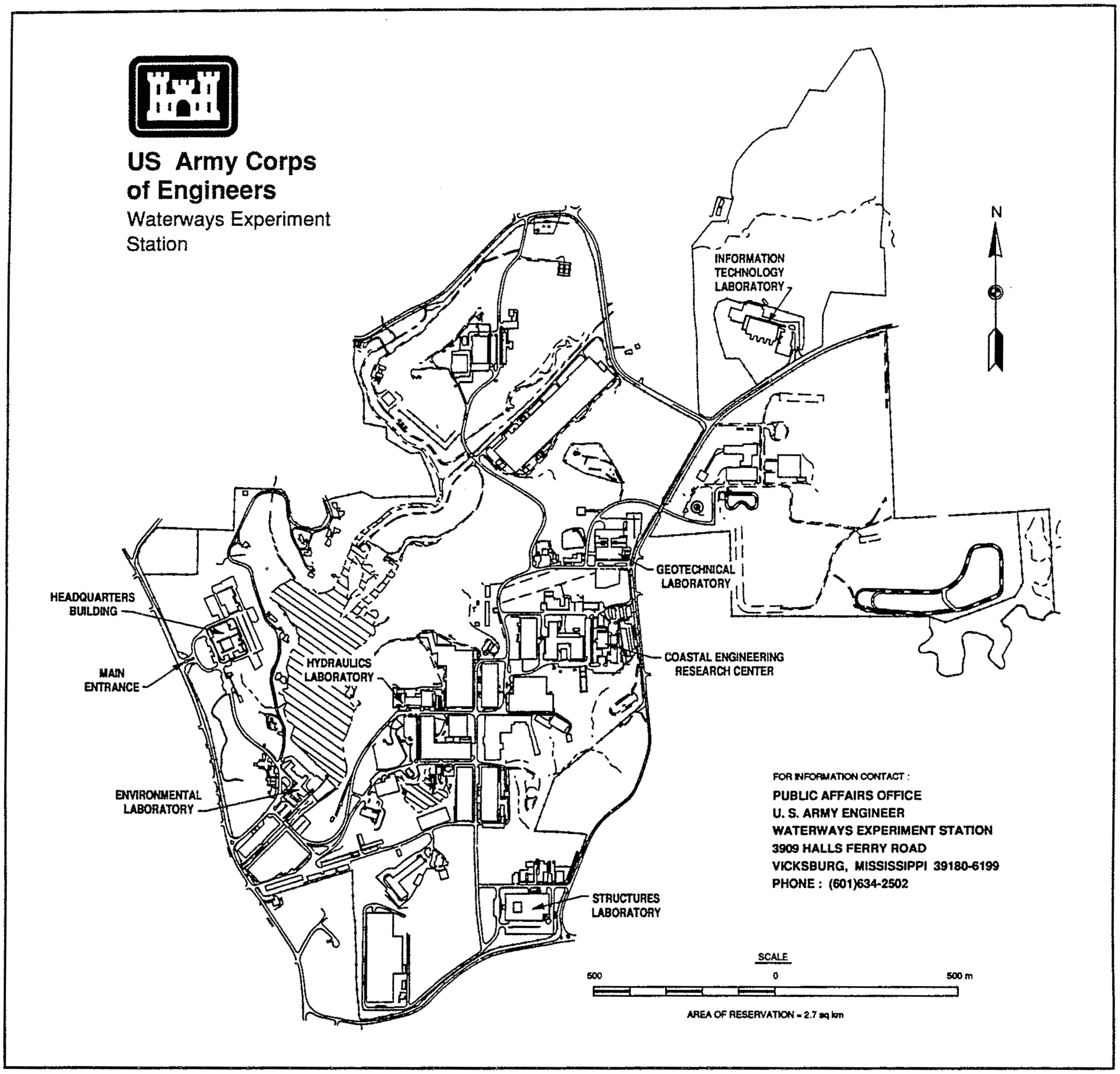

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Preface

This report summarizes a workshop held in Vicksburg, Mississippi, on 21-22 May 1991, to examine scour hole problems experienced by the Corps of Engineers in wave/current flow environments in the vicinity of coastal structures. The workshop was funded through the US Army Engineer Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC), Coastal Research Program Work Unit 32684, "Scour Holes at the Ends of Structures." HQUSAE Technical Monitors for the Coastal Engineering Programs are John H. Lockhart, Jr., John G. Housley, Barry W. Holliday, and David Roellig.

The report was written by Mr. Jeff Lillycrop, Engineering Applications Unit (EAU), Coastal Structures and Evaluation Branch (CSEB), Engineering Development Division (EDD), CERC, and Dr. Steven A. Hughes, Wave Dynamics Division (WDD), CERC. Dr. Yen-Hsi Chu was Chief, EAU; Ms. Joan Pope was Chief, CSEB; Mr. Thomas W. Richardson was Chief, EDD; and Mr. C. E. Chatham. Jr., was Chief, WDD. Dr. James R. Houston was Director, CERC, and Mr. Charles C. Calhoun, Jr., was Assistant Director, CERC, during report preparation. Ms. Carolyn Holmes was Program Manager of the Coastal Engineering Programs.

District and Division representatives participating in the workshop included Mr. Bill Dennis from the Wilmington District, Mr. Francis Escoffier, formerly with the Mobile District, Mr. Jeff Gebert from the Philadelphia District, Mr. Ross Kittleman from the Detroit District, Mr. Mike Mohr from the Buffalo District, Mr. Gil Nersesian from the New York District, Mr. John Oliver from the North Pacific Division, and Mr. Pete Robinson from the Mobile District.

Coastal Engineering Research Center representatives participating in the workshop include Ms. Julie Rosati, Mr. David Mark, and Dr. Edward Thompson, Research Division, CERC; Messrs. Mike Briggs, William Seabergh, and Earnest Smith, and Drs. Jimmy Fowler and Steven Hughes, WDD, CERC; and Mssrs. Jeff Lillycrop and William Preslan and Drs. Yen-Hsi Chu and Joon Rhee, EDD, CERC.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander of WES was COL Leonard G. Hassell, EN.

Conversion Factors, Non-SI to SI Units of Measurement

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

Multiply	By	To Obtain
acres	4,046.873	square metres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
degrees (angle)	0.01745329	radians
feet	0.3048	metres
miles (U.S. nautical)	1.852	kilometres
miles (U.S. statute)	1.609347	kilometres
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square metres
square miles	2.589998	square kilometres
tons (2,000 pounds, mass)	907.1947	kilograms

1 Introduction

This report expands on an earlier unpublished report entitled "Scour Hole Problems Experienced by the Corps of Engineers: Workshop Summary" (Hughes 1992). Additional data from case studies are presented and discussed, and a number of scour hole problems that were not presented at the workshop held in May 1991 have been added and discussed.

In many cases, the occurrence of scour is treated not as the cause of a structure's failure but rather as a by-product or derivative of its failure. This is evidenced by project repairs aimed at rebuilding a larger version of a failed structure without attempting to mitigate the cause of the failure, namely the scour. When a post-damage assessment is made of a failed structure, it often concentrates only on the structure's degraded dimensions, omitting scour-related measurements in the vicinity of the failure. The reason for this is perhaps that very little is known about the basic scour mechanism, and conversely, much is known about construction (and reconstruction) of rubble mound structures. In addition, scour holes can be very transient in nature, and change dimensions before surveys can be initiated.

The hydromechanics involved in scour hole development encompass many interrelated processes. Singularly, some of these processes are well understood and often quantifiable (tides, tidal currents, and waves). Other processes such as sediment transport and wave/current/structure interactions are less understood but perhaps just as important in scour hole development. Why does a scour hole form at the tip of one jetty (of a two-jetty system) and not at the other, such as at Indian River Inlet, Delaware? Why do scour holes develop on the outside of a jetty's trunk, such as at Suislaw? Why does scour occur adjacent to an inner section of jetty, along the throat, but not immediately across the inlet and adjacent to the other jetty, such as at Little River Inlet, South Carolina. Is scour a manifestation of an unstable inlet?

Objectives of the scour hole research program being conducted at the US Army Engineer Waterways Experiment Station (WES) Coastal Engineering Research Center (CERC) are to (a) gain an understanding of what hydrodynamic conditions cause scour holes to develop and what processes are occurring during such development; (b) develop a procedure for predicting the general configuration and major dimensions of scour holes formed under specified hydrodynamic conditions, and (c) develop and refine laboratory procedures for modeling scour hole development and impacts on structural stability.

The approach, a three-stage effort (Informative Stage, Discovery Stage, and Engineering Stage), builds on knowledge gained in each previous stage. The Informative Stage consists of initial problem scoping and assessment, and this report presents field data from Corps projects that have experienced scour. Examination of these problems will help focus research aimed at understanding and quantifying the physical processes involved in scour.

The same case studies presented by Hughes in 1991 are re-presented in this report, often with additional information on the scour hole or processes related to scour, along with additional case studies that were not discussed at the May 1991 workshop yet support this effort to understand and quantify the development of scour holes at the ends of structures.

2 Case Studies

Scour hole problems experienced at Corps of Engineers projects are described in the following case studies. Some of the projects and problems have a long history, whereas other projects are just beginning to experience signs of scour. Fifteen projects were presented by Corps of Engineers District personnel at the scour hole workshop held in May 1991 (Hughes 1991). An additional six case studies have been added, thus providing a reasonably comprehensive summary of typical scour problems within the Corps of Engineers.

Moriches Inlet

Moriches Inlet, New York, is one of three improved inlets on Long Island that experience scour-hole-related problems. Figure 1 is a location map showing the inlet. Moriches Inlet was stabilized by the State of New York in the mid-1950's by the construction of two rubble-mound jetties that provide a 750-ft-wide channel.[1] The inlet connects the Atlantic Ocean with the small Moriches Bay, which in turn has small connections to the larger Great South Bay to the west and Shinnecock Bay to the east. Generally, depths within Moriches Bay are less than 6 ft, except in the navigation channels.

The inlet has a dominant ebb tidal current that passes to the ocean primarily in two natural channels. The east channel carries the most discharge, and it tends to run parallel to the back shoreline of the barrier island. The strong flows in the east channel have eroded the backshore several hundred feet over the years. In 1980, the barrier island east of the east jetty was breached by a storm, necessitating a $10-million repair.

During summer, the offshore bar shoals cause navigation problems as vessels traverse the bar. This problem is being addressed by dredging a 100,000-cu-ft deposition basin abreast of the navigation channel to take the material that normally would be deposited on the bar.

Bathymetry from 1968 shows no scour holes at Moriches Inlet (Chu and Nersesian 1992). However, data from 1974 (Figure 2) show the

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page viii.

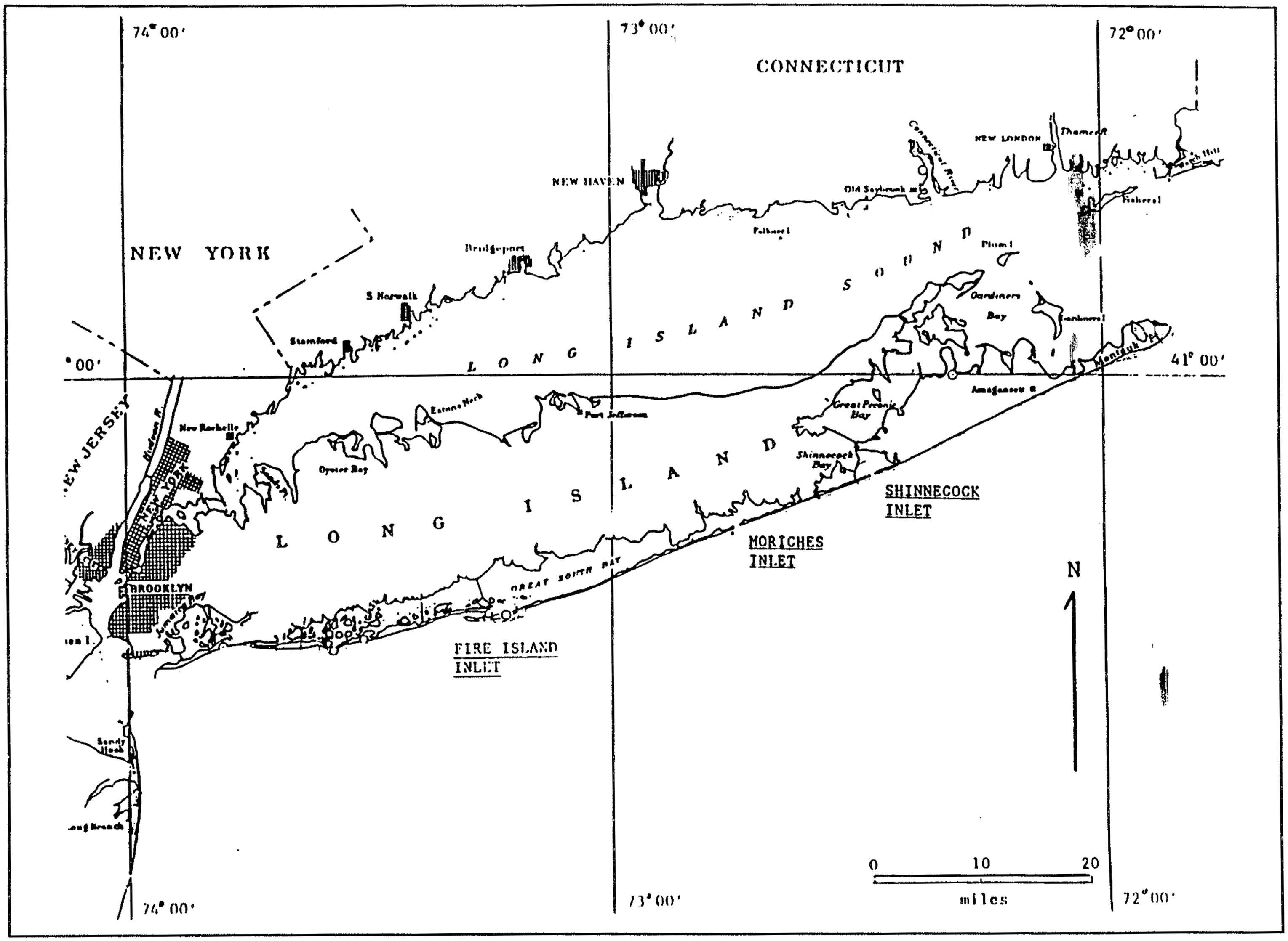

Figure 1. Long Island, New York site location map

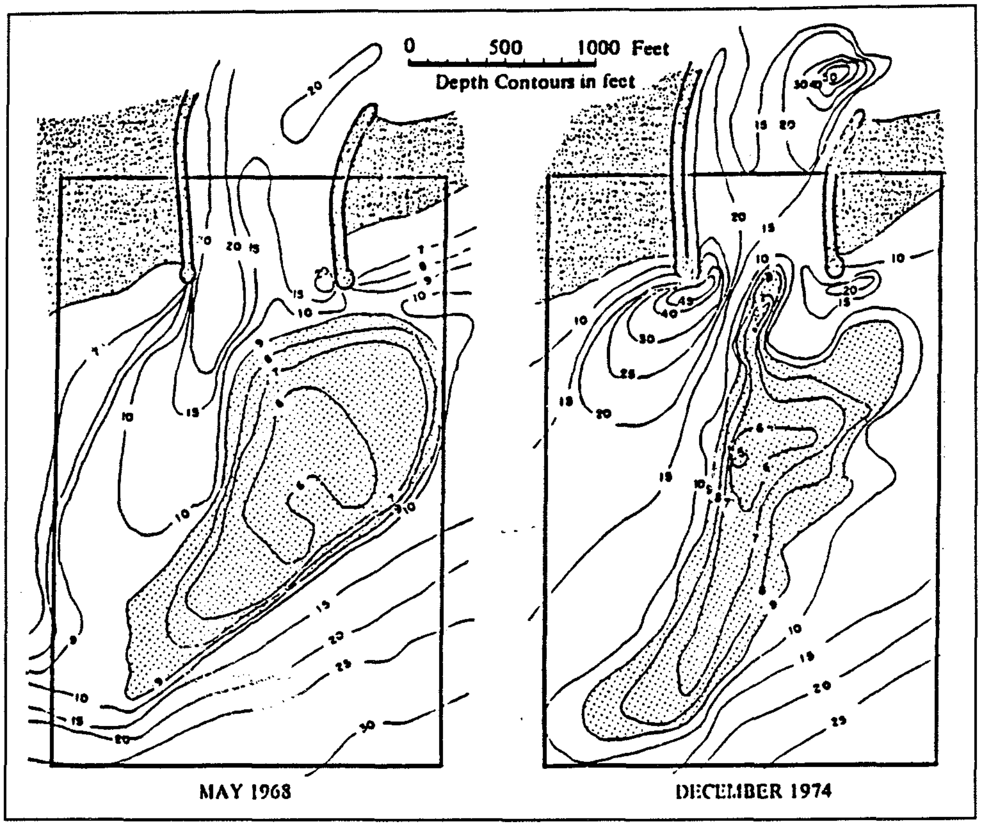

Figure 2. 1968 and 1974 bathymetry of Moriches Inlet

existence of three scour holes, one located in the back bay, and two at the jetty tips. The hole located at the east jetty is transient, appearing and disappearing as illustrated in Figure 3. Chu and Nersesian (1992) speculate this transient trend may be caused by variations in longshore transport. The net transport in the vicinity of the inlet is from east to west; thus, as transport increases, the scour hole fills; as transport decreases, the hole reforms.

Over the years the scour hole at the west jetty tip has changed dimensions, and Table 1 summarizes the historic dimensions of the scour hole located at the tip of the west jetty (after Chu and Nersesian (1992)).

Between 1987 and 1989, both jetties at Moriches Inlet were refurbished at a cost of approximately $4 million. It was found during the general design memorandum study phase that deterioration of the west jetty head was due in large part to undermining caused by the presence of the deep scour hole located just seaward of the jetty head. The scour hole is thought to be caused by swift ebb currents flowing out the east branch channel, moving diagonally across the entrance channel, and passing seaward of the west jetty tip. The intersection of the ebb jet with incoming waves creates an eddy which is thought to contribute to the scour problem.

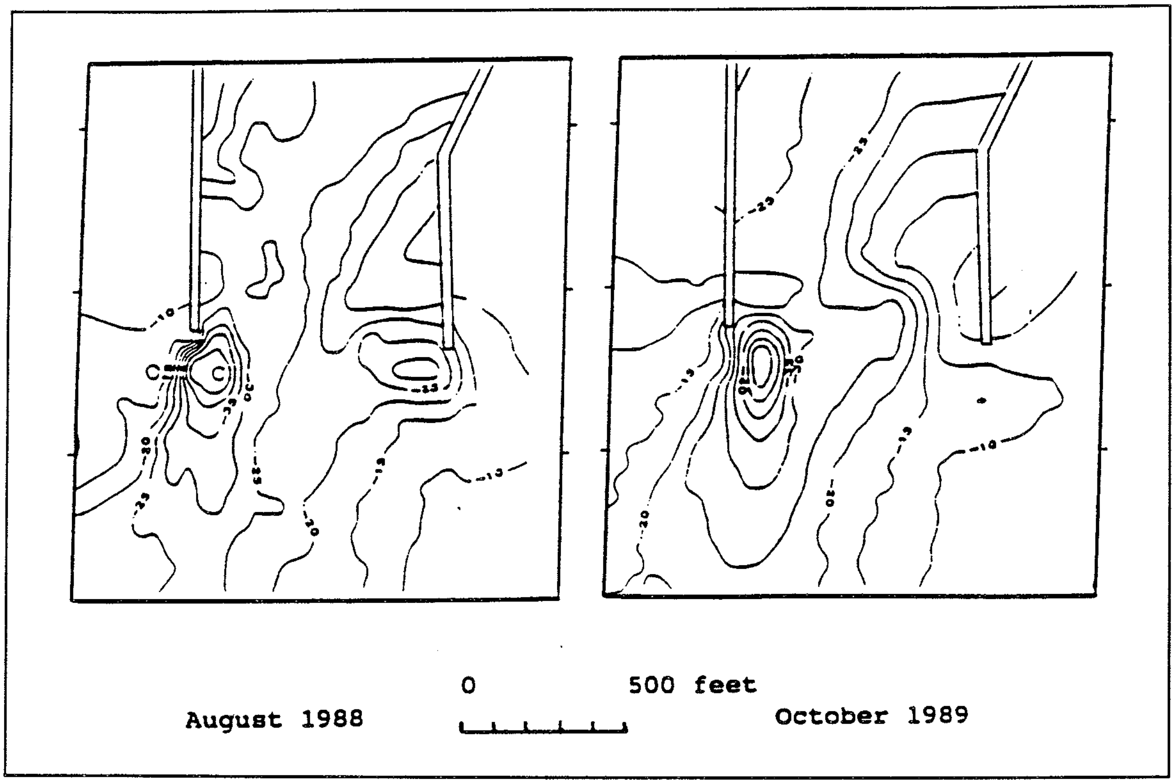

Figure 3. 1988 and 1989 bathymetry of Moriches Inlet

Table 1
Historic Dimensions
West Jetty, Moriches Inlet

Date	Area[1]	Diameter[2]	Depth[3]
Jul 74	--	--	35.4
Dec 74	--	--	50.0
Mar 78	--	--	53.5
Oct 86	7.6	98	44.9
Mar 88	12.5	126	46.5
Aug 88	22.5	169	51.5
Oct 89	25.0	178	53.7
Aug 91	28.5	187	51.0
Jul 92	--	--	45.0

[1] Area is in 10^3 sq ft encompassed by -40 National Geodetic Vertical Datum (NGVD).
[2] Equivalent diameter in feet for a circular contour area.
[3] Scour hole depth in feet; datum NGVD.

Project surveys in 1988 indicated that the scour hole was deepening and enlarging at a fast rate which would necessitate greater quantities of construction materials. Corrective action called for filling the scour hole to the 35-ft depth using sand from the offshore bar and capping the area with a stone scour blanket. The required sand quantity was estimated to be 12,000 cu yd. The scour blanket dimensions are estimated to be 300 ft by 400 ft, and its design is based on the *Shore Protection Manual* (SPM 1984), which calls for a bedding layer approximately 1 ft thick and a 5-ft-thick layer of armor stone.

Due to financial constraints, the filling and capping of the scour hole and the construction of the jetty head were postponed. Future plans call for a $2.5-million project to perform the corrective actions and complete the west jetty head as per original design.

Presently Moriches Inlet is being monitored by CERC to determine if the scour hole is continuing to grow, jeopardizing the west jetty toe protection. The study includes evaluation of the scour hole's evolution, an inlet monitoring program, and a regional geologic investigation. Scour hole evolution assesses historic bathymetry with wave and current data to determine rate of growth. The monitoring program includes measurement of currents and inspection of the jetty using side-scan sonar to determine present conditions. The geologic investigation evaluated the regional stratigraphy, which was determined to be a primary element in scour problems being experienced at Indian River Inlet, Delaware (see discussion of Indian River Inlet).

The scour hole problem at Moriches Inlet is very similar to the scour that is occurring at Shinnecock Inlet (see next section). The primary scour mechanism is thought to be the strong ebb flow currents that exit the bay from the east channel and move diagonally across the mouth of the entrance until they pass just in front of the west jetty. At this point there is a possibility of the jetty initiating a rotational flow similar to vortex shedding which, in turn, causes the scour problem. Another scenario is that incident wave energy is interacting with the strong ebb current as the flow moves beyond the sheltering influence of the east jetty. This interaction may result in turbulence strong enough to mobilize the sediment, which is then swept away by the currents.

It appears that armoring of the backside of the barrier island just east of the inlet promoted a strengthening of the ebb current flowing out of the east channel. This hypothesis is supported by the subsequent appearance of the scour hole shortly after completion of the repair.

The field studies conducted at both Moriches and Shinnecock inlets strongly support the hypothesis that jetty tip scour holes are caused by turbulent eddies created during the flood tide. As flood tidal flow enters the inlet, flow separation occurs at the jetty tips creating turbulent eddies capable of transporting bottom sediments. This hypothesis supports scour hole formation at both jetty tips at both locations because the eddy formation is localized within the immediate vicinity at the scour hole locations.

Shinnecock Inlet, New York

Shinnecock Inlet, New York is located 10 miles east of Moriches Inlet (Figure 1), and can almost be considered a twin of Moriches Inlet. The present inlet was formed by a hurricane in 1938, and a series of engineering projects resulted in the inlet being stabilized. Stone jetties were constructed on both sides of the inlet between 1952 and 1954, separated by a distance of about 815 ft.

Shinnecock Inlet connects the Atlantic Ocean with Shinnecock Bay, which is about 9 miles long and varies in width between 0.4 and 2.8 miles. Average depths in the bay are less than 6 ft, except in the Intracoastal Waterway, where depths can be as great as 20 ft. Shinnecock Bay has a small connection to Moriches Bay on the west, and the hydrodynamic characteristics of the two inlets are probably linked.

The inlet has a dominant ebb tidal current that passes to the ocean primarily through a channel that parallels the back shore of the barrier island east of the inlet, similar to what occurs at Moriches Inlet. Rapid flows in this channel have severely degraded a revetment located on the backshore, allowing erosion to occur. A contract to repair the revetment and backfill the eroded area was to be awarded in July 1992. The ebb tidal flow appears to traverse the inlet diagonally east to west.

The navigation channel project depth is normally at elevation -10 ft mean low water (mlw), and a deposition basin straddling the channel is dredged to -20 ft mlw to help keep the offshore bar reduced so that navigation is less hazardous. When the bar is allowed to shoal, boats enter the inlet over the scour hole, which places them broadside to the waves. Three lives were lost over the bar in 1985. Material dredged from the offshore bar and deposition basin is pumped about 1.5 miles and placed along the western beach in the intertidal zone (2 - 3 ft above mlw) by the hydraulic pipeline dredge. The unit cost was $3.20 per cubic yard.

A 70-ft-deep scour hole has developed at Shinnecock Inlet adjacent to the west jetty as shown in Figure 4. This scour hole is similar to the one at Moriches Inlet; however, the problem is more severe at Shinnecock because the west jetty has been undermined and 60 - 70 ft of the jetty head has disappeared. There is also concern that the scour hole might enlarge to the point that additional toe protection material may be lost and more of the structure will be damaged.

The location and shape of the scour hole suggests that it was formed in a similar manner as hypothesized for Moriches Inlet. Strong ebb flows from the east channel are entering the inlet diagonally and flowing across the channel until they interact with either the jetty structure or the unsheltered incident wave field. In either case, it appears that large-scale rotational flows may be generated that mobilize sediment which is swept away by the current. This hypothesis is supported by the observed "scallop" shape of the hole, which is

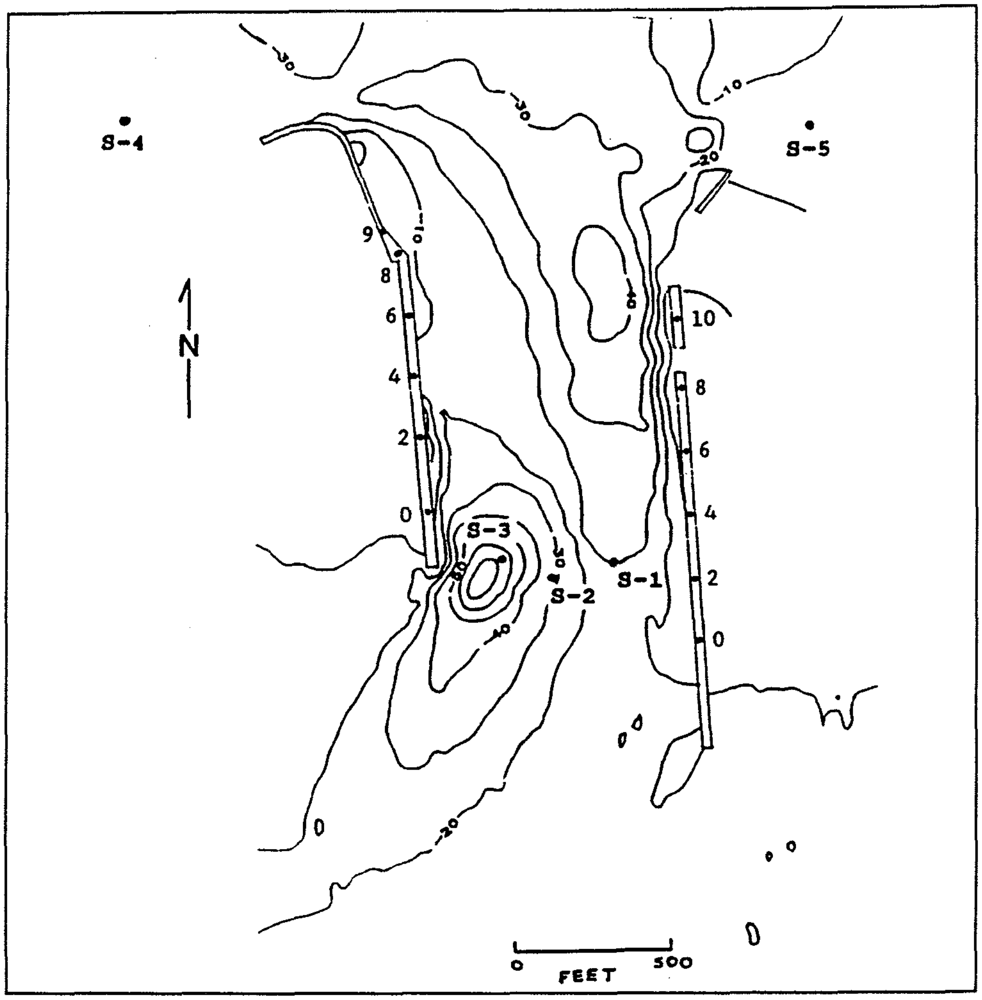

Figure 4. Shinnecock Inlet scour hole

typical of scour caused by strong currents. There was also a diver report stating that currents created a whirlpool effect in the vicinity of the scour hole.

The tidal range varies between 3.5 and 4.0 ft, and the maximum ebb current was estimated to be about 7 ft/sec. The bottom material consists of littoral sand, but it was speculated that possibly the sand overlays clays and marine deposits that could be more easily eroded. Monitoring data should clarify this issue.

The east jetty structure is also in need of rehabilitation. About 190 ft of the east jetty has been lost, and it is thought that this damage stemmed from a temporary scour hole that had formed at the tip of the structure. This hole was about elevation -17 ft mlw, and it was probably a direct result of storm wave activity. The actual failure of the structure might be related to a combination of toe instability due to the scour hole and heavy wave action on the jetty itself that caused armor units to slump into the scour hole.

Present inlet rehabilitation plans call for expenditure of $3.8 million to infill the 70-ft-deep scour hole to elevation -35 ft mlw using small rubble stone.

The hole is then to be capped with a stone blanket similar to that planned for Moriches Inlet. The scour blanket dimensions are estimated to be 300 ft by 400 ft, and its design is based on the *Shore Protection Manual* (SPM 1984), which calls for a bedding layer approximately 1 ft thick and a 5-ft-thick layer of armor stone. It is hoped that this corrective action will solve the scour problem, but there remains the possibility that the scour hole will reform to one side or the other of the scour blanket. Included in the inlet rehabilitation plan is rebuilding of the east jetty and bay-side revetment, and repair of the west jetty. The revetment is to be extended approximately 100 ft north; it has not been determined what effect this may have on the bay-side scour hole.

Previous structure repairs are estimated to have cost $4 million, and estimates for needed structure repairs at Shinnecock Inlet have increased from $6 million to $14 million.

At this writing, CERC was participating in a monitoring effort at Shinnecock Inlet to obtain current measurements, to determine if the scour hole is continuing to grow, and to determine if there is any more deterioration of the jetty structure. The monitoring does not include nearshore wave measurements. Table 2 summarizes the scour hole's historic dimensions.

Table 2
Historic Dimensions
West Jetty, Shinnecock Inlet

Date	Area[1]	Diameter[2]	Depth[3]
Jun 84	--	--	70.5
Nov 84	--	--	66.3
Mar 85	--	--	57.2
Jul 86	19.4	157	56.7
Jun 87	33.1	205	75.5
Nov 89	47.5	246	76.5
Aug 90	45.0	239	71.2
Sep 90[4]	--	--	35.0
Dec 90	11.3	120	55.0
Aug 91	50.0	252	65.4
Jul 92	--	--	72.5

[1] Area is in 10^3 sq ft encompassed by -40 National Geodetic Vertical Datum (NGVD).
[2] Equivalent diameter in feet for a circular contour area.
[3] Scour hole depth in feet; datum NGVD.
[4] Scour hole filled.

Between August and December, 1990, the scour hole was filled to about elevation -35 ft mlw using material dredged from the deposition basin. Within 1-1/2 months, the hole had deepened about 15 - 20 ft, indicating the need for placement of a scour blanket after filling the hole with dredged material.

The New York District stated that littoral drift estimates at Shinnecock Inlet were in the range of 480,000 cu yd over an 18-month period with the net drift being east to west. In the past 5 years the frequency and intensity of northeasters has been low. This might have contributed to less littoral material being available in the system to infill the scour hole.

Fire Island Inlet, New York

Fire Island Inlet, New York is located on Long Island to the west of Moriches Inlet as indicated in Figure 1. The inlet exhibits classic features of an overlapping inlet formed by littoral transport in a dominant direction. In 1941 a jetty was constructed to stabilize the westward migration of the inlet. The fillet to the east side of the jetty was soon filled to capacity. It is estimated that approximately 600,000 cu yd is transported around the jetty with some portion of the bypassed sediment being deposited in the entrance channel. When the navigation channel is dredged, material is placed as a feeder beach for Gilgo Beach on the western side of the inlet.

After stabilization of the jetty, erosion began to occur on the bay side of the overlapping spit. About 350 ft of shoreline was lost from the bay side, making the spit quite narrow at the shoreward end of the jetty. In the 1980's, portions of the jetty were flanked during storm conditions. There was also discussion during the May 1991 workshop at WES about a scour channel on the west side of the inlet channel.

Scouring still continues along the bay side of the overlapping portion of the inlet, and possibly the New York District will begin dredging material from the finger shoals area again. This location is the best for navigation safety. It was noted that inner bank erosion and structure flanking are somewhat common occurrences. Mean sediment grain size at Fire Island Inlet was stated to be 0.3 - 0.35 mm.

Indian River Inlet, Delaware

Prior to the 1920's, Indian River Inlet, Delaware was a natural inlet connecting Indian River and Rehoboth Bay to the Atlantic Ocean (Figure 5). Surveys indicated the natural inlet migrated over a 2-mile-long zone centered on its present location. As a natural channel, the inlet was dominated by wave processes and littoral transport, and the shallow, unstable channel periodically closed. Attempts at channel dredging by local interests in the 1920's failed to keep the channel open.

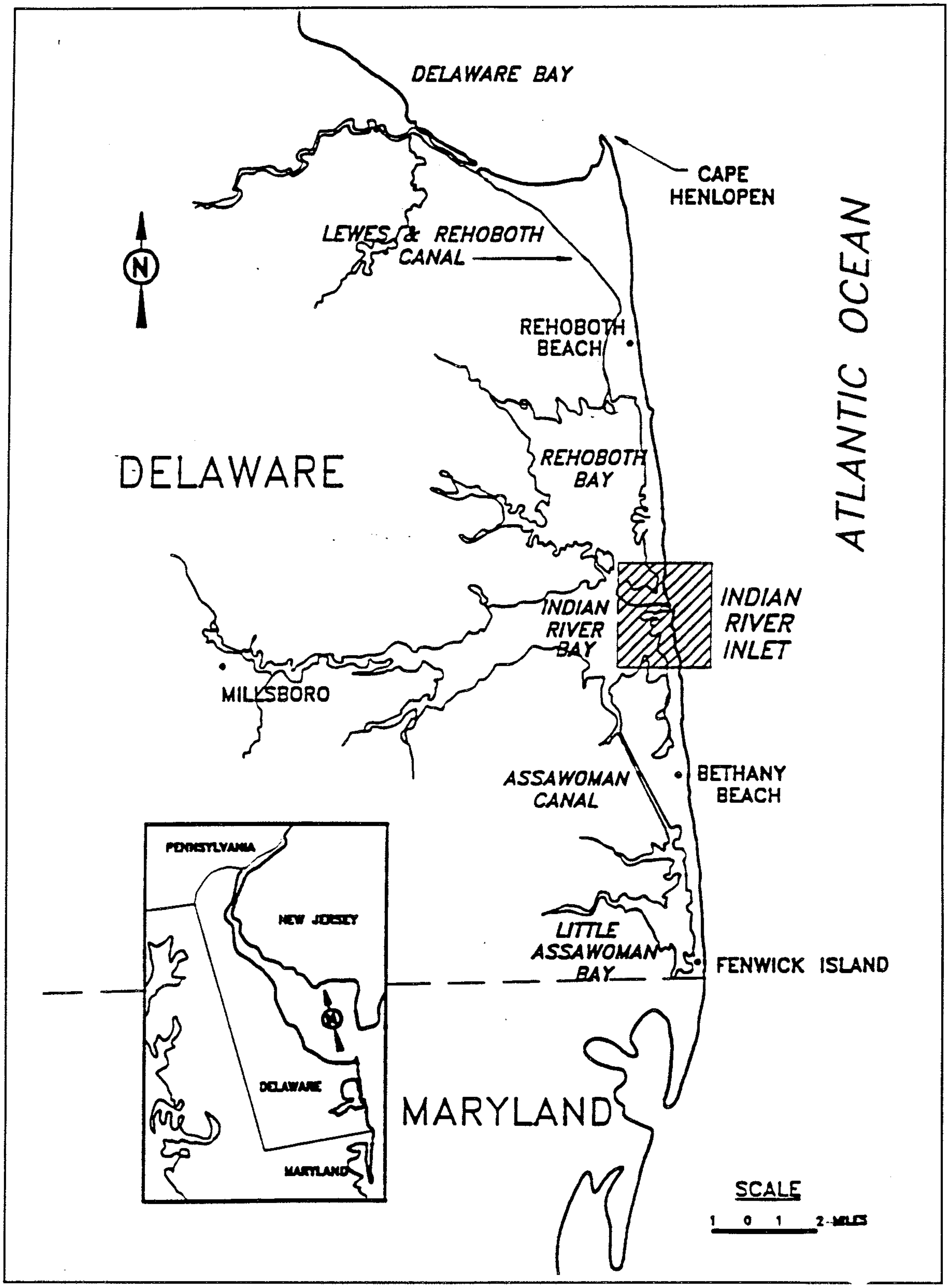

Figure 5. Indian River Inlet, Delaware, site location map

The Federal construction project began in February 1938. Dredging of the 200- by 14-ft channel was completed in October 1938. Parallel rubble-mound jetties, 1,500 ft in length, were constructed in 1938 and 1939. Their crest elevation was +6.0 ft mlw with a crown width of 10.0 ft and side slopes of 1V:2H (at the seaward end). The jetty cross section along the seaward end is a typical rubble-mound design consisting of bedding stone for a foundation, a corestone center, and large armor stones for capping. Immediately following construction of the jetties, inlet bank erosion developed requiring construction of bulkheads (1941-1943). These bulkheads were extended in 1963 due, again, to continued erosion of the inlet banks adjacent to the existing jetties/ bulkheads. Periodically, rubble material has been placed on the jetties to repair storm damage (Smith 1988).

A wooden trestle bridge across the inlet was closed in 1940 when the C. W. Cullen Bridge was opened. The new bridge had a 182-ft center swing span, was 694 ft long, and sat on approximately 80 support piles. This bridge remained in service until 1965, when a new bridge supported by two large piers was opened.

Indian River Inlet lies directly over a historic Delaware River riverbed that filled during the Holocene period with loose clays and silts. This silty-clay mix, which is highly erosive, is covered with a veneer approximately 30-40 ft thick consisting of modern sands (Anders, Lillicrop, and Gebert 1990).

Construction of the jetty system also interrupted the predominantly northward longshore sand transport, resulting in erosion of the northern shoreline and accretion on the southern shoreline. Mitigation of the erosion was first performed in 1957 using sand dredged from the inner bay. In 1972 sand was dredged from the Indian River Inlet flood shoal and placed on the northern beach. Altogether about 2.3 million cu yd have been taken from the inlet flood shoal on five separate occasions and placed on the northern beach. The dredged material was classed as medium sand with a mean diameter of 0.2 - 0.3 mm. A sand bypass plant began pumping sand at Indian River Inlet in January 1990. The bypass plant is designed to handle about 100,000 cu yd per year, which is about the same amount of material that has been accumulating on the ebb shoals.

The hydraulics of Indian River Bay and Rehoboth Bay have changed dramatically since the inlet was created in the late 1930's. The ebb tidal prism has increased from approximately 27.5 by 10^6 cu ft in 1931 to 3.7 by 10^8 cu ft in 1948 to 1.5 by 10^9 cu ft in 1986. The tide range inside the inlet went from near zero in 1931 to 2.5 ft in 1948 to 2.7 ft in 1986. Inlet velocities increased from 2.4 ft/sec in 1948 to 6.6 ft/sec in 1986, and during field measurements made in 1988, maximum recorded velocities exceeded 8 ft/sec during spring ebb tidal flows. Ocean tides are substantially greater than tides immediately inside the inlet at the US Coast Guard station, as illustrated in Figure 6, which shows the difference in elevation between the two locations.

Since construction of the Federal project, the inlet has gradually increased in depth, from elevations approximately -14 ft mlw to -40 ft mlw. Figure 7

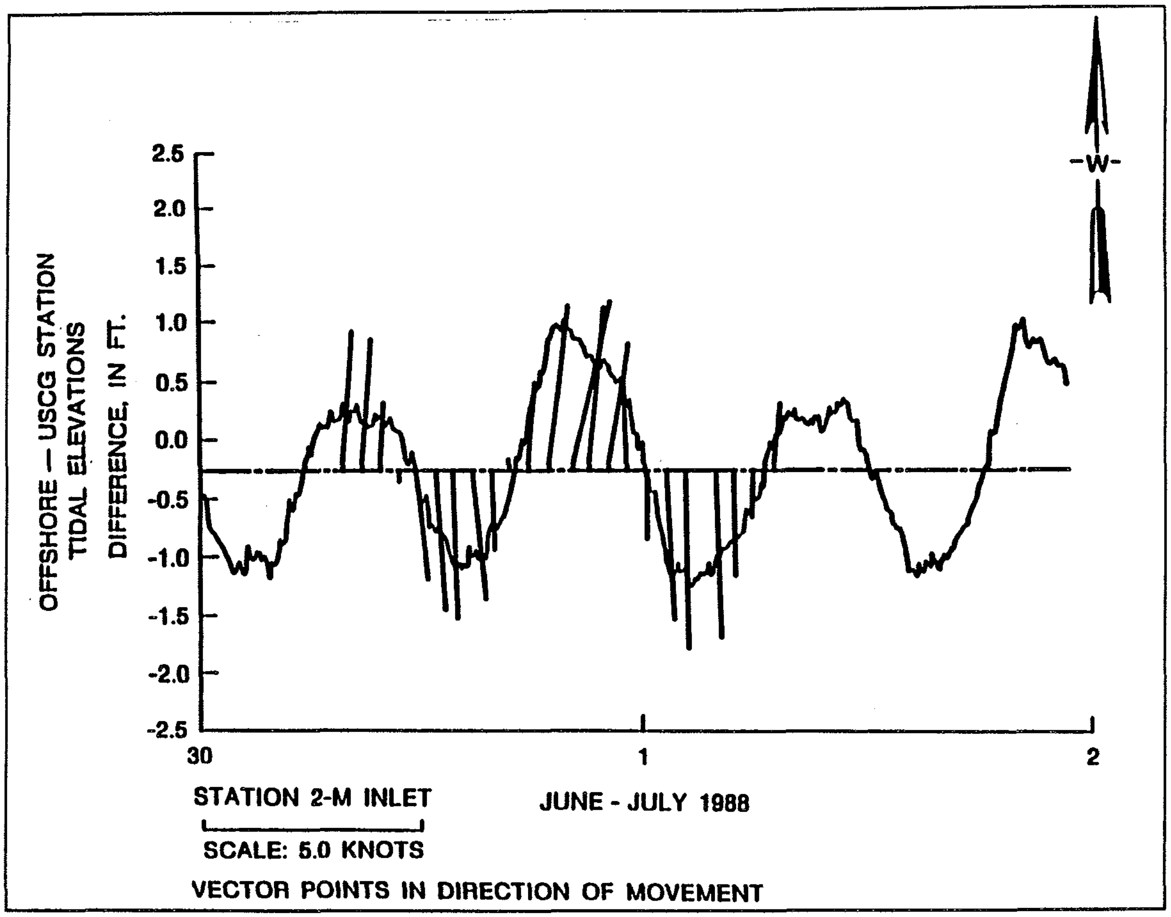

Figure 6. Residual tide signal at Indian River Inlet

shows 1988 bathymetry conditions, and Figure 8 presents inlet cross-sectional area at different dates since construction. The increase up until the mid-1970's was gradual. In the mid-1970's the inlet cross-sectional area increase accelerated. During this same period, several large, localized scour holes formed at the tip of the north jetty and immediately on either side of the bridge piers. The scour holes at the bridge piers have depths greater than elevation -90 mlw and are continuing to deepen. The scour hole at the jetty tip has caused structural failure, and approximately 300 ft of jetty has been lost. Scour at the bridge has caused remedial action to be taken by the Delaware State Department of Transportation. In 1989 the state spent $2.7 million to place rubble material adjacent to the bridge piers in order to halt undermining.

Results of a CERC study to investigate the general trend of increasing depths at Indian River Inlet and extreme scour at the inlet show that prior to the mid-1970's the inlet gradually increased in average depth and cross-sectional area. Following the mid-1970's, the inlet area continued to increase, but at a faster rate, and several large scour holes developed adjacent to the north jetty and the two bridge pilings. The study looked at possible causes including (a) removal of the old bridge in 1965, which may have reduced friction through the inlet and thus allowed greater current velocities and sediment

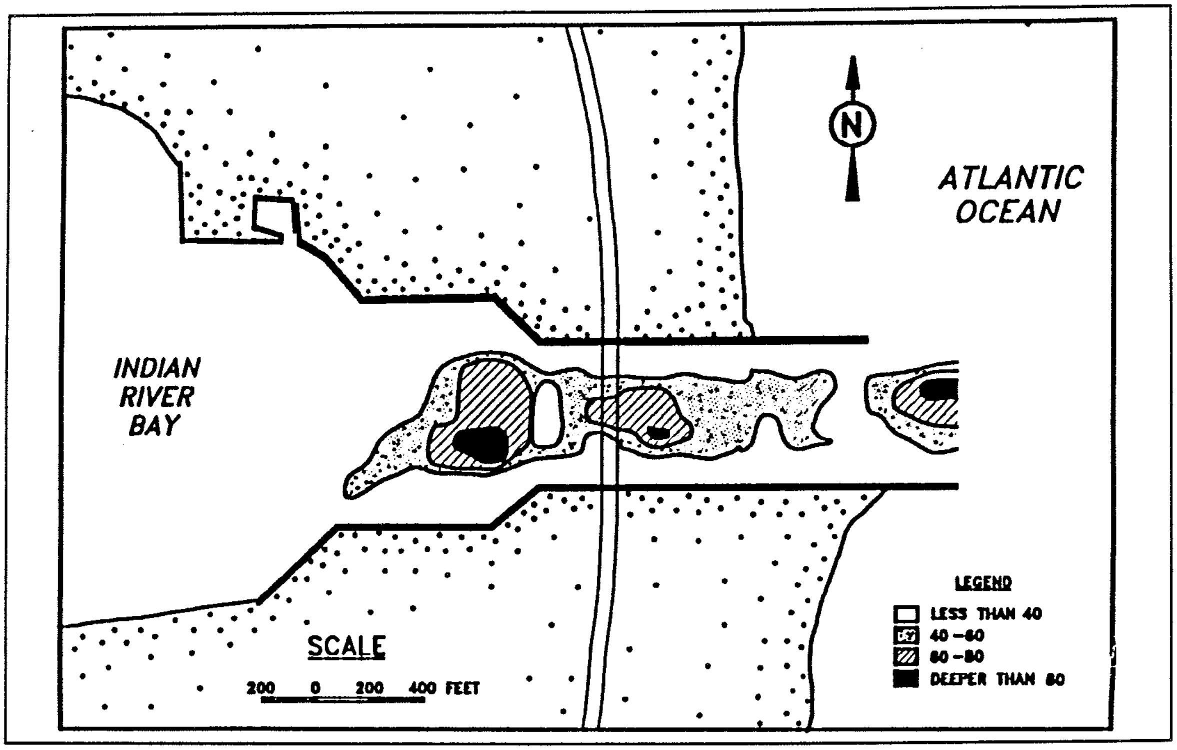

Figure 7. 1988 bathymetry, Indian River Inlet

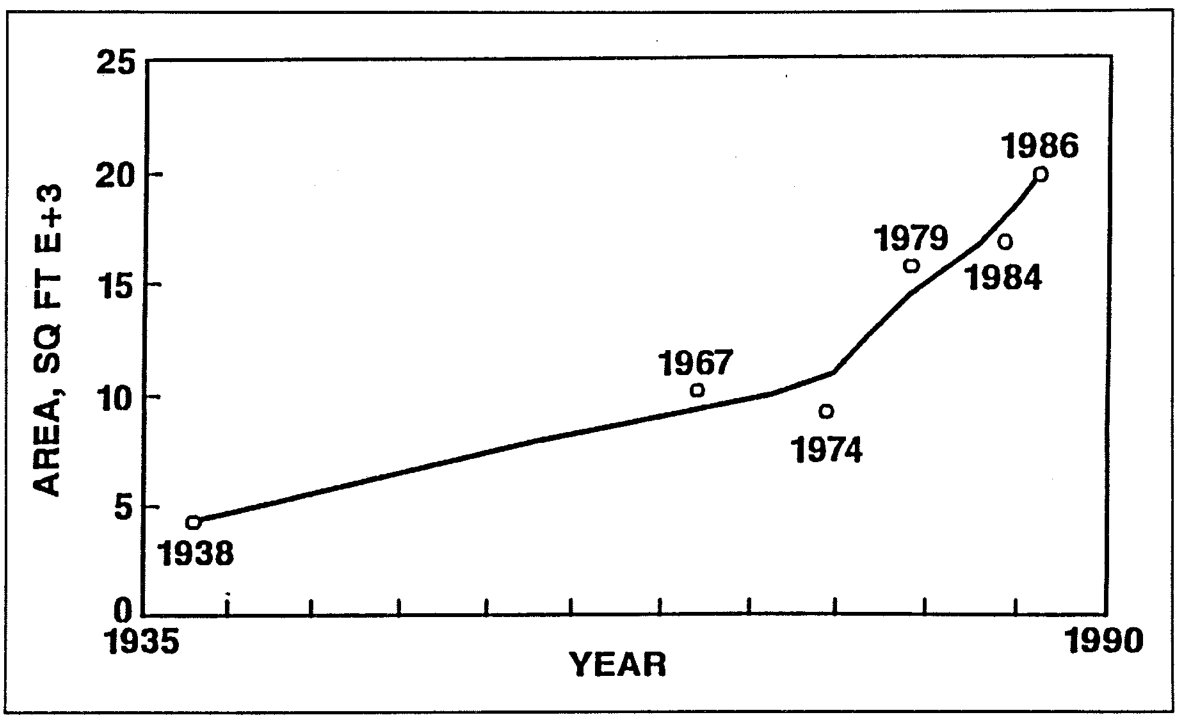

Figure 8. Inlet cross sections, Indian River Inlet

transport potential, (b) mining of the flood tidal delta, which may have reduced friction across the delta allowing increased tidal current velocities and sediment transport potential, and (c) geologic influences such as the bed material. A hydrodynamic numerical model was employed to assess different bathymetries and tidal characteristics to determine cause and effect arising from modifications to the inlet (Lillycrop et al., in preparation).

This report concludes that although the man-made alterations to the inlet may have been involved in exacerbating both the general trend of increasing depths and the localized extreme scour at the north jetty and the two bridge piles, the primary cause of cross-sectional area increase was erosion into the highly erodible silt clay layer. Figure 9 illustrates the inlet's condition over several time periods. Between 1974 and 1978, the inlet drastically increased in cross-sectional area. This sudden increase in cross-sectional area allowed increases in tidal current velocities and tidal prism.

Lillycrop et al. (in preparation) make the following conclusions:

a. The inlet cross-sectional area will continue to enlarge. Inlet stability theory shows that the inlet is not stable and, depending on which stability theory is used, the inlet cross-sectional area may increase in size from 1988 conditions by a factor of over three times. In 1988 the minimum depth was approximately 40 ft and stability theory predicts depths as great as 140 ft may be required to reach "equilibrium." An actual stable cross-sectional area cannot be determined with precision using existing inlet stability theory. Stability theory assumes depth-integrated flow and a horizontal bottom bathymetry. This is clearly not the case at Indian River Inlet as witnessed by the strong gyres at the water surface caused by a vertical velocity component and the rapidly varying bathymetry of the inlet.

b. The tidal prism will continue to increase. The hydrodynamic numerical model has shown that increasing depths from 1988 conditions in increments of 5 ft, up to 20 ft, will cause the tidal prism to continue to increase. For the prism to decrease the inlet must shoal in order to increase friction and choke off the amount of water entering the inlet. There is no evidence that this could happen. Although the hydrodynamic model did not include sediment transport, when 1988 channel depths were increased by 20 ft, maximum velocities decreased to conditions that existed in 1984. The 1984 current velocities are clearly sufficient to cause deepening of the inlet as evidenced by continued tidal prism increases since 1984.

c. Due to "*a*" and "*b*," the inlet has the potential to continue to deepen, possibly eventually eroding to the Pleistocene layer that is much more compacted than the Holocene layer. The extreme scour holes are already approaching the Pleistocene layer (located at approximately -100 ft, NGVD). Both inlet stability theory and the numerical model show it is quite probable that even then erosion will continue.

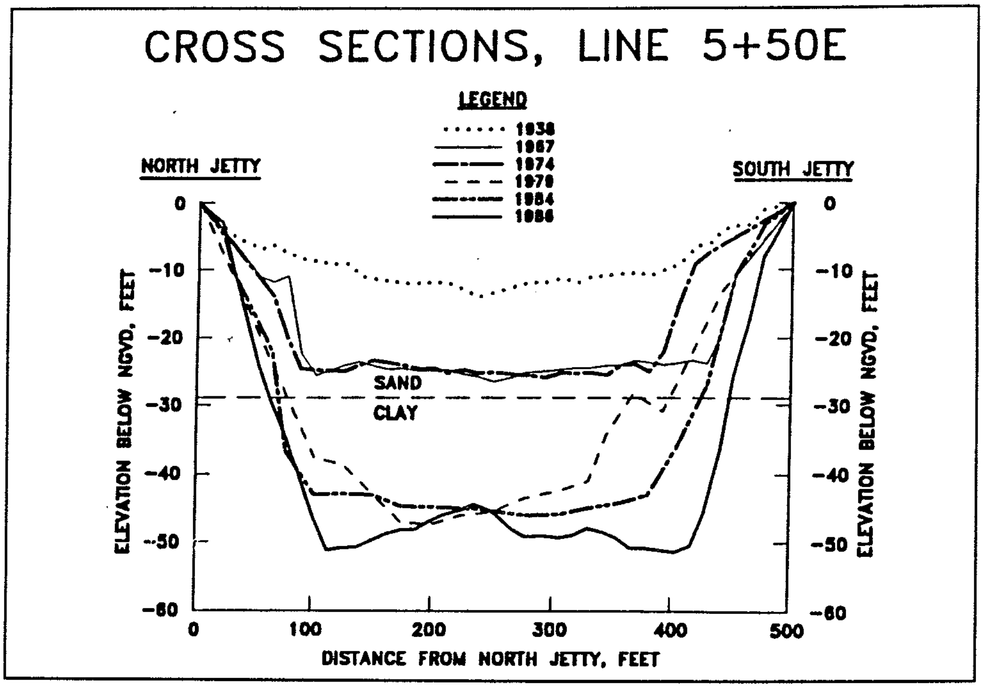

Figure 9. Inlet cross-sectional changes, Indian River Inlet

This could occur either through horizontal enlargement of the extreme scour holes, through overall deepening of the entire inlet, or through a combination of both. Eventually, both jetties could be seriously damaged or even lost as a result of scour hole enlargement and inlet deepening.

d. Any effect that man-made changes to the inlet had on overall tidal prism and inlet stability were small compared with changes caused by increasing inlet depths. The significant increases in inlet depth occurred as a result of erosion into the silt and clay layer, which was caused by the general trend of increasing depths (inlet instability). Although results of the numerical model showed small changes to the tidal prism after several flood shoal mining events, the increases were very small in comparison to the average annual increase in tidal prism. Small changes in current velocity would also be expected due to removal of the old bridge piles. However, as shown by adjusting values of Manning's "n," removal of the old bridge could not have affected inlet friction or velocities significantly.

e. There is a high probability that the extreme, localized scour at the north jetty was initiated through structure/tidal current/wave interactions. This interaction focused energy along the jetty, thus increasing sediment transport and exacerbating erosion through the thin sand veneer and into the silts/clay layer. Once the sand layer had eroded, the softer Holocene material was quickly scoured.

f. There is a high probability that extreme, localized scour did not occur at the south jetty because of the strong, asymmetrical sediment transport characteristics of the area. A net northerly transport of 110,000 cu yd is constantly replacing sand that is eroded from the vicinity of the south jetty. This is evident from the location of the primary inlet shoal.

g. Artificial sand bypassing at Indian River Inlet will reduce the supply of sand that is feeding the primary inlet shoal. This shoal is responsible for replacing eroded sands at the south jetty and maintaining the minimum inlet cross section. A reduction in transport into the inlet can cause accelerated erosion at the south jetty, and an increase in minimum cross-sectional area. This could eventually create conditions at the south jetty similar to conditions at the north jetty.

Ocean City Inlet, Maryland

Ocean City Inlet, Maryland, is located about 35 miles south of Delaware Bay. To the south of the inlet is Assateague Island and to the north is Isle of Wight (Figure 10). Rubble-mound jetties were constructed in the mid-1930's to stabilize the meandering inlet. In 1934 the north jetty was built to an elevation of +2.7 ft NGVD, and subsequently modified to varying elevations ranging between +5.7 ft and +10.7 ft NGVD. The south jetty was built in 1935 to an elevation of +4.7 ft NGVD. It paralleled the north jetty for about 750 ft from the landward end seaward, then angled toward the north jetty, constricting the inlet from 1,100 to 600 ft wide. The last 530 ft of the south jetty again paralleled the north jetty (Smith 1988).

Soon after construction, the natural inlet channel migrated toward the south jetty causing scour and undermining along an 800-ft-long section of the structure. The degraded south jetty section was not immediately repaired because the inlet/jetty system remained functionally operable. A scour hole also developed near the tip of the south jetty. Figure 11 illustrates the scour at the south jetty, based on survey data taken in November 1981.

Over time, significant erosion occurred along the north end of Assateague Island, adjacent to the jetty. The erosion twice caused near breaching of the island tip that supports the south jetty. Also, the inlet shoaling has been a continuous problem requiring the inlet to be dredged 15 times since stabilization. Total yardage removed has been approximately 6 million cu yd, and the present average annual shoaling rate is 30,000 cu yd.

Dean and Perlin (1977) conducted a study, including numerical analysis, of the shoaling and scour problem and estimated that the potential existed for the scour hole to continue to enlarge. Although the scour hole adjacent to the jetty was not considered part of the shoaling problem, if the hole should enlarge, the south jetty could suffer catastrophic failure. Failure of the south jetty could allow increased northerly sediment transport into the inlet, exacerbating the shoaling problem and creating hazardous navigation conditions.

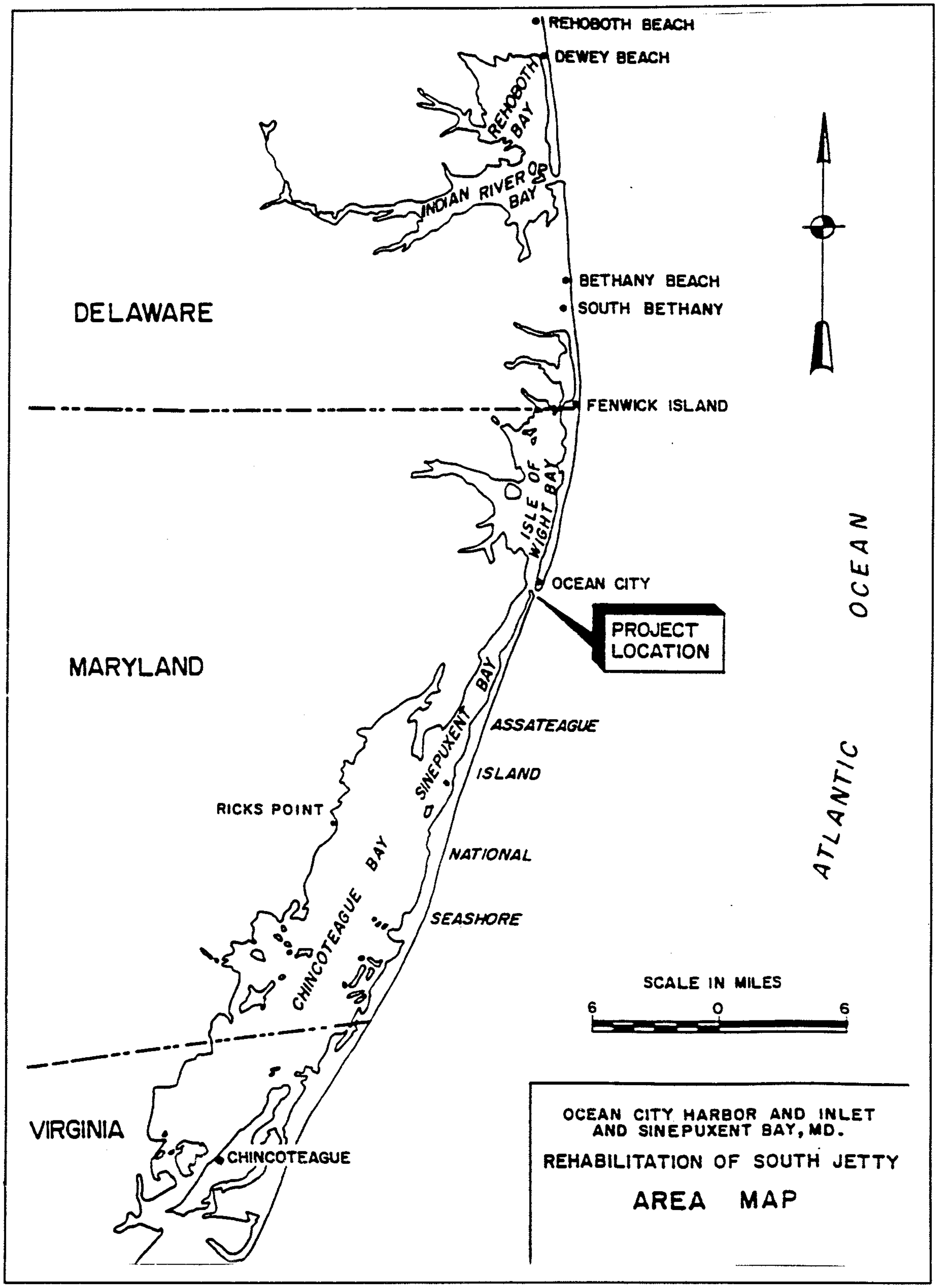

Figure 10. Ocean City, Maryland, site location map

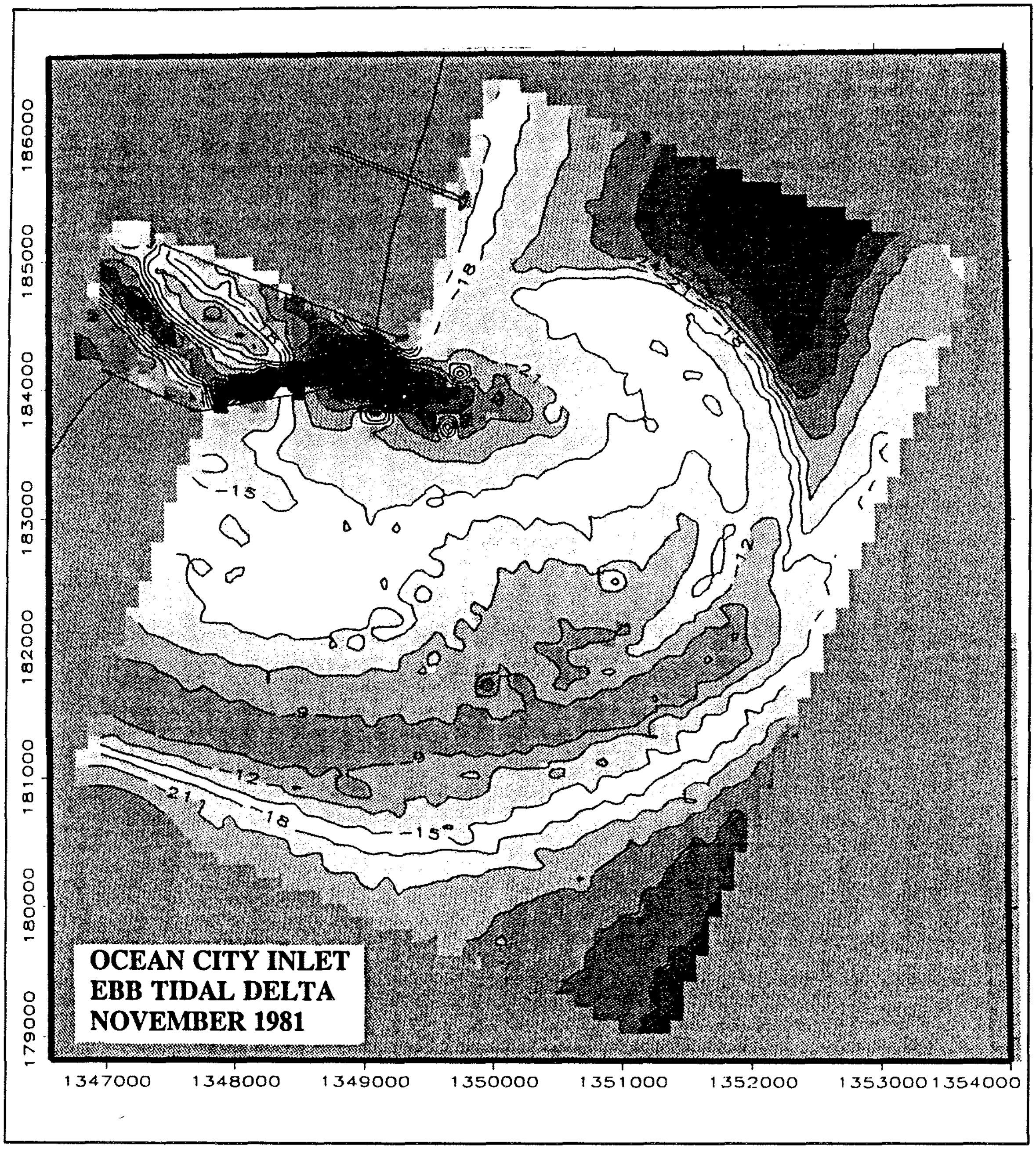

Figure 11. Scour hole at Ocean City, Maryland

In 1984 the Baltimore District filled the scour hole adjacent to the south jetty with sand hydraulically dredged from the inlet. The elevation was raised to -30 ft NGVD and capped with rubble stone weighing 50 to 200 lb. The cap was approximately 2 ft thick. In addition, an armor berm was created along this section of jetty, 2,000 ft long and 200 ft wide. Side-scan sonar was used to inspect the cap and berm in 1984 and 1990, and no subsequent erosion was found (Bass, Fulford, and Underwood, in preparation).

Oregon Inlet, North Carolina

Oregon Inlet is an unimproved inlet located on the Outer Banks of North Carolina about 50 miles north of Cape Hatteras. The inlet originally was opened by a hurricane in 1846. Oregon Inlet is between 2.0 - 2.5 miles wide, and it is spanned by the Bonner Bridge, which connects Bodie Island to the north with Pea Island to the south (Figure 12). The navigation channel has a depth of around 14 ft below mlw. Mean ocean tide range is about 4 ft, and at the Bonner Bridge the tide range is 3 ft.

The longshore sediment transport in the vicinity of Oregon Inlet has a high net drift from north to south with an estimated annual rate of 1 million cu yd. The inlet responds to the large southerly drift by migrating toward the south. This large transport rate also requires that navigation channel dredging be performed about 30 percent of the time.

The migration of Oregon Inlet to the south has caused erosion of Pea Island to the extent that, by 1989, the abutment of the state-owned Bonner Bridge was being threatened. This prompted the State of North Carolina Department of Transportation (DOT) to contract for the construction of a terminal groin on the south side of the inlet to stabilize the shoreline and protect the bridge abutment. A plan view of the terminal groin is shown in Figure 12. The winning bid for groin construction was $9.4 million, and the 19-month-long project was managed by the Corps of Engineers under contract to the North Carolina DOT.

In the initial plans, the groin was to be constructed in water depths of between 10 - 12 ft, decreasing to about 5 ft of depth as the groin reached the ebb shoal bar. A significant scour hole problem developed during construction of the terminal groin. The problem first arose as construction advanced out into the channel parallel to the bridge and perpendicular to the ebb flow current. The contractor maintained a toe protection scour blanket 50 ft in advance of construction; however, ebb-flowing currents on the inlet side of the groin created a continuous scour hole problem that ultimately required 50 percent more stone in the structure in order to obtain the design cross section. This resulted in a $4-million cost overrun (40 percent over the bid). The scoured portions on the Pea Island side of the groin filled in, but the inlet side scour hole remained after construction.

The extent of scour that occurred during construction is shown in Figure 13. Center-line stations on this figure refer to the positions indicated on the terminal groin plan view given in Figure 12.

It was speculated during the May 1991 workshop that the primary cause of scour at Oregon Inlet was the ebb-flow tidal current because the deepest scour was observed on the channel side of the groin. Waves were discounted as a process contributing to the scour because most waves break on the ebb shoal, thus decreasing their effect. However, there is a possibility that nearshore currents generated by waves during storm conditions could have contributed to the scour. Aerial photographs of the groin showed currents being trained along the structure.

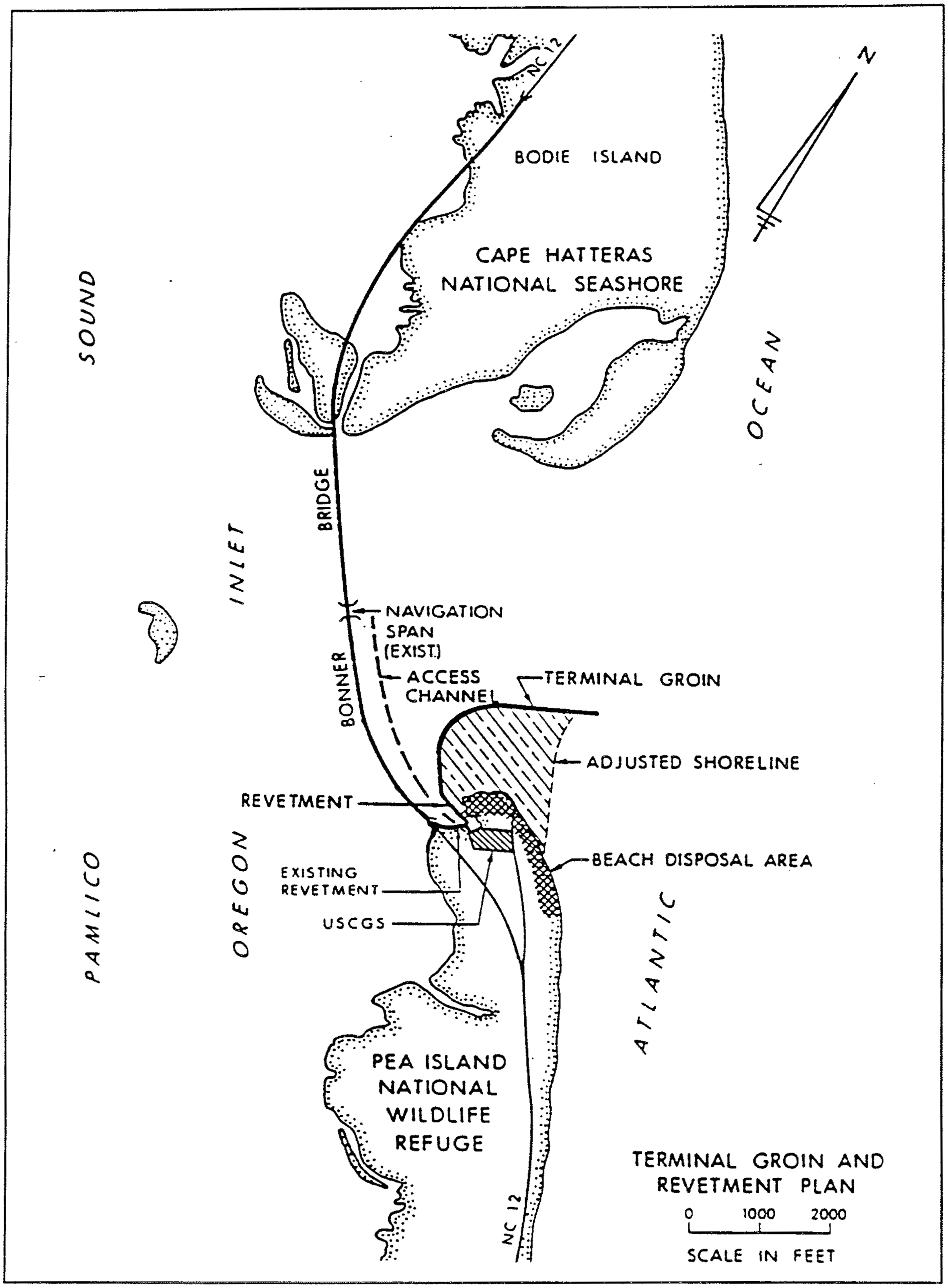

Figure 12. Oregon Inlet and terminal groin

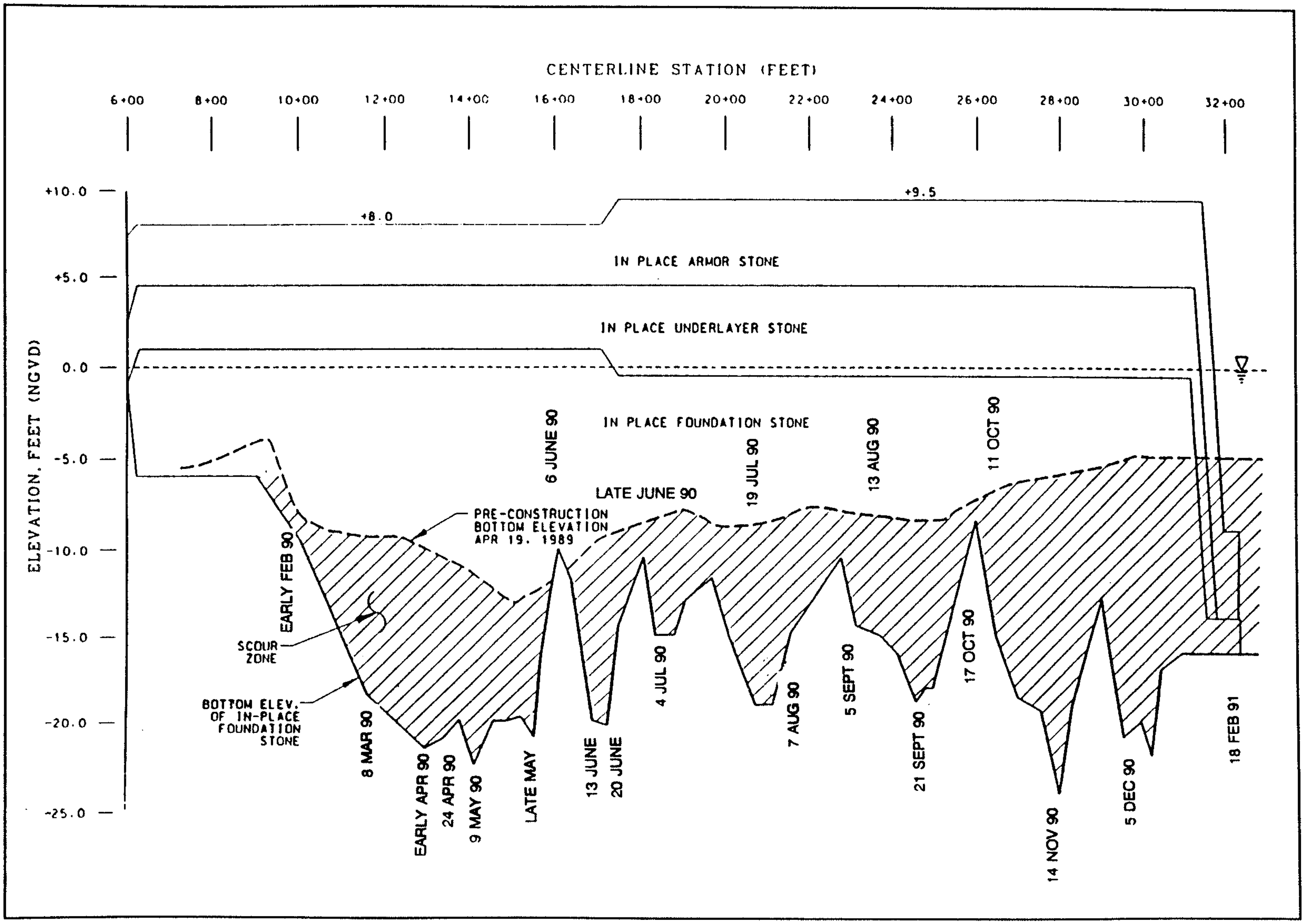

Figure 13. Scour during construction, Oregon Inlet, pre- and post-construction

The project has been monitored since April 1990. Shore-perpendicular beach profiles have been collected using a survey sled and total station five times since April 1990, on a semi-annual basis. Thirty-six survey stations were established on Bodie and Pea Islands and surveys were taken from behind the dune seaward to a -30-ft depth. Along with the surveys, a bottom-mounted electromagnetic current meter/pressure gage (PUV) gage has operated continuously since May 1990 collecting wave height, period, direction, and X-Y current speed and direction. The North Carolina DOT collects aerial photography every other month to monitor and quantify shoreline change.

During the summer of 1992, a report summarizing the monitoring effort was scheduled to be written.[1] Preliminary results of the monitoring showed that the fillet area south of the groin has filled with over 750,000 cu yd of sand, creating between 40 and 50 acres of beach. The design estimates were for creation of approximately 60 acres of beach with 500,000 to 1 million cu yd of material. The fillet adjacent to the groin has nearly reached holding capacity, evidenced by transport of sand around the end of the groin. A small shoal has formed on the channel side of the groin near the tip. At the tip, the deep channel that developed during construction remains and it appears to be caused by strong tidal currents.[1]

As the groin was constructed, there were periods of scour and no scour (even accretion) as shown in Figure 13. An attempt was made by the monitors to correlate wave height, period, and direction with scour depth. Figures 14, 15, and 16 show that, based on preliminary results from Miller (1992), none of the aforementioned wave parameters correlated with scour depth.

Although the recently completed terminal groin was state funded, there is a Corps project planned that would extend the terminal groin over the shoal to jetty length, and construct another jetty on the north side of the inlet to give a stabilized inlet with a 2,500-to 3,500-ft center-line width. This project is estimated to cost $65 million. If similar scour problems were to occur during construction of the new jetties, a conservative estimate would be the need for 25 percent more stone, which translates to about 20 percent additional cost, or $13 million. This conservative estimate of cost overrun might adversely impact the project on a cost/benefit basis.

Little River Inlet, South Carolina

Little River Inlet is located at the border of North and South Carolina (Figure 17). The inlet is the only navigable outlet from the Intracoastal Waterway to the Atlantic Ocean between Shallotte Inlet, North Carolina and Georgetown, South Carolina, a distance of approximately 68 miles. The inlet is part

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[1] Personal Communication, 1992, H. C. Miller, Field Research Facility, Coastal Engineering Research Center, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

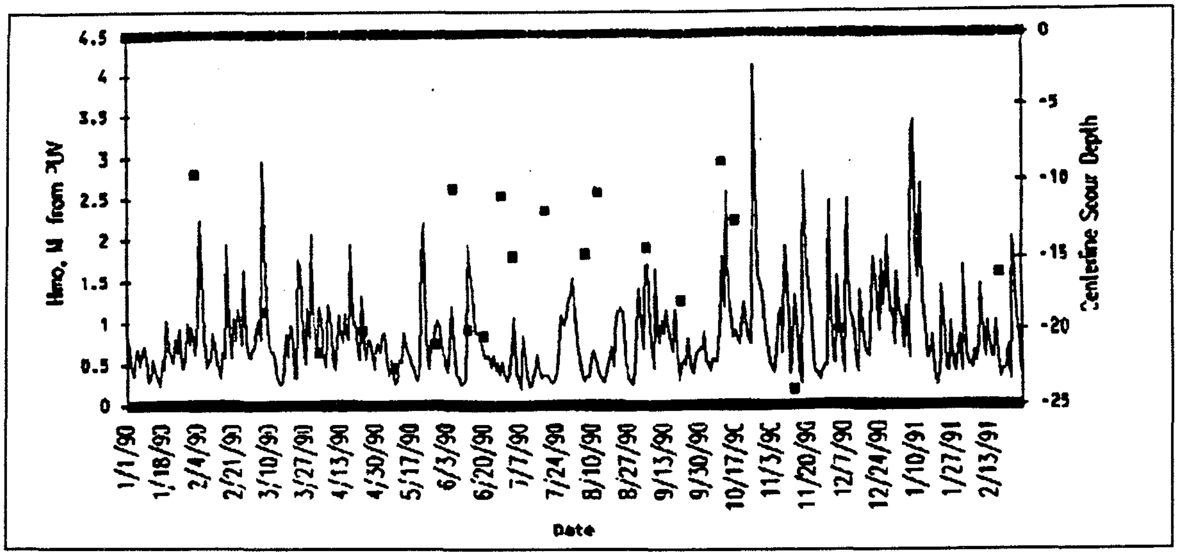

Figure 14. Center-line scour versus wave height

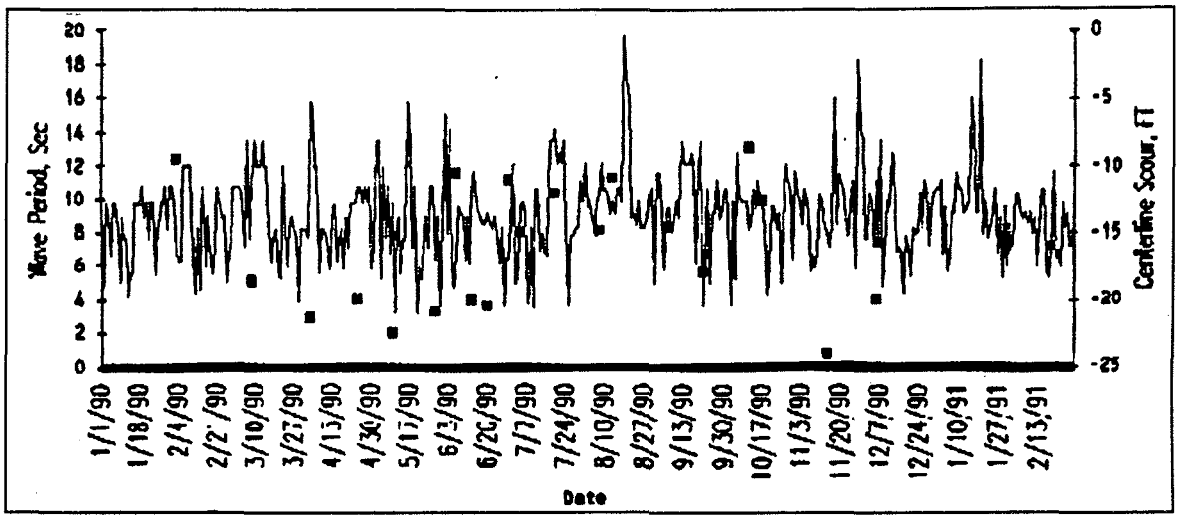

Figure 15. Center-line scour versus wave period

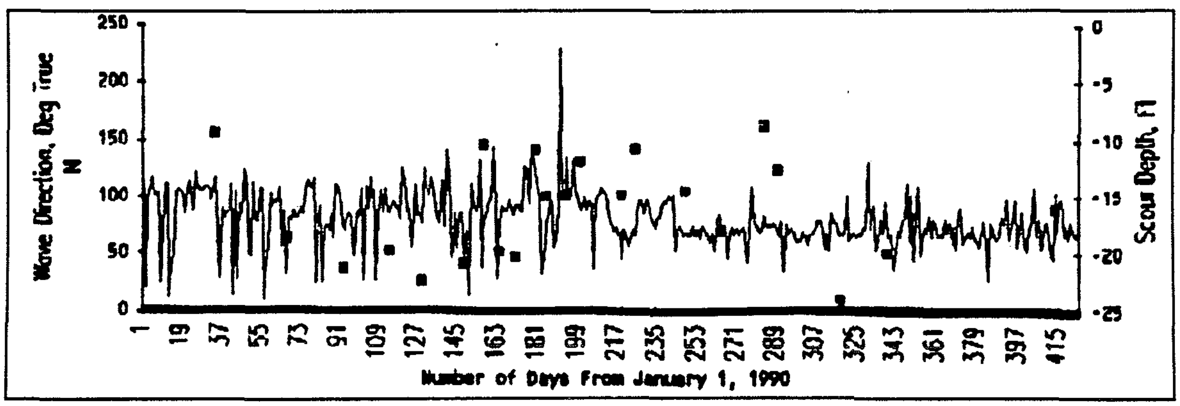

Figure 16. Center-line scour versus wave direction

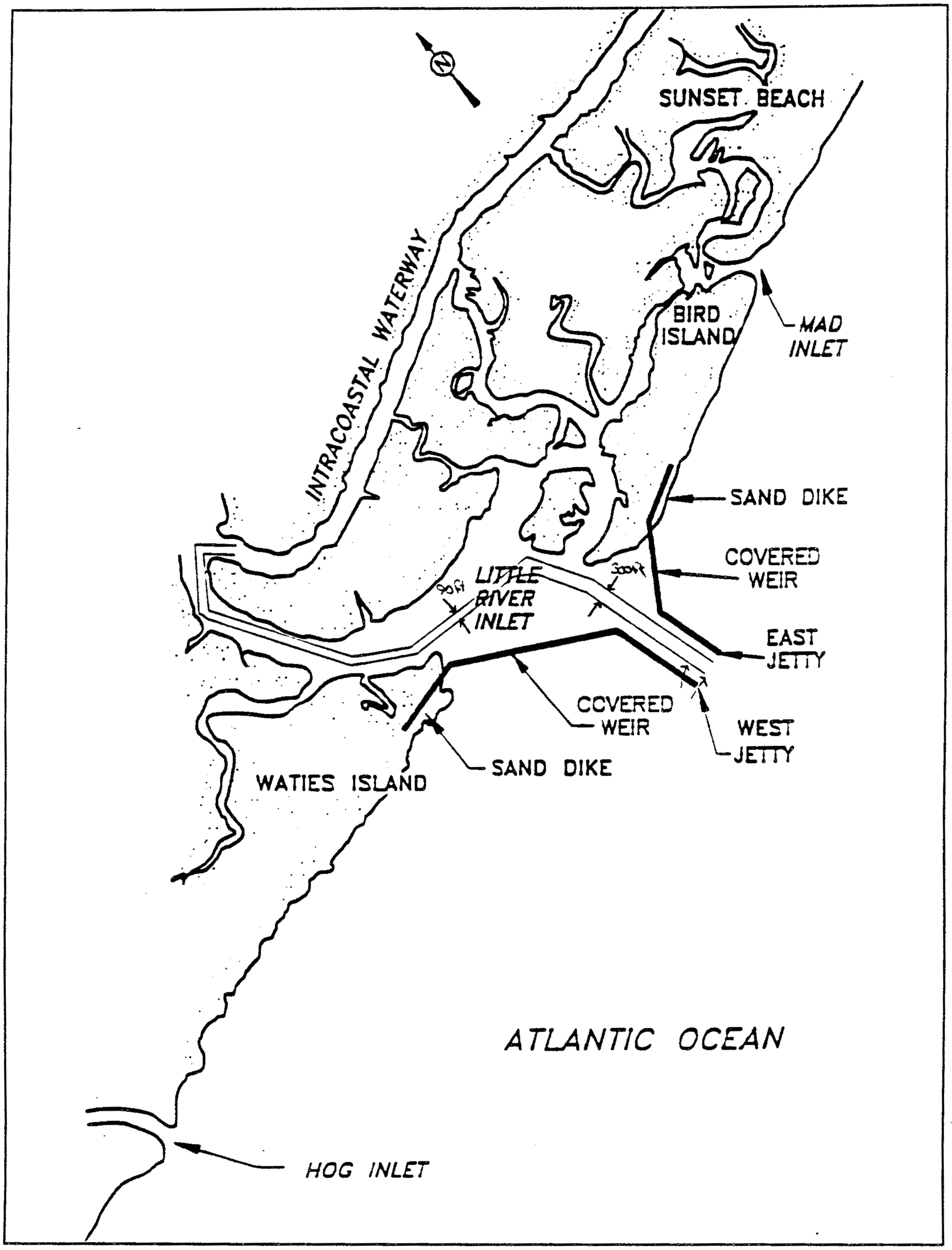

Figure 17. Little River Inlet, South Carolina, site location and project map

of 60 miles of shoreline along the northeastern shore of South Carolina known as the "Grand Strand." To the northeast is Bird Island and to the southwest is Waties Island, both privately owned and undeveloped (Chasten and Seabergh, in preparation). Historically, the undeveloped inlet had shifting and migrating sand shoals that made inlet navigation difficult and dangerous (Seabergh and Lane 1977). Congress authorized the stabilization of Little River Inlet in 1972 under Section 201 of the Flood Control Act of 1965. Construction of a two-jetty project was initiated in March 1981 and completed in July 1983.

The mean tidal range for Little River Inlet is approximately 5 ft with a prism of 505 million cu ft over a semidiurnal tidal cycle. The average significant wave height is estimated to be about 1.8 ft with a period of 5.1 sec (Jensen 1983).

The authorized Federal project (Figure 17) includes two rubble-mound jetties with sand transition dikes built at the landward end of both jetties. A low weir section was originally constructed but later covered with armor stone. Stone weighing up to 8 tons was used in construction of the jetties, which are approximately 3,300 ft (east jetty) and 3,800 ft (west jetty) long. The navigation channel bottom elevation is 12 ft mlw. The navigation channel is 300 ft wide, and 3,200 ft long through the entrance. The inner channel bottom elevation is 10 ft mlw. The inner channel is 90 ft wide and 9,050 ft long, stretching between the entrance channel and the Intracoastal Waterway. A fixed-bed hydraulic model was used in the 1970's to design the project, and included assessment of jetty alignment, length and spacing, weir sections, current patterns and speed, sediment movement (through use of tracers), and effect of inlet modifications on tidal prism and water quality (Seabergh and Lane 1977).

The inlet project was constructed between 1981 and 1983, including dredging of 513,000 cu yd for construction of the navigation channel. The inlet has been dredged only once since initial construction, in 1984 when 264,000 cu yd was dredged from the entrance channel and mostly placed along the inner side of the west jetty to mitigate scour (Chasten and Seabergh, in preparation). Prior to construction, the Charleston District implemented a monitoring effort in 1979 which continued through 1992. The program included collecting beach profile surveys, inlet hydrographic surveys, aerial photography, structural surveys, site inspections, and Littoral Environment Observation data collection.

Chasten and Seabergh (in preparation) presented an analysis of data collected between 1979 and 1989 which showed that the navigation project has had minimal impact on adjacent beaches. The study's conclusion was that there has been little interruption of longshore sediment transport across the inlet. However, there has been substantial change occurring at the inlet through development of scour holes at the tips of both the east and west jetties, and adjacent to the west jetty along the interior of the channel (Figure 18). Bathymetric surveys showed that the scour holes began to form at the jetty tips immediately after jetty construction. Scour along the inlet channel adjacent to the west jetty appears to be related to natural channel migration.

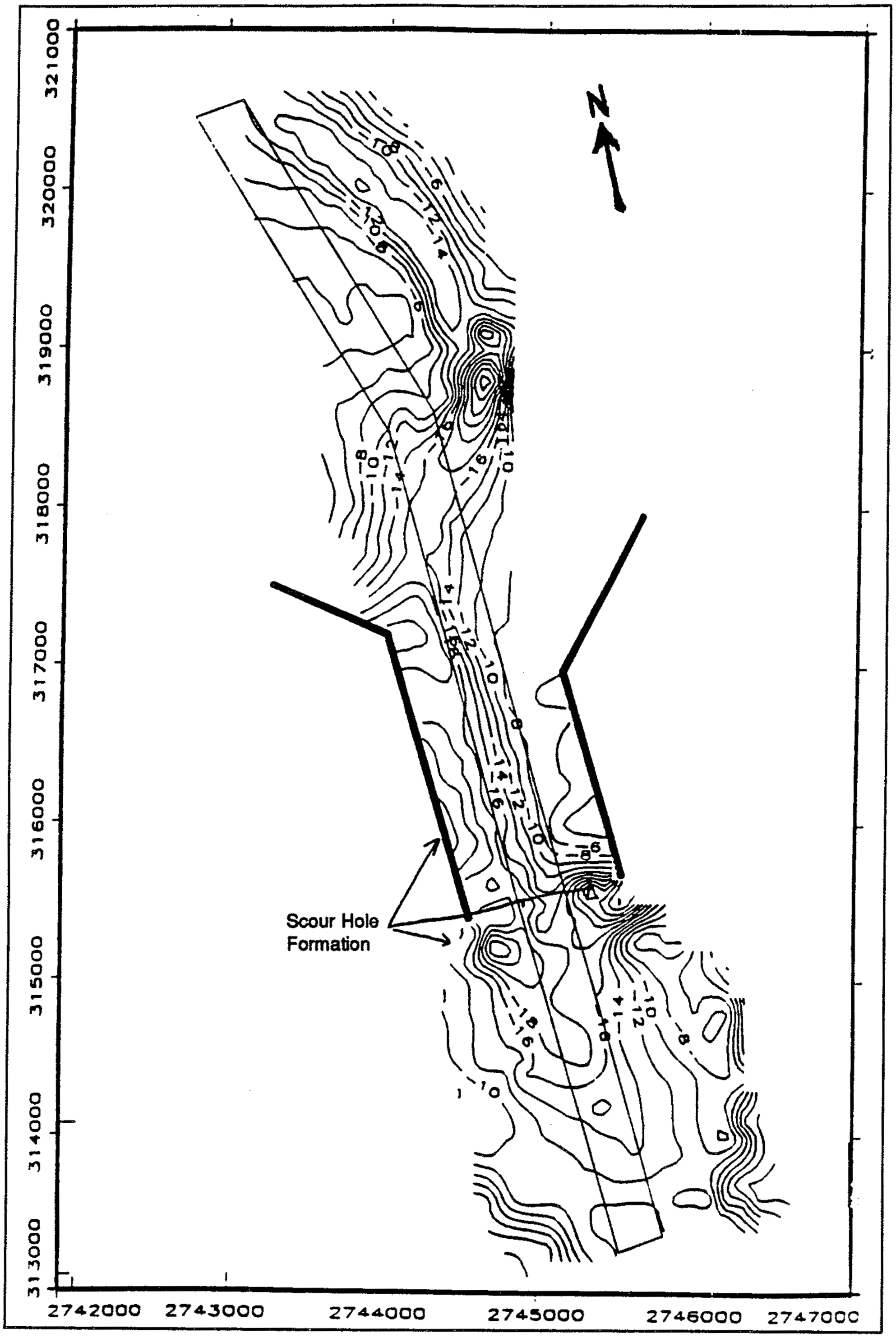

Figure 18. Scour holes at Little River Inlet

Scour at the tip of the east and west jetties appears to be caused by tidal current and structure interactions. The west jetty scour hole is approximately 10 to 15 ft deeper than the surrounding bottom. The hole at the east jetty is larger than the west jetty scour hole. The east scour hole began to form around October 1982 and had increased to a depth greater than 25 ft mlw by April 1983. In December 1983, material dredged from the inlet was used to fill the east scour hole. This filling was short-lived, however, as the deepening trend continued, and at this writing the hole was deeper than 30 ft mlw. The cause of scour at the jetty tips was suggested by Chasten and Seabergh (in preparation) to be due to tidal current and structure interaction. The deeper scour hole occurring at the east jetty is probably due to the proximity of the ebb tidal shoal, causing increased current speeds around the jetty tip.

Scour is also occurring along the west jetty adjacent to the inlet channel, and the cause appears to be different from that at the tips. Along this section, natural thalweg migration appears to be shifting the channel toward the jetty, scouring to a depth of about 20 to 25 ft mlw. Prior to construction of the navigation project, the natural channel shifted frequently; and at the time of construction of the west jetty, the natural channel was toward the southwest and Waties Island (Chasten and Seabergh, in preparation). This flow route was closed off as the west jetty was constructed and the ebb tidal flow began channelizing along the west jetty. In December 1983, dredged material from the inlet was placed in the scour hole but has since eroded away, and the hole continues to enlarge. Figure 19 shows a survey taken along the west jetty prior to dredged material placement and following placement. Note that the deepening trend continued immediately following fill placement.

Study conclusions presented by Chasten and Seabergh (in preparation) stated that the project depth of -12 ft mlw presently exists along most of the authorized navigation channel even though the inlet has not been dredged since 1984. In addition, the channel has migrated toward the west jetty, and the deepest water exists immediately adjacent to the west jetty.

The channel migration and jetty scour began following construction of the Federal navigation project and continued through 1989. Since 1989, the inlet continued to evolve with some changes, probably as a result of Hurricane Hugo. Chasten and Seabergh (in preparation) predicted that, with deepening of a natural feature near the east jetty, the inlet may adjust to a more centralized location for the natural thalweg thus relieving some of the scour potential at the west jetty.

However, scour at the tip of the jetties is continuing, which may eventually result in damage. Chasten and Seabergh (in preparation) stated that collapse of either jetty head section would not immediately affect the functionality of the jetties to stabilize the inlet, and reported that the rate of scour at the west jetty has slowed.

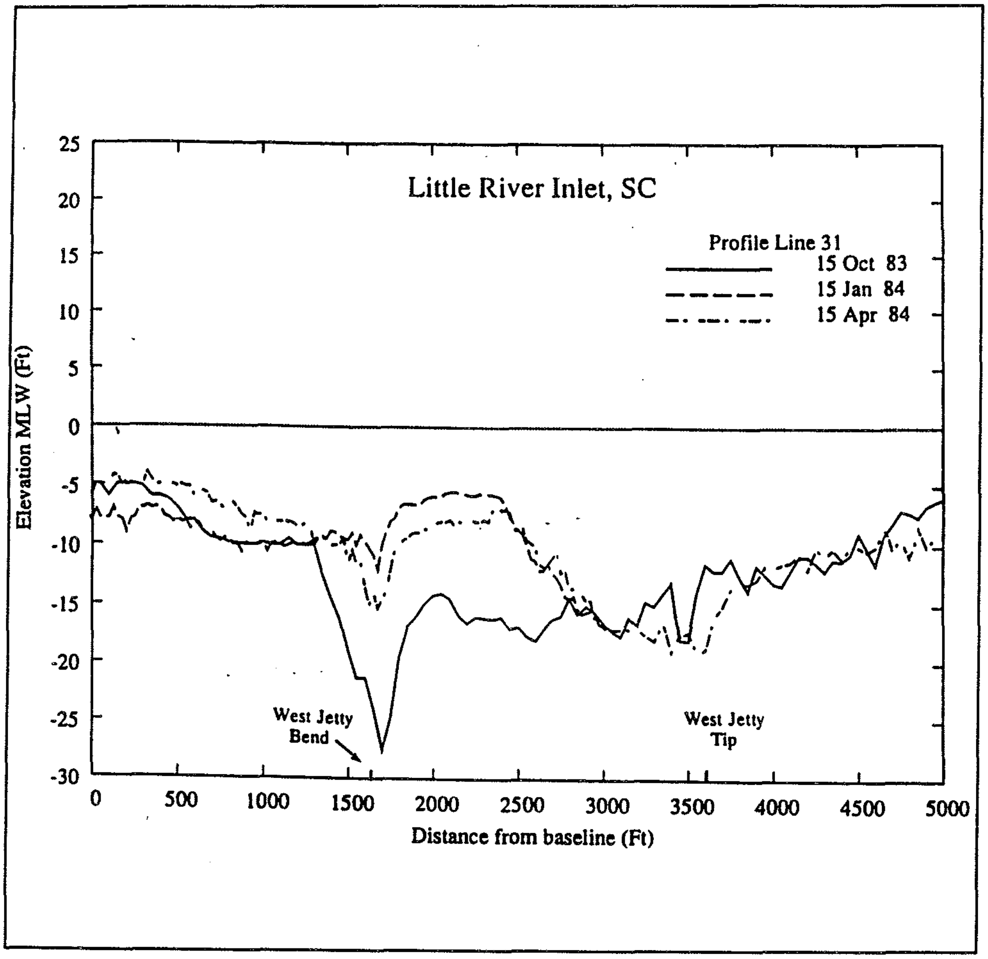

Figure 19. Little River Inlet bathymetry profile

St. Johns River, Florida

The entrance to Jacksonville Harbor from the Atlantic Ocean traverses approximately 20 nautical miles of the St. Johns River. Approximately 3 nautical miles from the Atlantic Ocean, at a bend in the channel, is Mile Point, located on the north side of the channel (Figure 20). Significant scour is occurring along this reach, causing bank erosion. Two scour holes have formed, one small hole about 65 ft deep and a second scour trench approximately 45 ft deep and 1,500 ft long running east/west. Surrounding bottom depths are in the 10- to 20-ft range. As the scour holes have increased in size, significant shoreline erosion has resulted. Riverine mechanics predict that scour should occur on the outside of a channel bend and deposition along the inside of the bend. Unlike more typical river settings, scour at Mile Point is located on the inside of the bend.

Tides at Mile Point have a mean range of over 4 ft, and maximum currents are reported to be in excess of 10 ft/sec, experienced on ebb tidal cycles. The port of Jacksonville services large ships hundreds of feet in length from around the world. Ship travel through the channel is frequent.

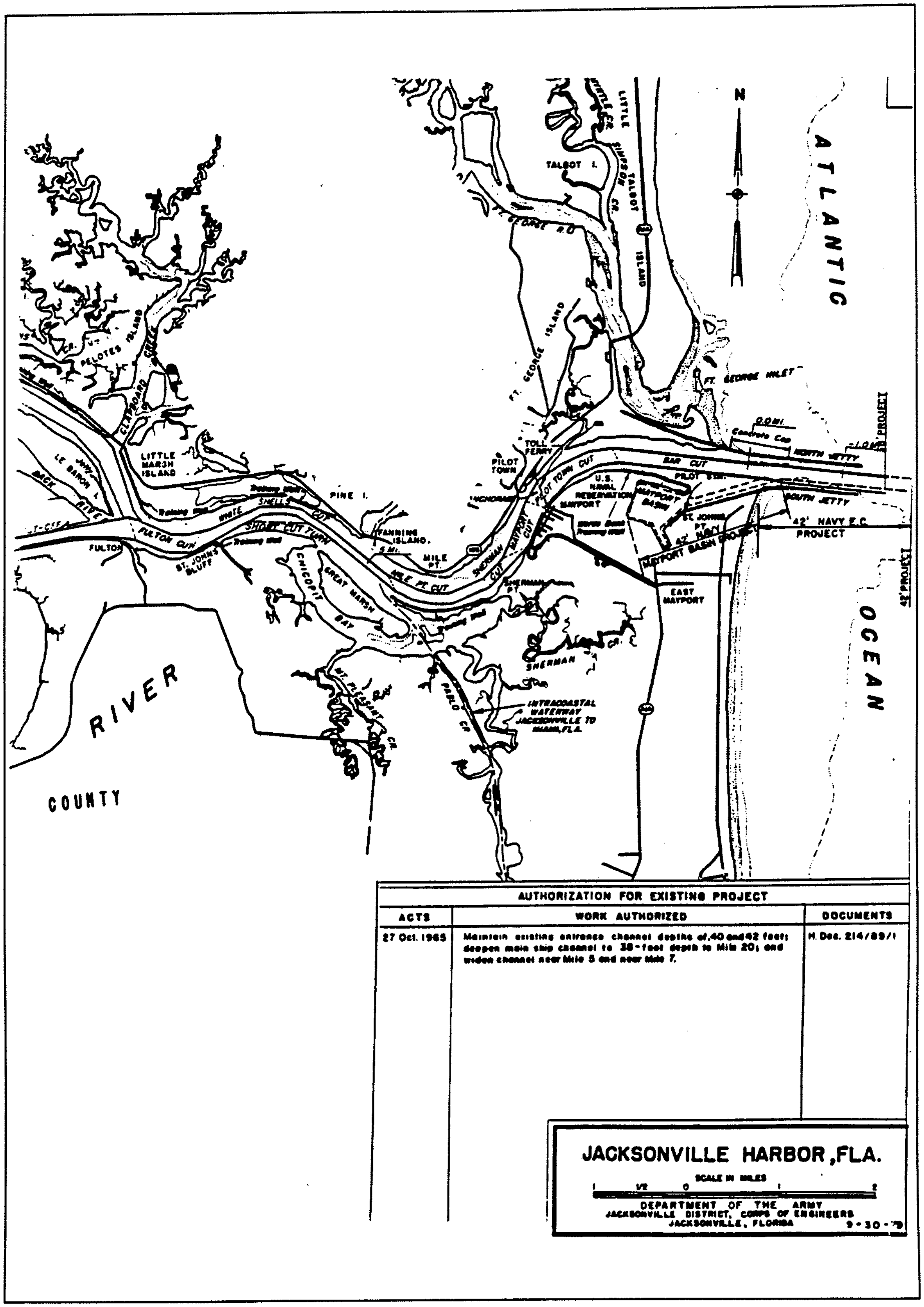

Figure 20. St. Johns River, Florida, site location map

The Jacksonville District reports that, recently, property along the bend has eroded from 35 to 100 ft. A cause of scour has yet to be identified. The Federal navigation channel is located over 900 ft south of the scour holes. The navigation channel has been dredged for over 100 years, and this scour problem is a recent occurrence.

Ponce de Leon Inlet, Florida

Ponce de Leon Inlet is located a few miles south of Daytona Beach, Florida. A navigation project was constructed in 1968 that included two rubble-mound jetties, a weir, and a navigation channel 15 ft deep and 200 ft wide (Figure 21). The weir section was 1,800 ft long (300 ft at +4 ft mlw and the remaining 1,500 ft at mlw) and included an impoundment basin. The weir was designed in 1968 when no criteria existed for the design of weir jetties (Hemsley and Briggs 1988). A monitoring effort was initiated to determine the weir's performance. Within a few years of construction, a pattern of erosion adjacent to the north jetty and deposition adjacent to the south jetty was observed, opposite of that expected. As a result, the weir section was closed in 1983 by placing large armor stone over the weir.

Prior to closing the weir, a study was conducted that included the measurement of tidal elevations and currents through the inlet. On 27 January 1984, maximum measured current velocities were approximately 3.8 ft/sec. Sediment in the area is fine to medium, characteristic of much of northeast Florida.

Prior to construction of the inlet, the natural channel migrated over the ebb delta, but remained relatively stable. Following construction, the channel migrated toward the north jetty (Figure 22). After the weir was closed in 1983, the inlet continued to evolve and the natural channel migrated. Locations within the inlet that were once islands are now channels, and areas that were once channels are now islands. Included in the inlet's evolution is the development of a scour hole adjacent to the north jetty. It is approximately 200 ft long and 35 ft deep (surrounding bottom depths are approximately 10 to 15 ft). The postulated cause of the scour is migration of the natural thalweg adjacent to the jetty.

Panama City Entrance, Florida

The Panama City Harbor, Florida, entrance channel is shown in Figure 23. The channel was constructed to provide a more direct route from the Gulf of Mexico to the harbor facilities located at Panama City, FL, and was completed in 1934. The channel has an authorized depth of -32 ft, mlw, and width ranging from 450 ft across the entrance bar and halfway through the inlet where it constricts to approximately 300 ft. The inlet is stabilized by two stone jetties approximately 1,500 ft apart.

The mean diurnal tidal range at the entrance channel is 1.3 ft (National Ocean Service 1991). Current speeds measured in the inlet in July 1987 (Lillycrop, Rosati and McGehee 1989) were 2.6 ft/sec and 2.8 ft/sec for flood and ebb flows, respectively. Sediment in the area is relatively uniform, consisting of fine- to medium-sized quartz sand ranging from approximately 0.2 mm to 0.35 mm.

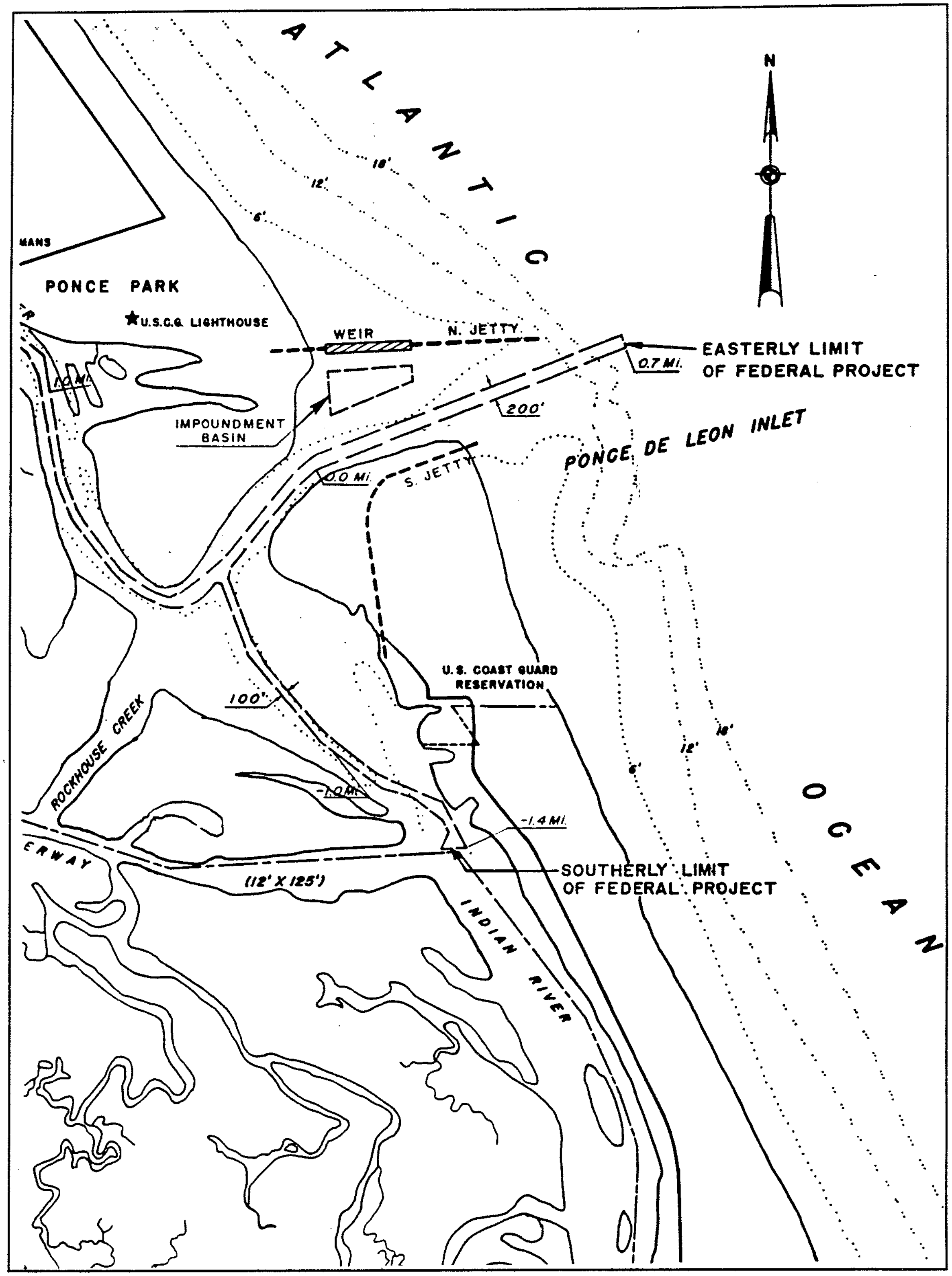

Figure 21. Ponce de Leon, Florida, site location map

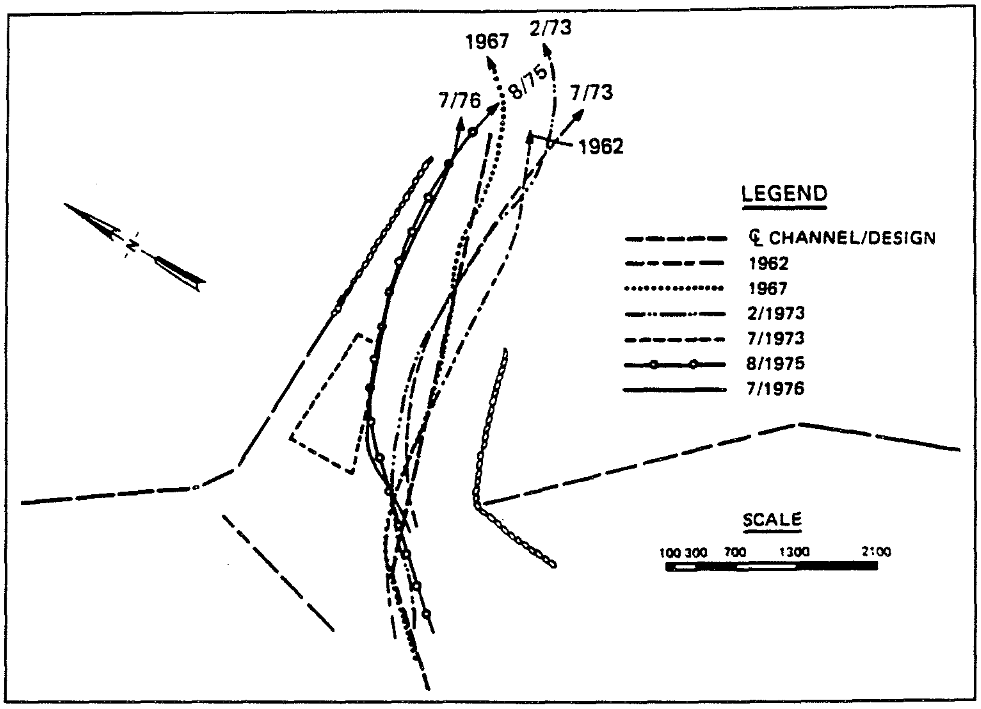

Figure 22. Historical center line of channel, Ponce de Leon Inlet (after Jones and Mehta (1978)).

The channel was dredged across the Land's End Peninsula, creating an entrance channel, and the jetties were built to stabilize the inlet. The jetties were constructed of riprap and extended to the -12-ft mlw offshore depth contour. These jetties were built on rock mattresses with steel sheet-pile cores along the jetty axis (Lillycrop, Rosati, and McGehee 1989). The east jetty extended from the low water line 500 ft offshore, and the west jetty from the low water line 550 ft offshore. Both jetties had a crest elevation of +6 ft mlw. The jetties were extended landward to mitigate severe erosion occurring along the inlet's channel banks (Figure 24).

The jetties and extensions have required continuous maintenance since they were completed in 1934. Since 1950, over 65,000 tons of stone have been required, much of which has been used to rehabilitate the west jetty tip. Following construction, the inlet stabilized with the natural channel thalweg located adjacent to the west jetty. As seen on Figure 25, the federally authorized navigation channel is located along the center line of the inlet. However, the inlet's thalweg is located adjacent to the west jetty where natural depths are greater than -40 ft mlw. Armor stones are displaced during storm events, and foundation materials and armor stones are lost as scour and deepening around the jetty tip continues.

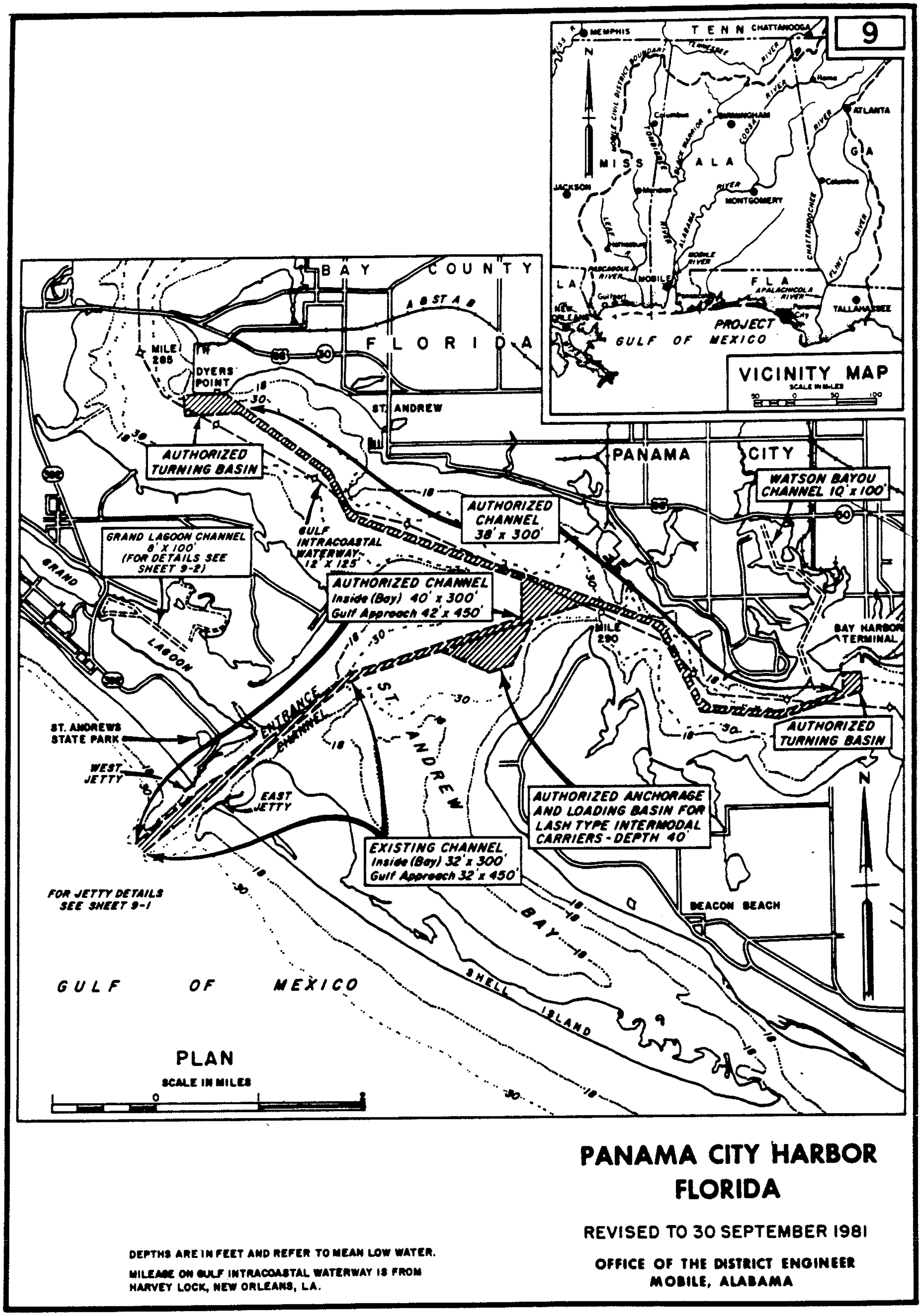

Figure 23. Panama City, Florida, site location map

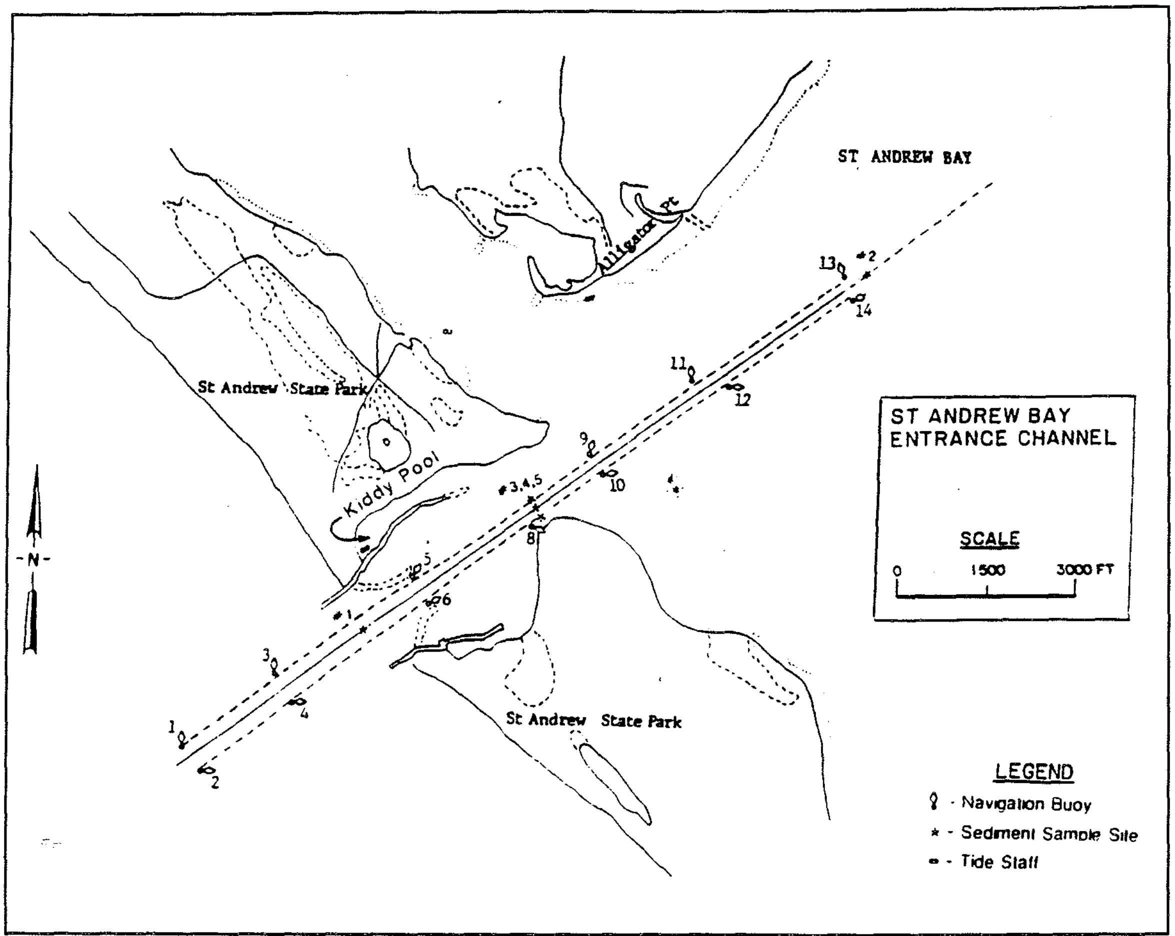

Figure 24. Entrance channel at Panama City

East Pass, Florida

East Pass is located at Destin, FL, on the Florida Panhandle midway between Pensacola and Panama City (Figure 26). It is the only direct entrance from the Gulf of Mexico into Choctawhatchee Bay. A Federal project consisting of a navigation channel 100 ft wide by 6 ft deep was constructed in 1931 and was later deepened to 12 ft in 1945. The channel had a general history of rapid shoaling followed by dredging (Morang 1992). During the period 1967 - 1969 East Pass was improved with the construction of two converging jetties spaced 1,000 ft apart at the ends, and by a realignment of the navigation channel toward the center of the pass (Figure 27). The east jetty was 2,270 ft long, and the west jetty was 4,850 ft long; both terminated at the -6 ft mlw contour.

Since construction of the jetties the entrance channel at East Pass has migrated toward the east boundary of the entrance, causing severe erosion along the shoreline of the pass. In 1977, as part of a general rehabilitation, an attempt was made to divert the channel back into the center of the improved

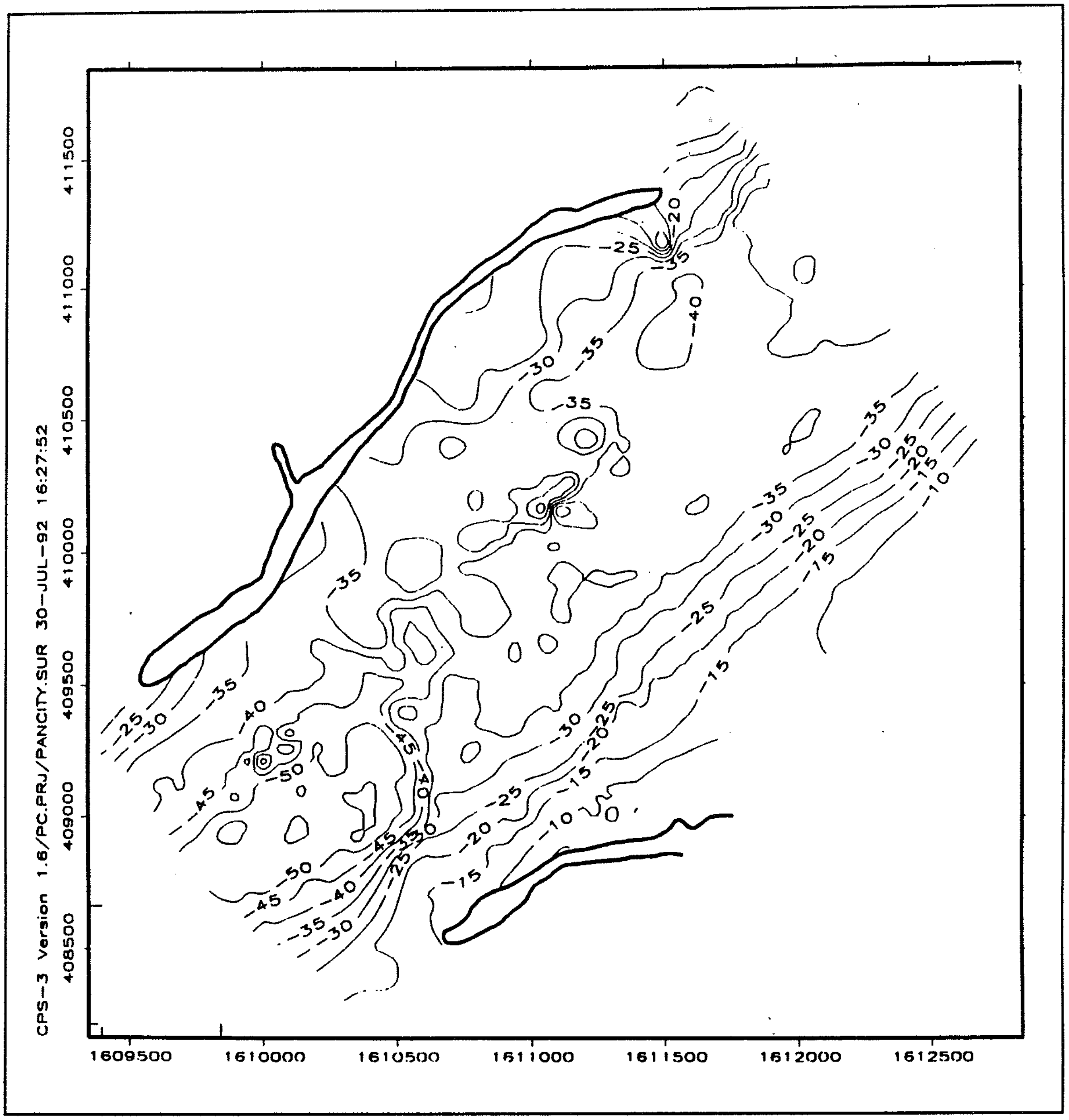

Figure 25. Bathymetry at Panama City

entrance. This was done by constructing a 300-ft-long spur jetty perpendicular to the landward end of the east jetty and extending out into the channel. The object was to deflect the strong ebb tidal currents that were causing erosion. It was feared that if the erosion was left to continue, the main jetty would be undermined.

In the 1980's, a 55-ft-deep scour hole developed that ultimately resulted in the loss of the spur dike at a rate of nearly 100 ft/year. This scour hole represents scouring nearly 25 - 30 ft below the normal bottom depth in the area. Figure 28 shows a plan view of the location of the scour hole at the spur groin and another scour hole at the tip of the west jetty.

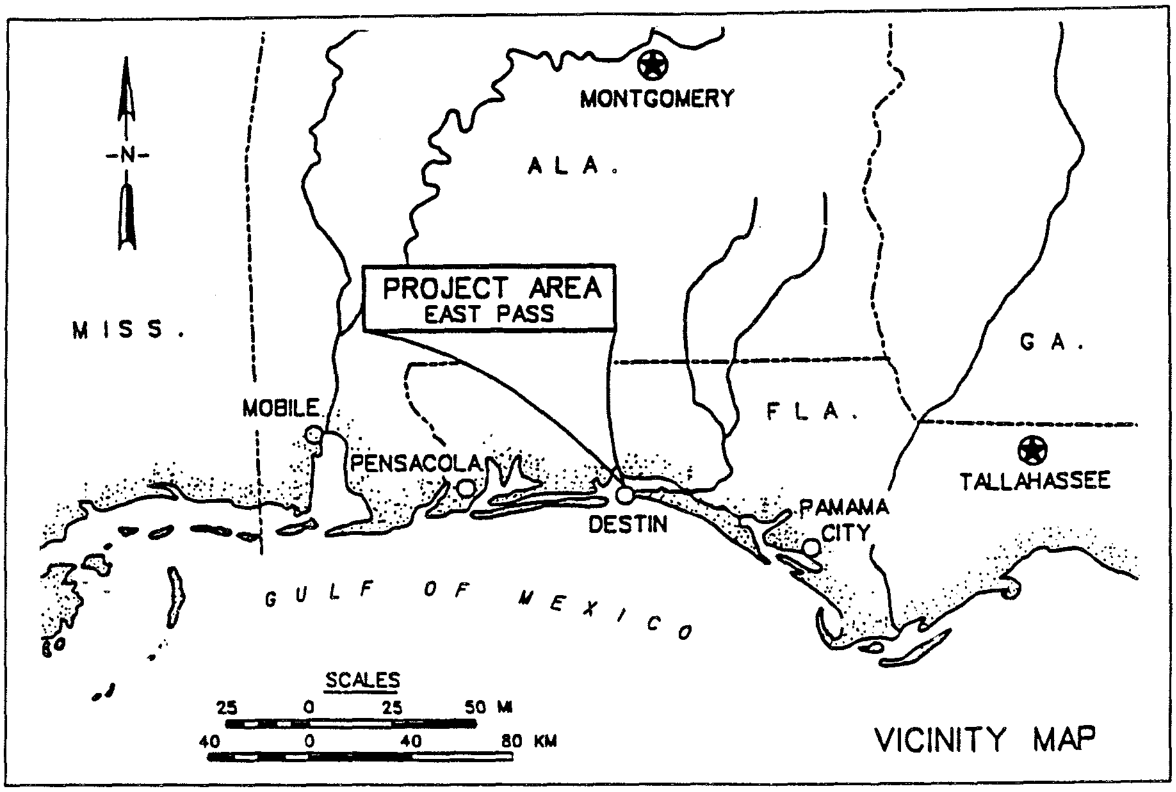

Figure 26. East Pass, Florida, site location map

In October 1983 a field measurement effort was undertaken to measure current velocities through the inlet. The maximum ebb current speeds were 4.5 ft/sec and maximum flood speeds were 2.8 ft/sec. The tidal range was small at 2 - 3 ft.

Since development of the scour hole at the end of the spur groin the hole has been filled twice with material dredged from the navigation channel. In 1988 it was filled with dredged material and capped with concrete rubble, but this disappeared after a short while. The swift ebb-flowing tidal currents continued to scour the hole and damage the groin. The scour near the tip of the west jetty has depths up to 45 ft; but this scour hole has not yet posed any risk to the west jetty and, in fact, helps maintain the authorized channel depth.

In 1984 a study of the inlet and scour problem was initiated under the Monitoring Completed Coastal Projects (MCCP)research program, funded by the Office, Chief of Engineers. The study, completed in 1991, postulated "physical processes are still attempting to force the inlet east" toward its former stable location. The driving mechanisms are wave forces from the predominantly southwest direction, and flood-tidal shoal geometry and interaction with tidal currents. These cause natural thalweg migration to the east that has progressed so that the thalweg now lies adjacent to the east jetty and spur groin.

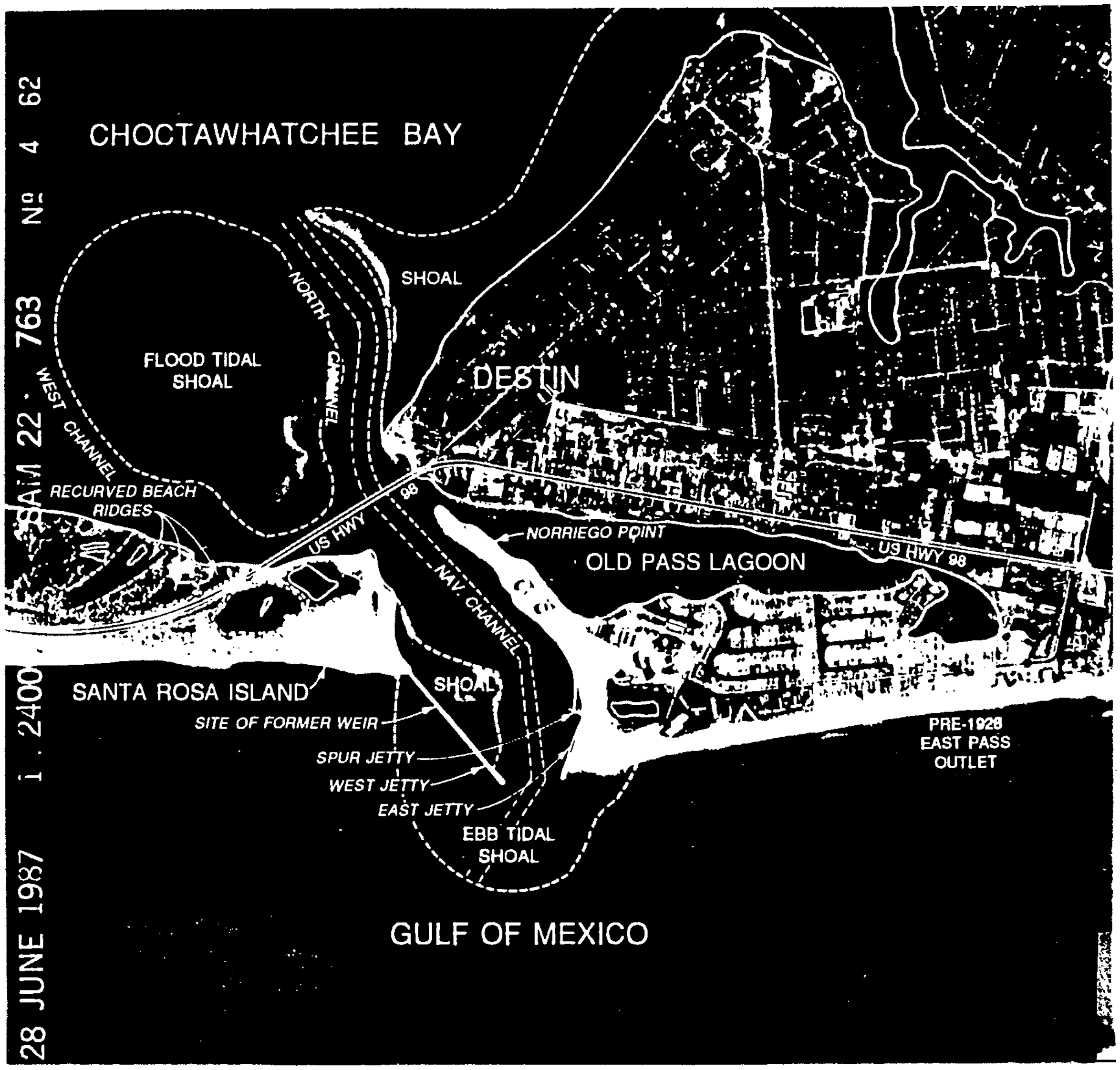

Figure 27. East Pass navigation project (Morang 1992)

To minimize adverse scour, the report recommends the following (Morang 1992):

a. The spur groin can be rebuilt with extensive toe protection to prevent collapse. The scour hole near the tip of the spur would have to be filled and then armored to prevent future scour. While the use of concrete and rubble fill in the past provided only temporary relief, an engineered approach employing precisely placed armor units might be more successful.

b. The scour hole at the tip of the west jetty should also be filled and capped with armor stone to prevent damage to the jetty.

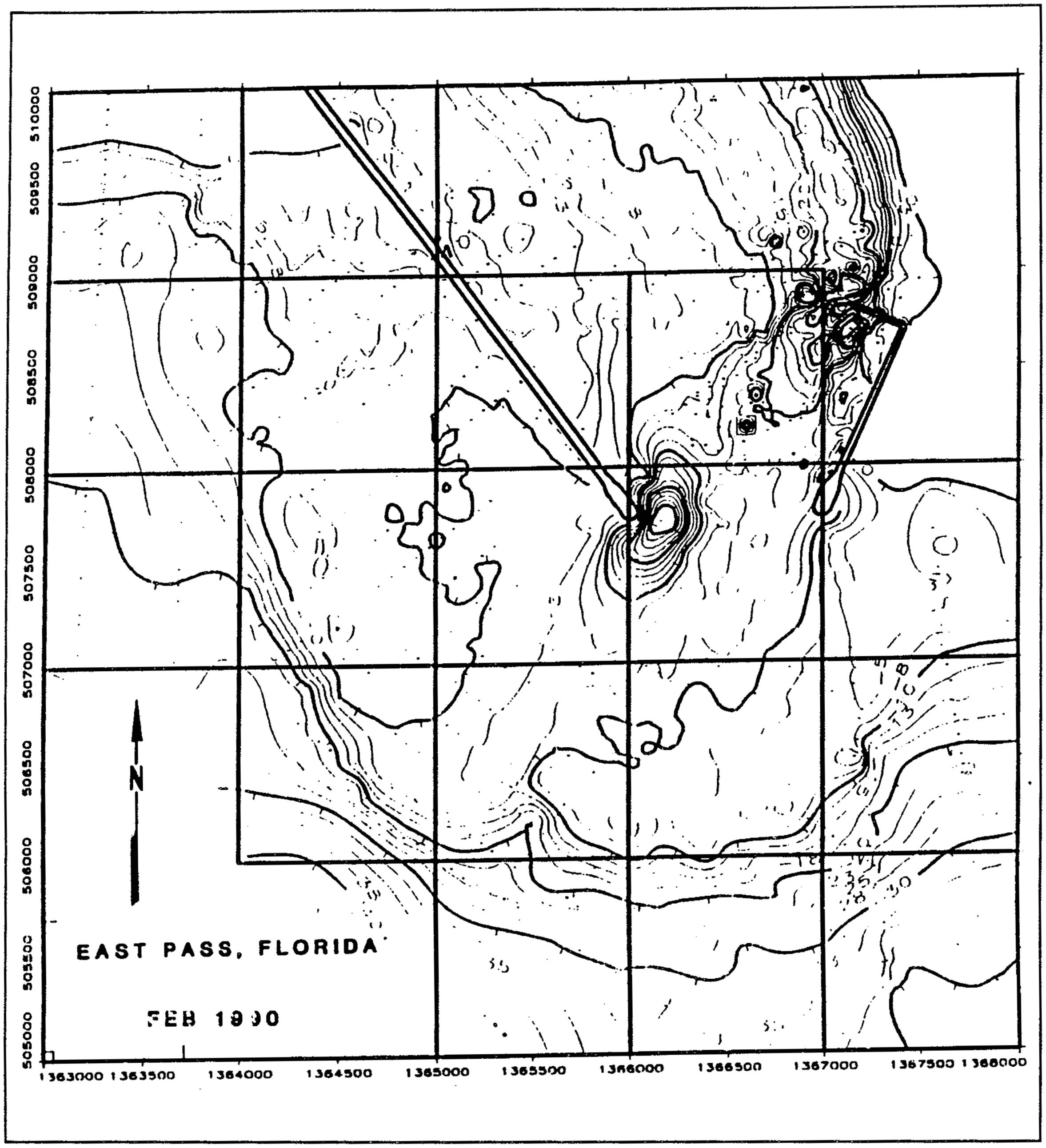

Figure 28. East Pass scour holes (Morang 1992)

Present rehabilitation plans call for filling the scour hole at the tip of the groin using dredged material, capping the hole with stone, repairing the jetties, and rebuilding 100 ft of the spur groin, at a cost of $1.3 million. It is not known whether this repair will permanently solve the problem at East Pass.

Morro Bay, California

Morro Bay is a small craft commercial harbor located approximately midway between San Francisco and Los Angeles, CA. The harbor is located near the center of Estero Bay, a large shoreline indentation that shelters the harbor from some wave approach angles. The harbor is protected by two rubble-mound breakwaters (Figure 29) that provide a 900-ft-wide opening. The north jetty runs somewhat parallel to the shoreline.

Natural depths in the channel area are typically about 20 ft, and during times of heavy wave action the entrance can be difficult to navigate.

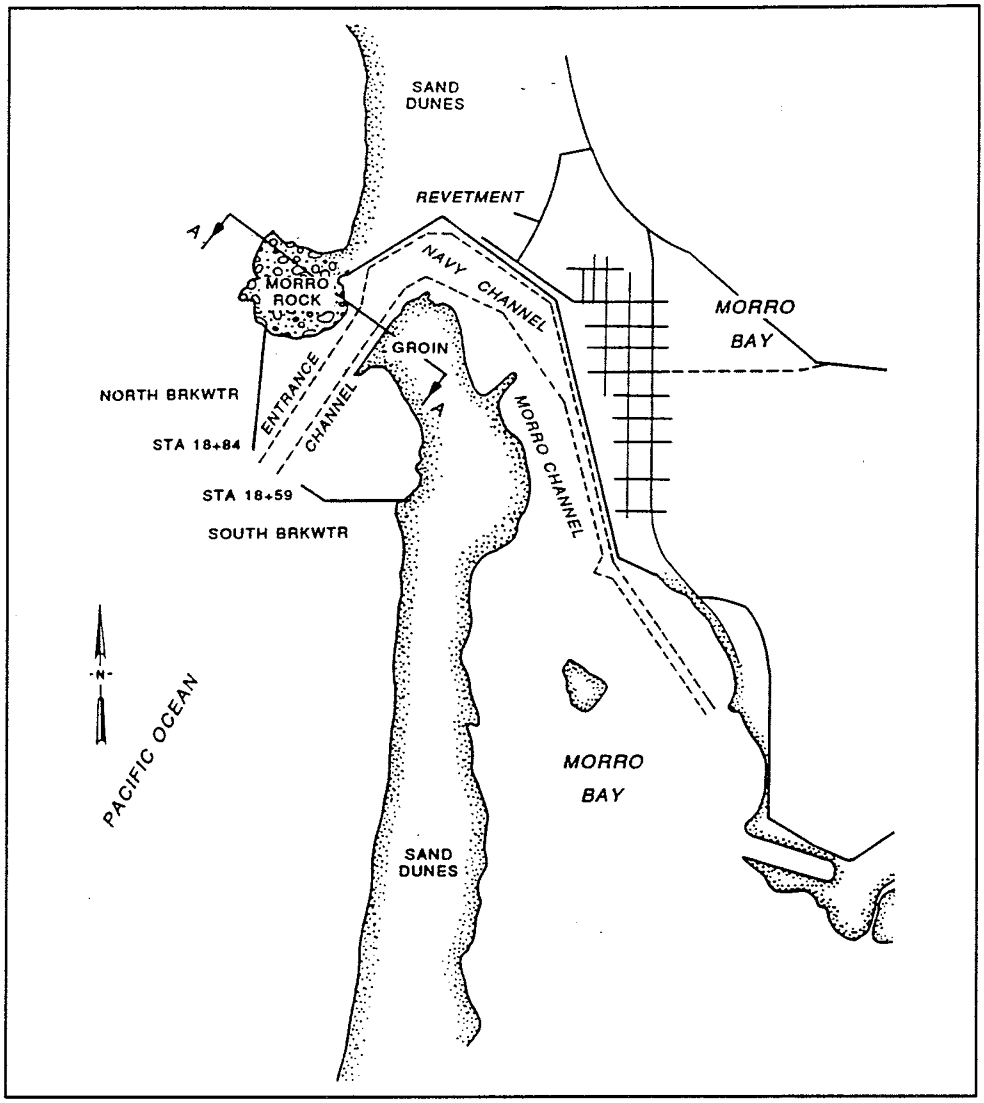

Figure 29. Morro Bay, California, site location map

A scour hole was discovered off the tip of the north jetty after the January - March 1991 winter storm season. This particular winter was characterized by several intense storm sequences, including a storm in early March 1991 in which the significant wave height reached 17.5 ft.

Figure 30 is a plan view of the scour hole as it existed during the survey of March 11, 1991. The maximum depth is 30 ft below mean lower low water (mllw), and it was pointed out that the survey was performed 8 days after the storm, and, thus, there could have been some infilling of the hole in the meantime.

The cross section indicated on Figure 30 is shown on Figure 31. Survey data did not extend up to the toe of the jetty, so there is some question as to whether the structure's toe might be in jeopardy.

This scour hole seems to have resulted from the large storm waves with long periods passing the north jetty head and causing a shedding-type vortex that scours the bottom. It is not known whether tidal currents in the channel had any impact on the suspected scour mechanism.

Humboldt Bay, California

Humboldt Bay is a harbor located on the Pacific coast about 225 miles north of San Francisco, CA. The entrance to the bay is protected by two rubble-mound jetties separated by a distance of approximately 2,800 ft. Jetty construction dates back to before the turn of the century, and the Humboldt jetties are two of the oldest manmade structures on the Pacific coast subjected to extreme wave attack. The entrance and its structures are illustrated in Figure 32.

Geologically, the bay is underlain by consolidated sediments thousands of feet thick. These are Tertiary age sandstones, siltstones, and mudstones. Surficial sediments, aproximately the upper 100 ft, are unconsolidated materials deposited within the last 11,000 years. Before the jetties were constructed, a natural channel existed in the center of what is now Humboldt Bay channel. The natural channel had depths greater than 95 ft deep. Since the jetties were constructed shoaling has become significant, particularly near the tip of thenorth jetty. The deepest portions of the channel are now adjacent to the south jetty, due to dredging of the main ship channel.

Deep-water waves are most frequent from the west (47 percent of the year) and northwest (37 percent of the year), but the largest waves are most often associated with infrequent waves from the southwest (7 percent of the time). Wave heights of over 20 ft can occur annually and it is estimated that waves in the 25- to 27-ft range could impact the jetties for up to 1 hr annually. As waves approach the jetties, nearshore bathymetry causes shoaling and refraction, which focuses wave energy along the inner face of the entrance bar,

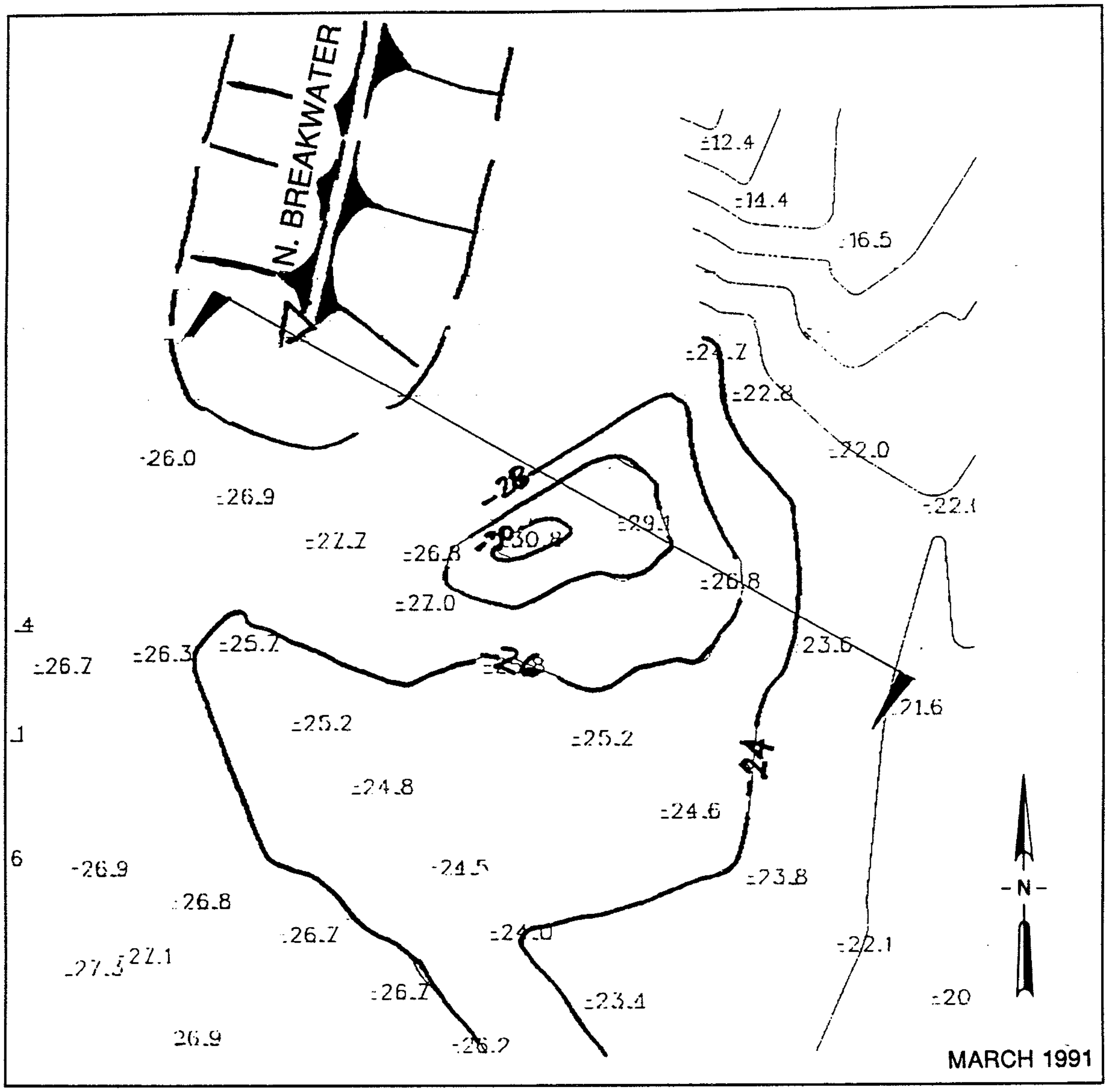

Figure 30. Morro Bay scour hole, plan view

on the outer channel entrance area, and at the region north of the north jetty head.

The south jetty was begun in 1889 as a training wall for ebb flow currents, and the north jetty was begun in 1891 to block littoral sediment from the north from reaching the navigation channel (Bottin 1988). Both were constructed on a 12-ft bed of brush mattresses about 4 ft thick. The largest rock used in the original construction was 8-ton stone. Following storm damage, the jetties were repaired with 6- to 20-ton stone, and 1,050- and 950-ton concrete monoliths were added at the seaward ends of the north and south jetties, respectively. The jetties were finished with a concrete slab 20 ft wide and 2 ft thick. During the period 1925-1927, parapet walls were added and mass concrete was poured on channel slopes to stabilize and protect the armor stone from overtopping waves. Twenty-ton stone was added during the period 1932 to 1958

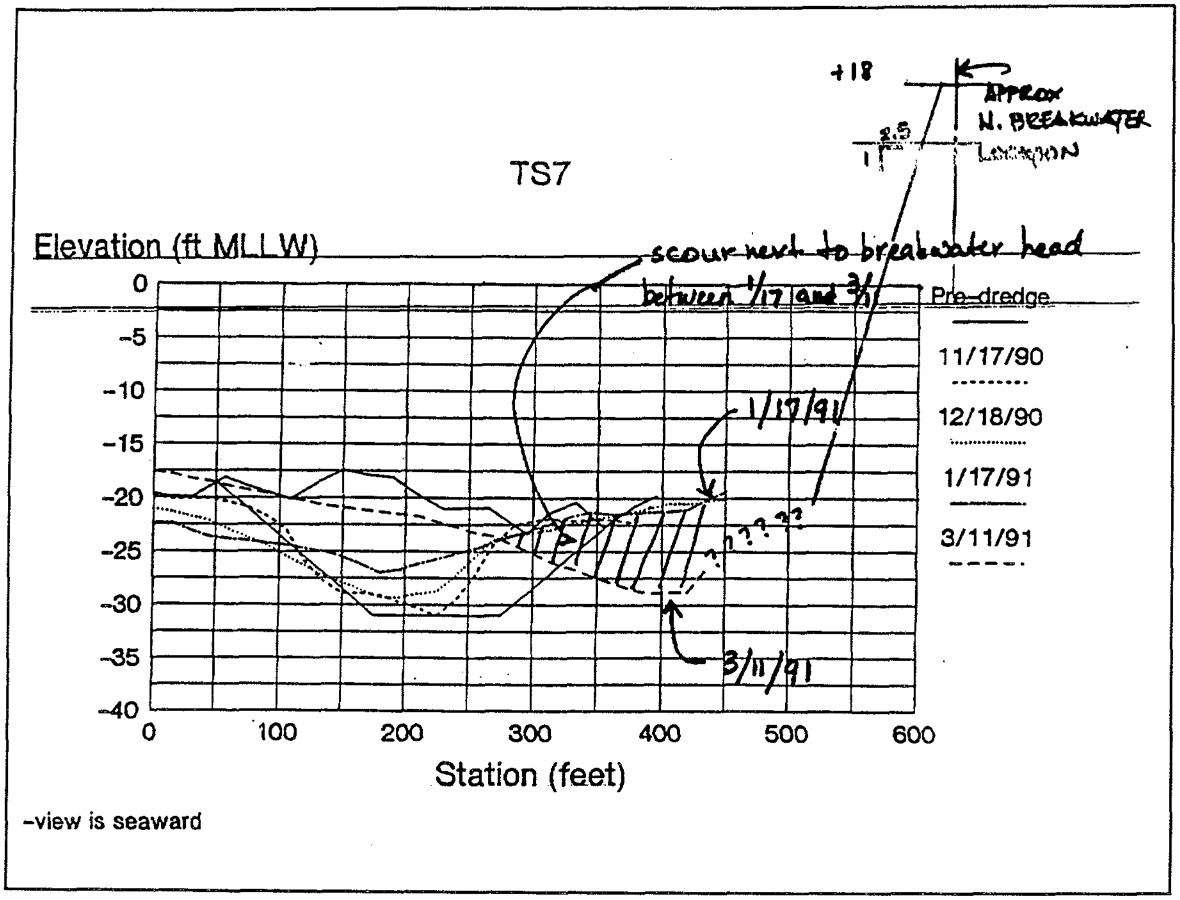

Figure 31. Morro Bay scour hole cross section

to repair jetty sections, and in 1958, 100-ton concrete blocks and 12-ton tetrahedrons were placed on the jetty heads. Following other repair efforts which eventually failed, the jetty was reconstructed using 20-ton stone and 42- and 43-ton dolosse on the jetty head.

Originally, the south jetty was built in the 1880's as a training wall for ebb flow currents, and the north jetty was built in the 1890's to block littoral sediment from the north from moving into the navigation channel. Although large quantities of sediment are moved in the longshore system at Humboldt Bay, the yearly net transport is nearly zero. In the summer, littoral drift is primarily north to south, whereas in the winter, the trend is reversed with sediment moving from south to north. The channel is maintained at a depth of 40 ft below mllw, and between 400,000 and 500,000 cu yd of sediment are dredged from the channel annually. The sand size is characterized as medium to fine.

Bathymetric data show three areas with significant active seasonal changes. Two are off the southwest side of the two jetty heads, and the third is along the channel side of the south jetty. The large holes tend to scour in the summer and fill in the winter. Off the south jetty head, soundings indicated depths almost to -70 ft mllw in August 1983 at station 85+50 and 350 ft off the center line. Surveys in 1984 showed this area had shoaled to -40 ft mllw in April,

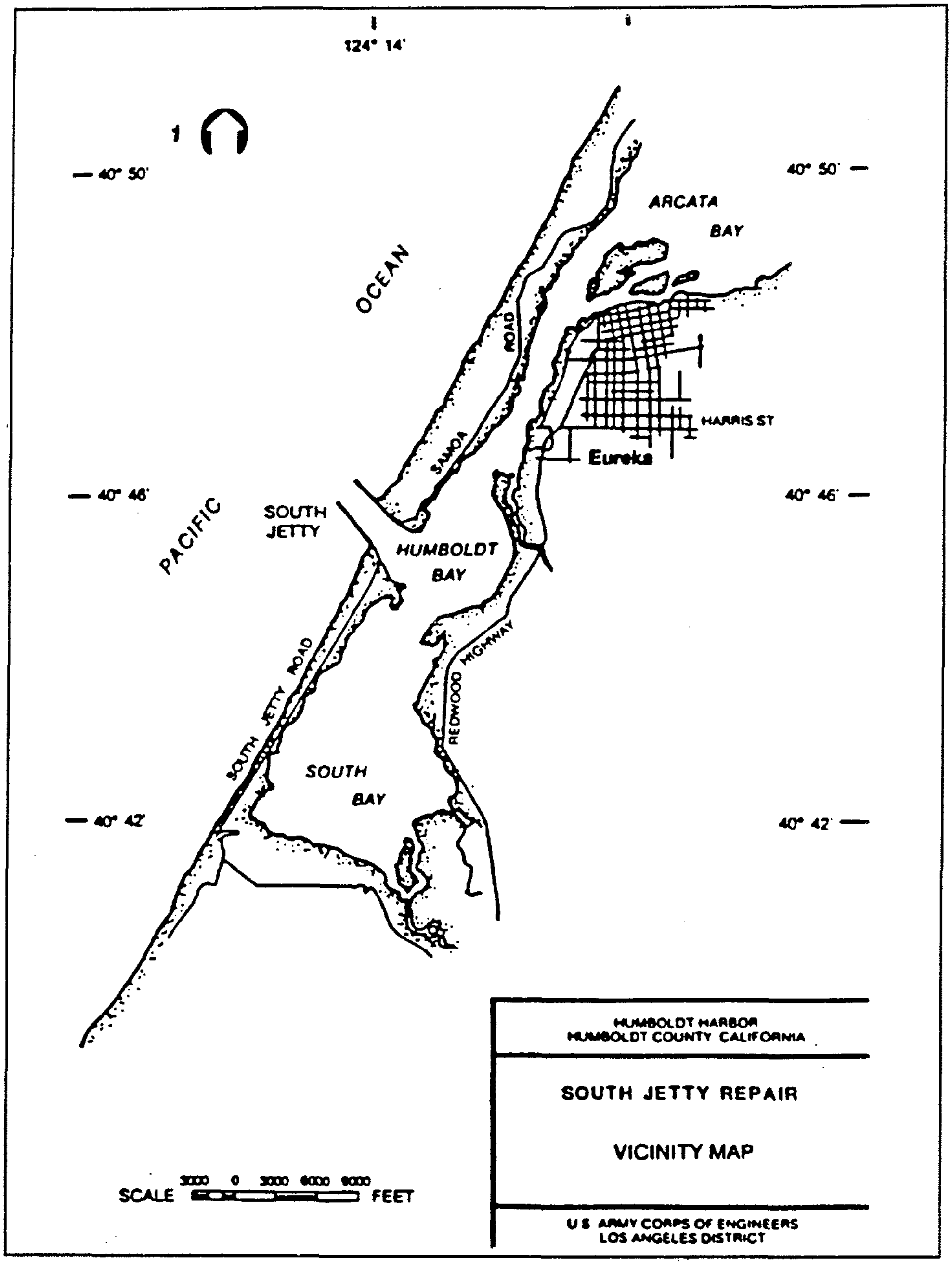

Figure 32. Humboldt Bay entrance channel

which was the most extreme shoaling between the two survey periods. The two scour holes adjacent to the jetty tips are slightly linear in shape, parallel with the jetties and deepest close to the toe. The hole at the north jetty is considerably larger ranging from 200 to 300 yd wide. Historic soundings do not show the scour holes so they are believed to be a modern feature. The third scour hole lies adjacent to the south jetty trunk between stations 47 and 62. It is approximately 100 yd wide, reaching depths greater than -60 ft mllw. Comparison with historic bathymetry show that, unlike the first two scour holes, this one has been present since construction of the jetties. Diver inspection of this scour hole revealed jetty stones of all sizes laying down the slope and across the scour channel into the ship channel.

The foundation materials under both jetties range from fine to medium fine sand, with the predominant material being poorly graded fine sand. With this range of material, currents exceeding approximately 3 ft/sec cause transport. Tidal currents at Humboldt have been measured in excess of 7 ft/sec by the U.S. Geological Survey. The inlet cross section is shallow on the north side, which reduces current speed on this side of the inlet and focuses it on the south side. Scour is occuring on the south side. The location of the scour holes at the jetty tips appears to be caused by a structure/longshore current interaction.

The structures at Humboldt Bay experience three types of scour, each apparently governed by different hydrodynamic processes. The first type of scour is caused primarily by the ebb-flow jet exiting the northerly interior channel, flowing diagonally across the entrance channel and impinging on the rubble-mound revetment on the south side of the entrance channel. This has resulted in scouring of the bottom near the toe of the south jetty along part of its length. Depth of scour was reported to be 60 - 70 ft.

The second type of scour occurs along the jetties on the side opposite to the channel. Longshore-moving currents and wave setup contribute to "rip-channels" that flow from the shore along the updrift jetty in a seaward direction. Floats have been used to estimate current speeds of about 5 knots (8 ft/sec) as the flow moves around the tips of the structures. This rapid flow scours a trench along the toe of the structures, and repeated dumping of stone to protect the structure has resulted in a flattening of the structure slope to about 1:5. Figure 33 shows a typical scour trench near the tip of the south jetty at Humboldt.

During the winter, when the rip currents scour a channel on the outside of the south jetty and the ebb currents scour near the toe on the inside of the jetty, the combined effect puts the structure in considerable danger of liquefaction-related failure.

The third type of scour is seasonal and tends to occur around the structure tips during the winter. It is thought that this scour is most likely wave-driven, with possibly some influence due to ebb tidal currents.

According to the U.S. Army Engineer South Pacific Division, operation and maintenance (O&M) costs directly or indirectly associated with scour at the Humboldt Bay jetties were $1.7 million in 1983, $6.8 million between 1983-86, and $1 million in 1991, for a total of $9.5 million over the 8-year period.

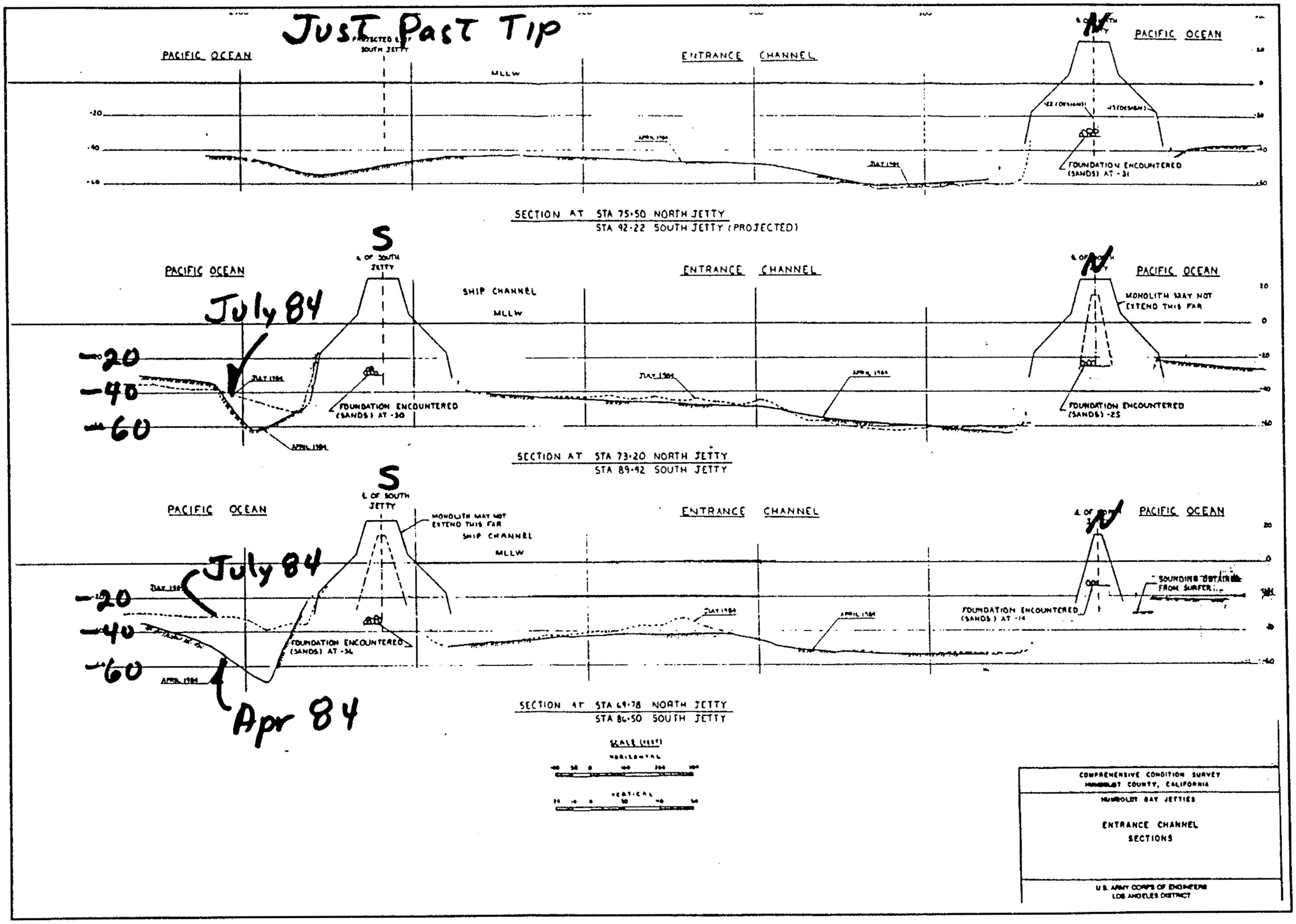

Figure 33. Humboldt Bay south jetty rip channel scour

Suislaw River, Oregon

The entrance to the Suislaw River is located on the Oregon coast approximately 154 miles south of the mouth of the Columbia River. The entrance channel is protected by a pair of rubble-mound jetties originally authorized in 1891 (Ward 1988). The present project was authorized in 1910, and specified a north jetty length of 7,500 ft and a south jetty length of 4,000 ft. During the period 1983 - 1985, both jetties were extended an additional 2,500 ft, and two spur jetties, 100 ft in length, were constructed at a 45-deg angle to the trunk of the jetty near the heads of the structures. These spurs make the jetty resemble a "crow's foot" when viewed from above. The purpose of the spurs is to deflect longshore-flowing sediment away from the tips of the structure and the entrance channel. Figure 34 shows the general layout of the entrance and its structures, including the spur jetties. The spur jetties are presently being monitored under the MCCP Program.

Two scour problems are occurring at Suislaw. The first problem, seen in Figure 34, is caused by longshore currents flowing from the north to south. The currents reach the north jetty and are deflected seaward along the jetty as a rip current. The current velocities are sufficient to scour a trench along the toe of the structure, thus giving concern for the integrity of the rubble mound. The scour trench extends along the spur jetty as well.

The second scour problem is occurring inside the entrance on the north side of the channel. River currents that flow toward the sea are deflected around a corner by the stabilized channel. Where this change of flow direction occurs, a large scour hole has developed. Maximum depths in the scour hole are about 40 ft below mllw, while depths in the adjacent channel average about 20 ft. Because the scour hole is located immediately adjacent to a bank revetment, there is potential for toe failure and subsequent deterioration of the revetment.

The types of scour observed at Suislaw are similar to the problems occurring at Humboldt Bay. The scour trench caused by the longshore currents meeting the north jetty is most likely seasonal, with the trench filling in during calmer periods. The effectiveness of the spur jetties is being evaluated in the MCCP Program.

Yaquina Bay, Oregon

Yaquina Bay is on the Oregon coast approximately 113 miles south of the mouth of the Columbia River. The entrance to the bay is protected by a jetty system that was authorized by Congress in 1880 (Ward 1988). Since initial construction, the north jetty at Yaquina has undergone extension or rehabilitation a total of seven times. The last three repair efforts (1966, 1978, and 1988) cost the Corps a total of $16 million.

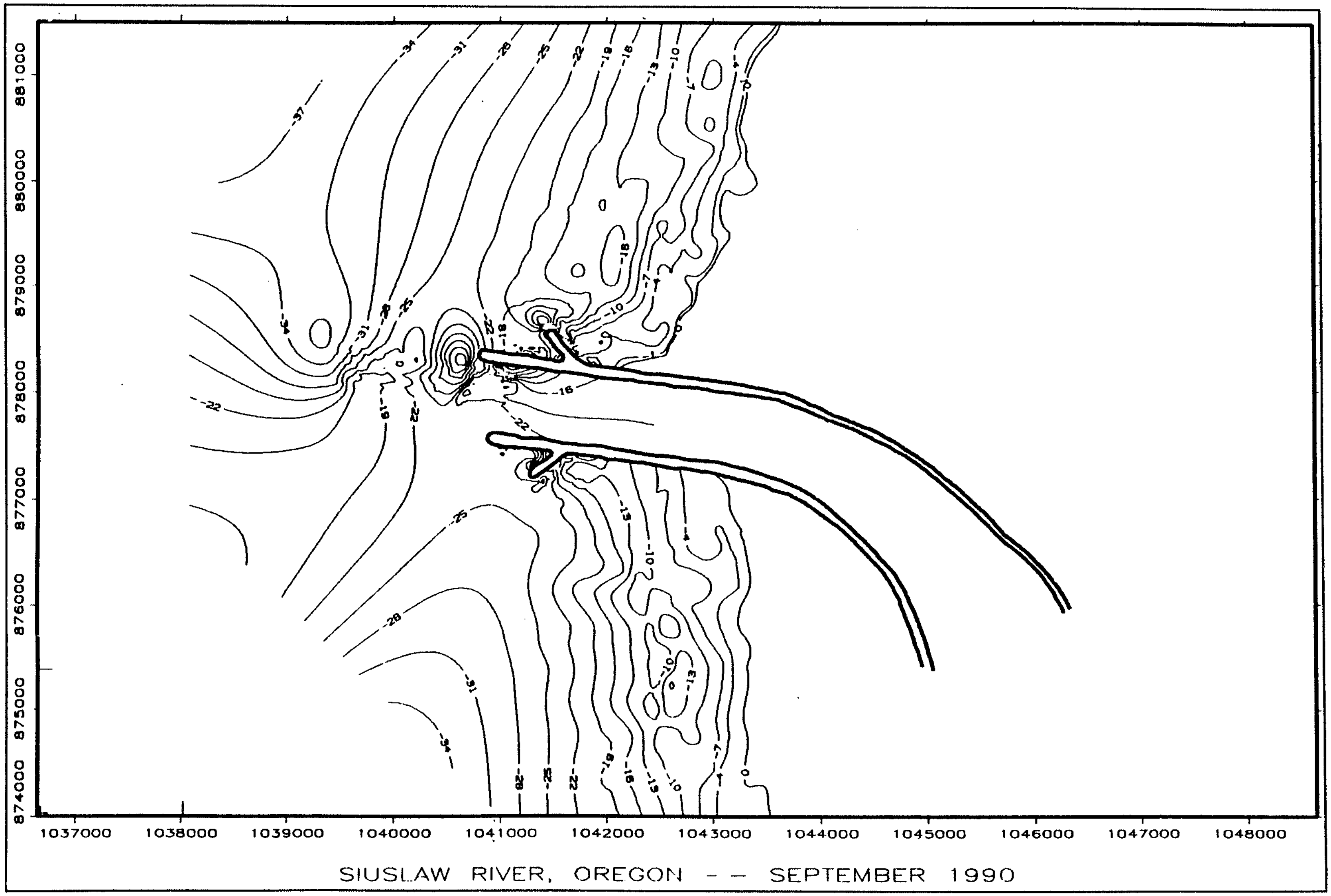

Figure 34. Jetties and bathymetry at Suislaw River Entrance

The three most recent repair efforts generally focused on repairing the outermost 400 ft of the jetty tip which waves had "beaten down" below the water level. Only the most recent repair was designed with the benefit of physical model tests; however, these tests were limited to study of armor stone stability under wave attack.

Monitoring of the Yaquina north jetty under the MCCP Program has revealed that the latest repair is starting to suffer the same fate as its predecessors, with a "notch" forming near the tip. Two workshops have been held to try and determine the cause of jetty deterioration at Yaquina. The most recent workshop, held in August 1991, appears to have narrowed the possible damage mechanisms to scour and toe instability.

The tip of the north Yaquina jetty intersects an offshore reef as indicated in Figure 35.

Very recent geophysical evidence indicates that the bottom material immediately landward of the reef is a fairly deep deposit of littoral sand. It is hypothesized that waves in severe storm conditions cross over the hard bottom of the reef and scour sediment from the bottom just landward of the reef and right at the toe of the "notch" area. This causes toe failure and slumping of the structure's armor layer into the hole. After the storm, milder wave conditions move littoral material into the scour hole and cover up some of the missing armor units.

A smaller scour hole persists at the head of the south Yaquina jetty, but it doesn't seem to be causing any problems related to the structures or the navigation channel.

Continued monitoring of the Yaquina north jetty should provide additional confirmation of the scour hypothesis stated above. This particular project points out the need for developing physical modeling capability to examine scour potential at coastal structures.

Tillamook Bay, Oregon

Tillamook Bay is located on the Oregon coast about 47 miles south of the Columbia River (Figure 36). The Corps project at Tillamook includes two rubble-mound jetties protecting the entrance to the bay and a dike that was constructed to repair a breach in a spit on the westerly side of the bay (Ward 1988). The north jetty was initially constructed between 1914 and 1917 to a length of 5,400 ft. Since then it has been rehabilitated several times, and the length was extended to 5,700 ft.

The south jetty was authorized in 1965 with a length of 8,000 ft, and construction to a length of 3,700 ft was completed during the period 1969 - 1971. Scour in front of the structure caused cost overruns, and construction stopped

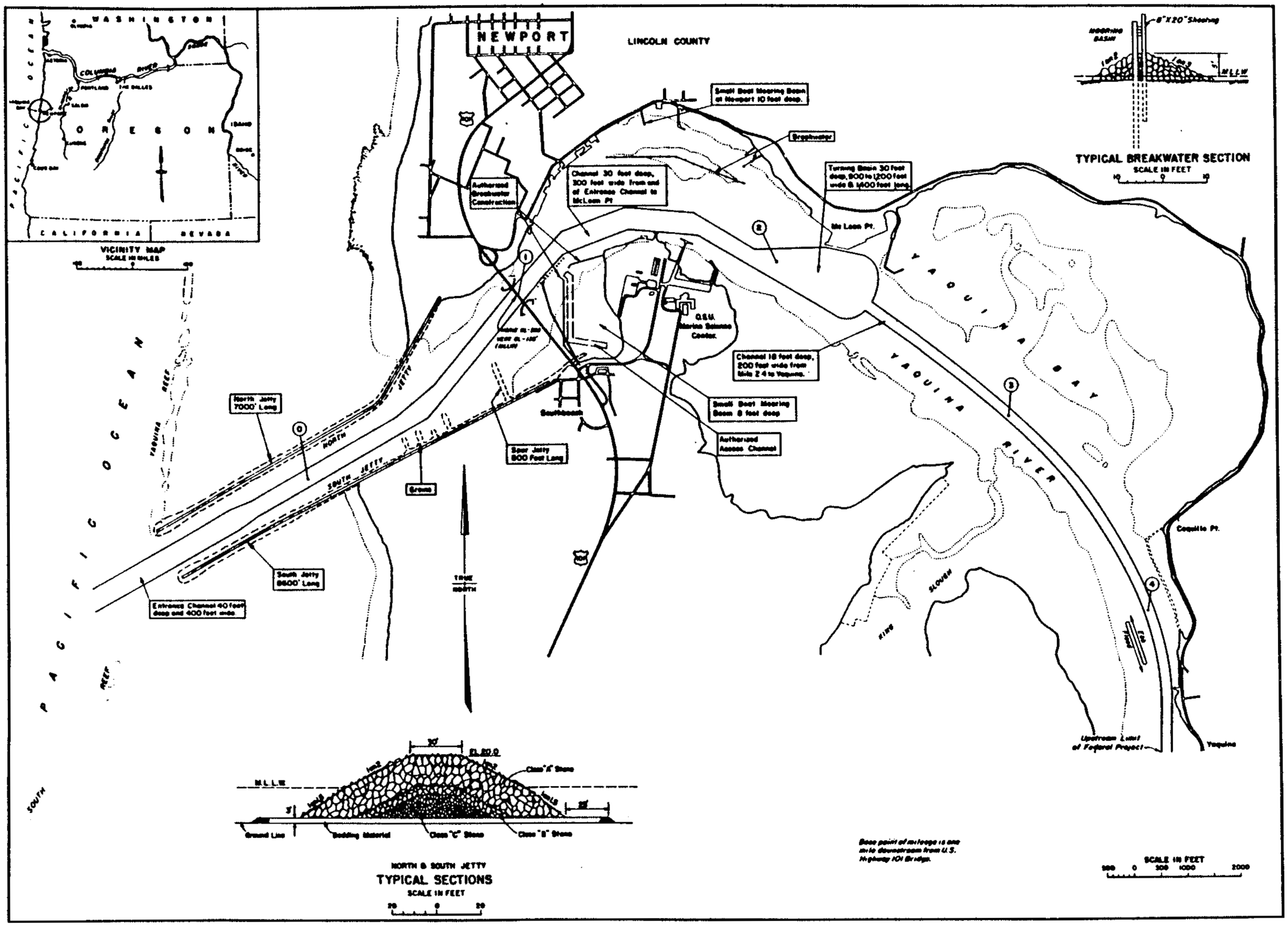

Figure 35. Yaquina Bay and Harbor, Oregon, site location map

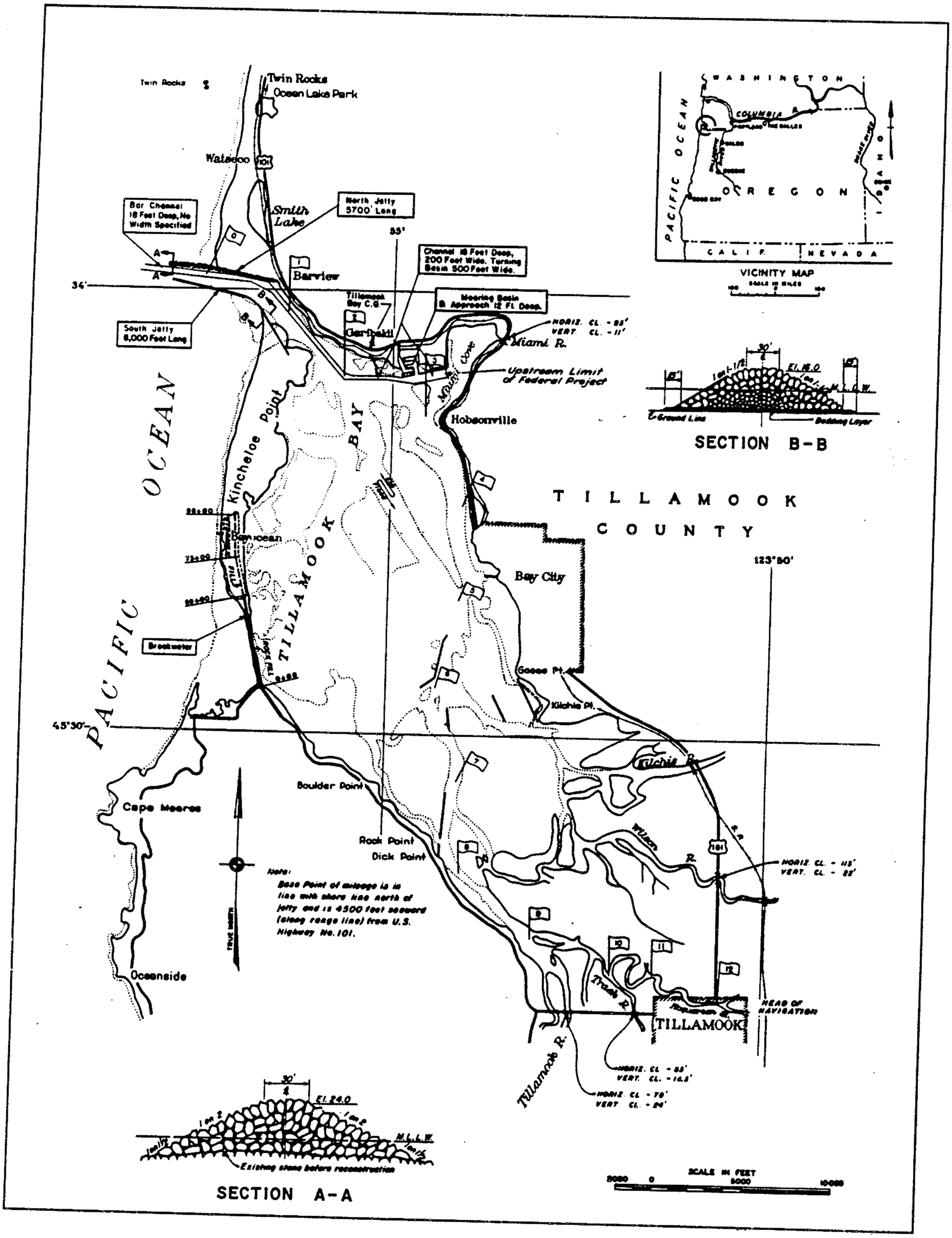

Figure 36. Tillamook Bay and Bar, Oregon, site location map

short of the planned 8,000 ft. During the period 1978 - 1979, the south jetty was extended to its full 8,000 ft length.

Scour accompanying construction of the south jetty was generally on the order of 5 - 10 ft below normal depths, and it occurred just ahead of construction. Scour holes have formed at the tips of both jetties. Surveys dated 1987 indicate a large kidney-shaped scour hole at the tip of the south jetty having a maximum depth of about 61 ft below mllw (Figure 37). Surrounding depths average about 30 - 40 ft. The authorized channel depth is 24 ft. There was once a scour hole at the tip of the north jetty, but it has disappeared along with 300 ft of the north jetty. The end of the north jetty was recapped during the summer of 1991.

A scour problem also exists along the channel side of the north jetty well inside the entrance channel. The shape and location of this hole indicate that it is probably formed by ebb-flowing currents exiting the bay and being directed by the geometry across the channel to the north side. The hole is about 50 ft deep while the surrounding area has a depth closer to 25 ft. The proximity of the hole adjacent to the structure causes concern about erosion of the structure toe.

Seismic testing was proposed to determine if the missing 300 ft of the north jetty might be attributed to a combination of scour hole formation and sand liquefaction. The scour at the tips of the structure is probably largely influenced by waves and currents, while scour in the interior channel is caused by current/structure interaction. Sand size in the area of Tillamook Bay is classed as medium.

Columbia River, Oregon

The Columbia River is the largest river on the Pacific Coast. Improvements to the mouth of the river, which forms the border between Washington and Oregon, were first proposed in 1882. Two years later Congress authorized construction of the south jetty to a length of 4.5 miles, and in 1895 construction was completed and required nearly 1 million tons of stone. An additional 2.5 miles were added to the south jetty during the period 1903 - 1913, and the north jetty was constructed to a length of 2.5 miles. Since that time, there has been a history of periodic repair, maintenance, and modification to the jetty structures. The ends of both jetties have deteriorated to water level, and now serve much like low-crested weirs. The general layout of the Columbia River entrance is shown in Figure 38. Shoaling in the navigation channel varies the channel depth between 55 ft and 48 ft, depending on the dredging cycle.

A large scour hole is located just south of the submerged end of the north jetty (Figure 39). This hole tends to scour to depths on the order of 80 ft

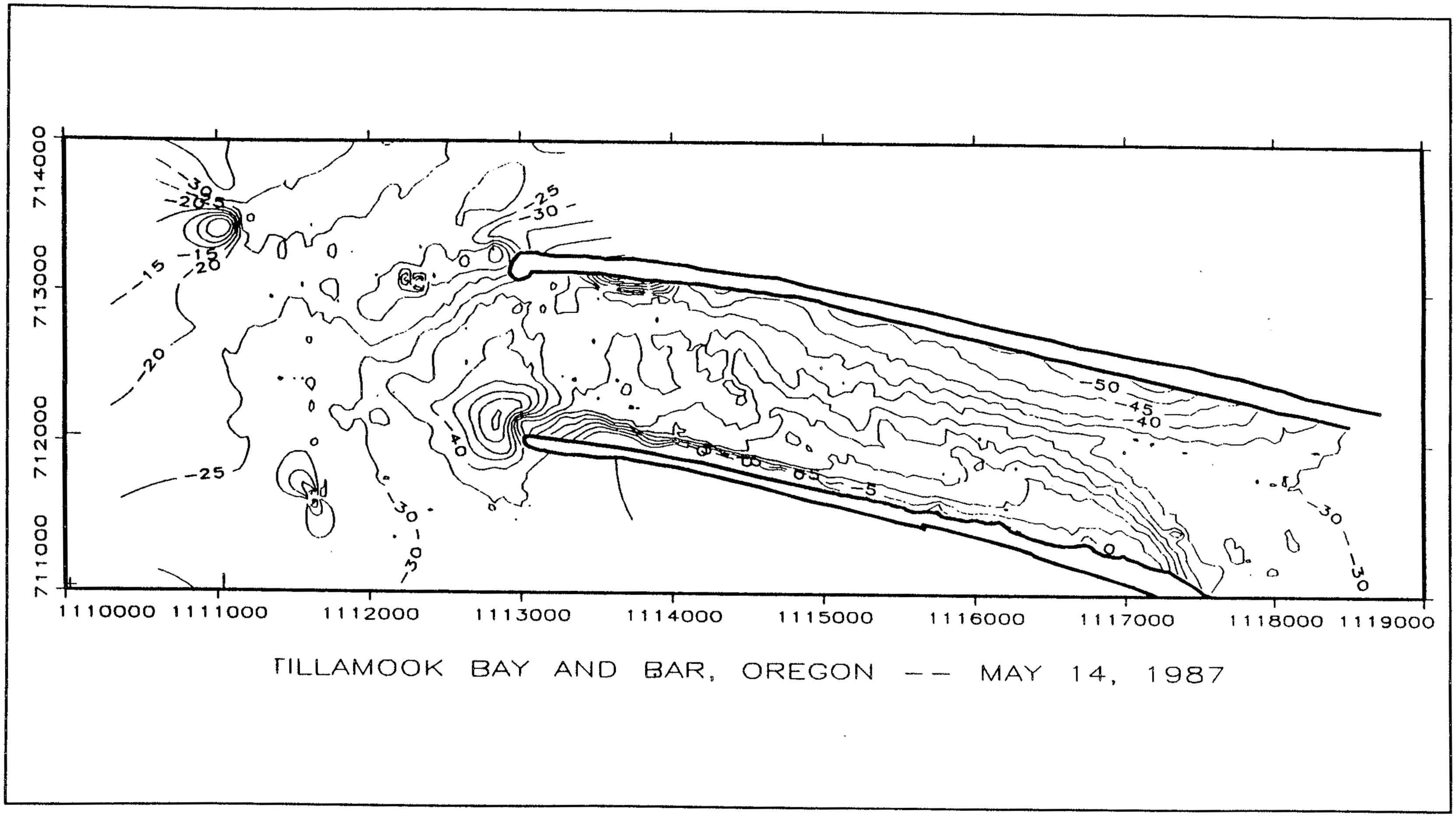

Figure 37. Tillamook Bay and Bar, May 14, 1987

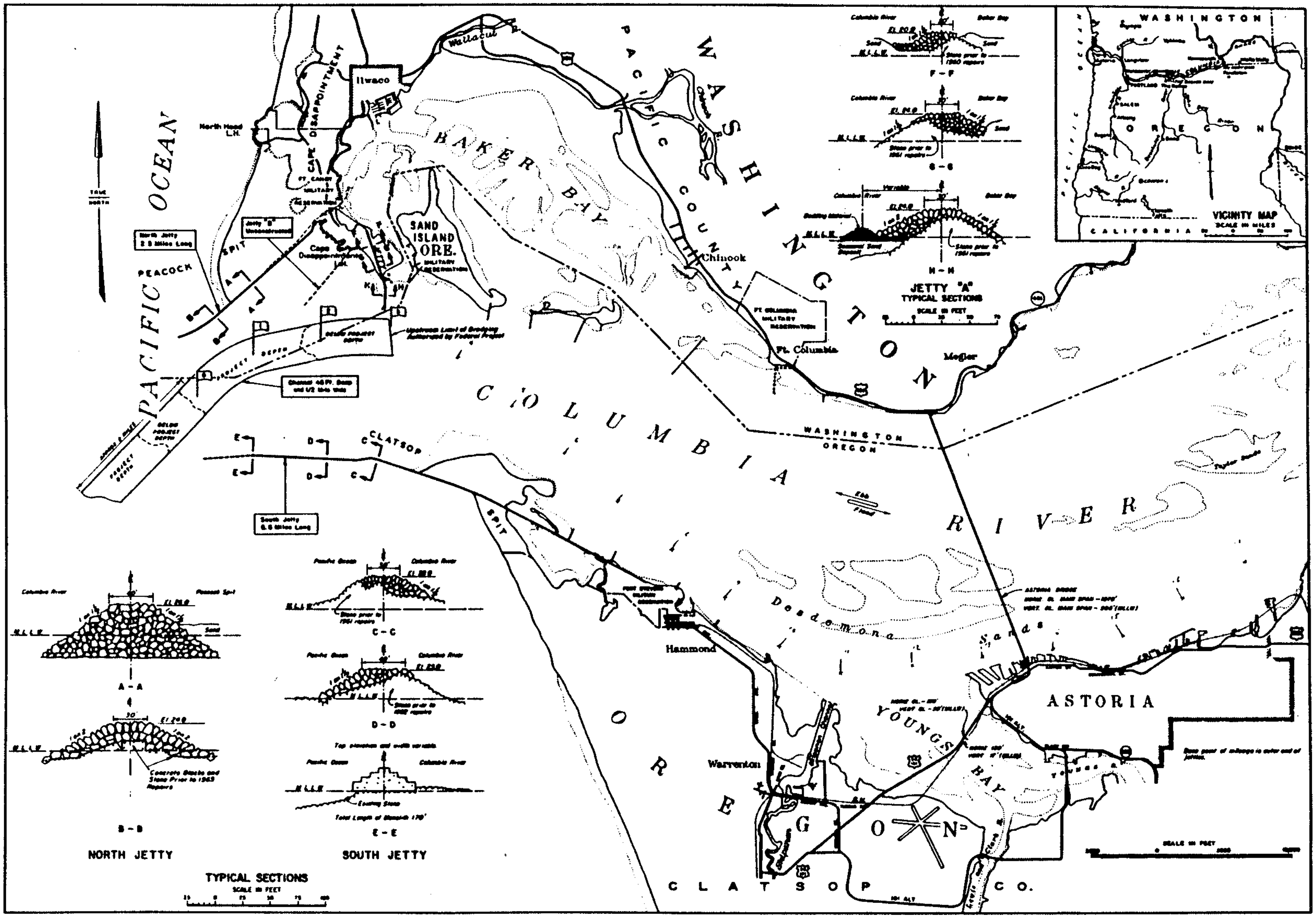

Figure 38. Columbia River Entrance Channel, Oregon, site location map

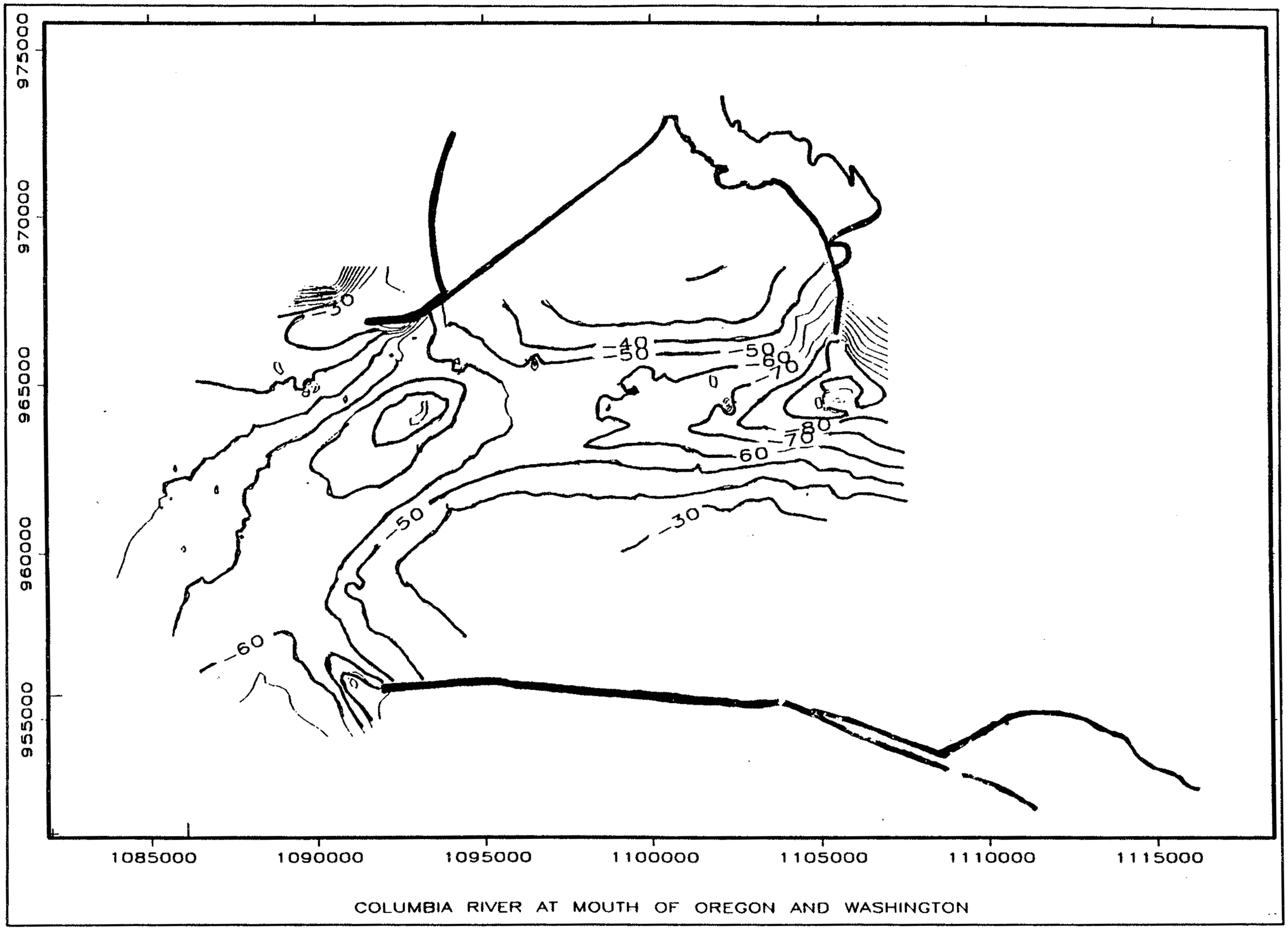

Figure 39. Columbia entrance bathymetry

below mllw, and the Corps uses it as a deposition basin for interior navigation channel dredging. After disposal of material the depth is typically 60 ft, but over time this material disappears (presumably not back into the channel).

A similar scour hole exists just seaward of the submerged portion of the south jetty. This hole has a maximum depth of around 95 ft, and most likely is caused by wave/current/structure interaction.

Finally, there is a scour problem that occurs upstream of the jetties on the north side of the channel near the tip of a spur jetty referred to as "Jetty A." This scour hole has depths to 103 ft, whereas the surrounding bottom depths average between 50 and 70 ft. This problem is apparently current related. The mouth of the Columbia River offers unique challenges for the U.S. Army North Pacific Division, and the magnitude and extent of the scour holes are such that corrective action may not be feasible. Still, there is a need to understand the causes of the observed scour so that this understanding can be applied to smaller-scale projects.

Grays Harbor, Washington

Grays Harbor is located along the Washington coast at the mouth of the Chehalis River, which is approximately 45 miles north of the Columbia River Entrance. The harbor is 13 miles long and 11 miles wide (Figure 40). Two spits, Point Brown to the north and Point Chehalis to the south, form the barrier between the Pacific Ocean and the harbor. The entrance is approximately 6,500 ft wide and stabilized by rubble-mound jetties (Ward 1988). Construction of the south jetty began in 1898 and was completed in 1902. The jetty was 13,734 ft in length with an elevation of +8 ft mllw. The north jetty was begun in 1907 and was completed in 1913 with a length of 16,000 ft and height of +5 ft mllw. Through the years, the jetties were repaired and rehabilitated many times, eventually raising the structures to elevations of +20 ft mllw. Eventually, about 5,600 ft of the south jetty was left in a deteriorated yet partially functional condition, and the jetty has not been reconstructed as of this writing.

The jetties have modified the natural tidal circulation patterns of the entrance channel. The ebb currents exit along the southern portion of the entrance, which has caused deep scour against the south jetty from Point Chehalis seaward across the outer bar. Currents have at times scoured the southern 2,000 ft of entrance to depths greater than -70 ft mllw (U.S. Army Corps of Engineers 1988). This has caused undermining and failure of the jetty as well as increasing bar depths from about -15 ft to -35 ft mllw (from construction to present day). Ebb currents have been measured at 3.0 to 4.0 ft/sec, with a tide range greater than 8 ft.

The jetties have also undergone subsidence believed to be caused by the thick sand foundation supporting the structures. Storm waves with heights of 30 ft and greater cause percolation through the sandy foundation. This,

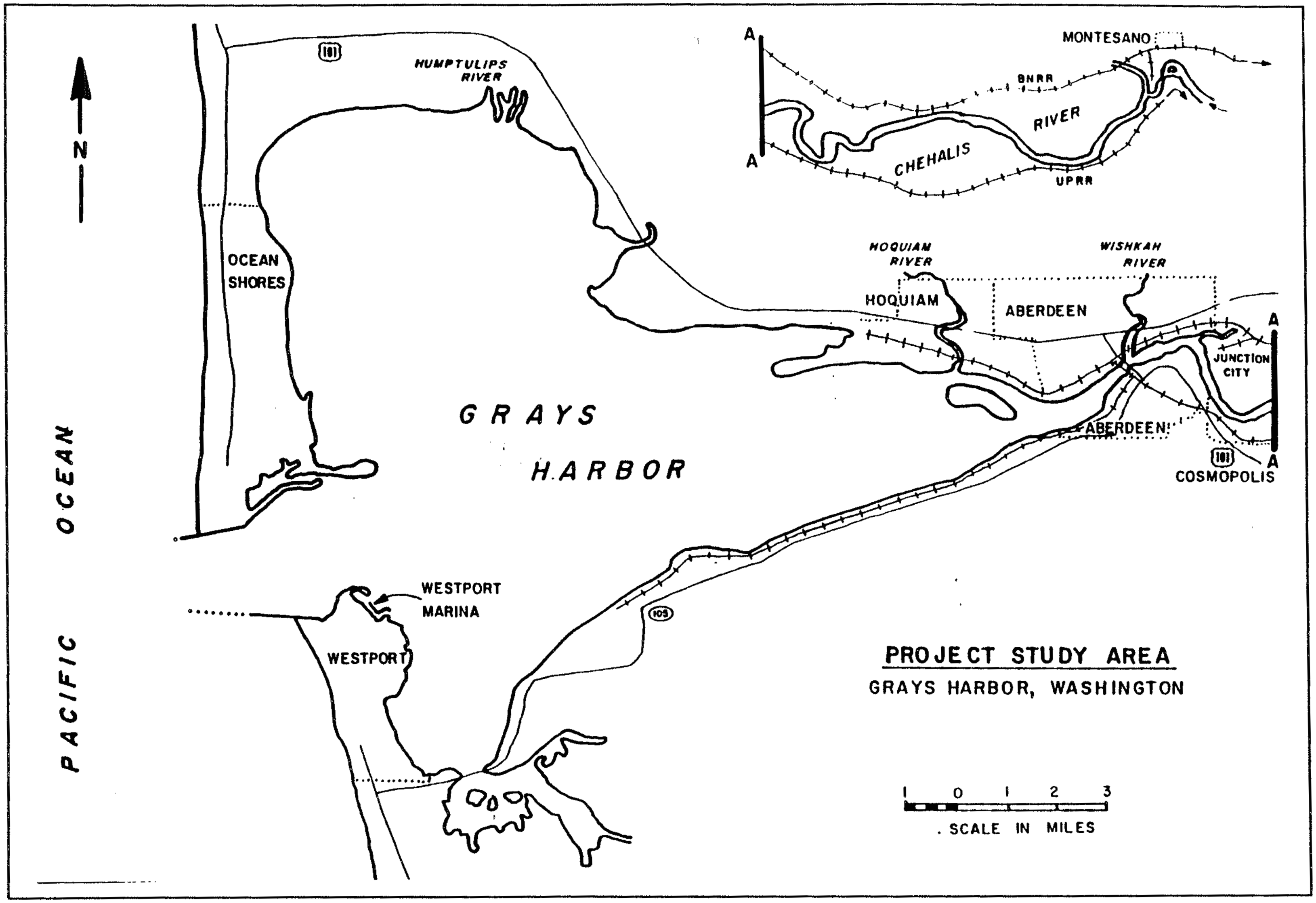

Figure 40. Grays Harbor, Washington, site location map

coupled with the tremendous weight of the armor units and the high structure elevations, caused the structures to subside.

Cattaraugus Harbor, New York

Cattaraugus Harbor, New York, on Lake Erie was completed in January 1983 (Bottin 1988b). Its location is shown in Figure 41. This shallow draft harbor is situated on a shoreline where the predominant littoral drift is south to north. The Cattaraugus Creek watershed covers approximately 558 sq miles in western New York (Hemsley, Bottin, and Mohr 1991). It is estimated that the total annual sediment transport from Cattaraugus Creek ranges between 520,000 and 780,000 tons per year, depending on the method used to make the estimate. Deepwater wave heights of 10.2, 10.8, and 11.5 ft, with periods of 8.3, 8.6, and 8.9 sec occur with return intervals of 5, 10, and 20 years, respectively (Hemsley, Bottin, and Mohr 1991). During October 1983, a significant wave height of 7.7 ft and period of 8.3 sec were measured at the project site. Average monthly lake levels have fluctuated over 5 ft during the period of record, 1900-1988.

The constructed project includes two breakwaters to stabilize the creek's entrance into Lake Erie and a navigation channel. The north breakwater is 600 ft long with a crest elevation of +12.5 ft LWD and side slopes of 1V:2H. The armor stone ranges in weight from 2 to 5 tons. The south breakwater is 1,850 ft long with a crest elevation of +12.5 ft LWD and side slopes of 1V:2H. The south breakwater armor stone, ranging from 4 to 9 tons, is larger than the north breakwater armor stone because this structure is more exposed and includes a curved end that protects both the entrance and north breakwater from storm waves. Total cost of the structure was approximately $6.1 million (Bottin 1988b). The navigation channel has an entrance channel 1,500 ft long and 100 ft wide with a bottom elevation of -5.5 ft lwd. This elevation provides a channel approximately 8 ft deep during the summer months. The project was monitored by the MCCP Program during the years 1983 - 1985.

The MCCP survey data indicated the development of a scour hole that apparently formed shortly after construction (Figure 42). This scour was located off the head of the breakwater structure with approximate dimensions of 800 ft in diameter and a depth of 4 ft below the usual bottom depth in the surrounding area. The scour contours are shown in Figure 42. Subsequently, natural littoral processes have filled in the scour hole to the point that by 1989 the hole was nearly filled in and the depth contours have been straightened. Presently there is no scour hole problem at Cattaraugus Harbor.

Many of the coastal processes on the Great Lakes can be linked to fluctuating water level cycles in the lakes. Lake Erie has the most variation due to hydraulic controls on the lake and the long fetch, which can produce large wind setup levels. The maximum water level variation in Lake Erie is about 16 ft.

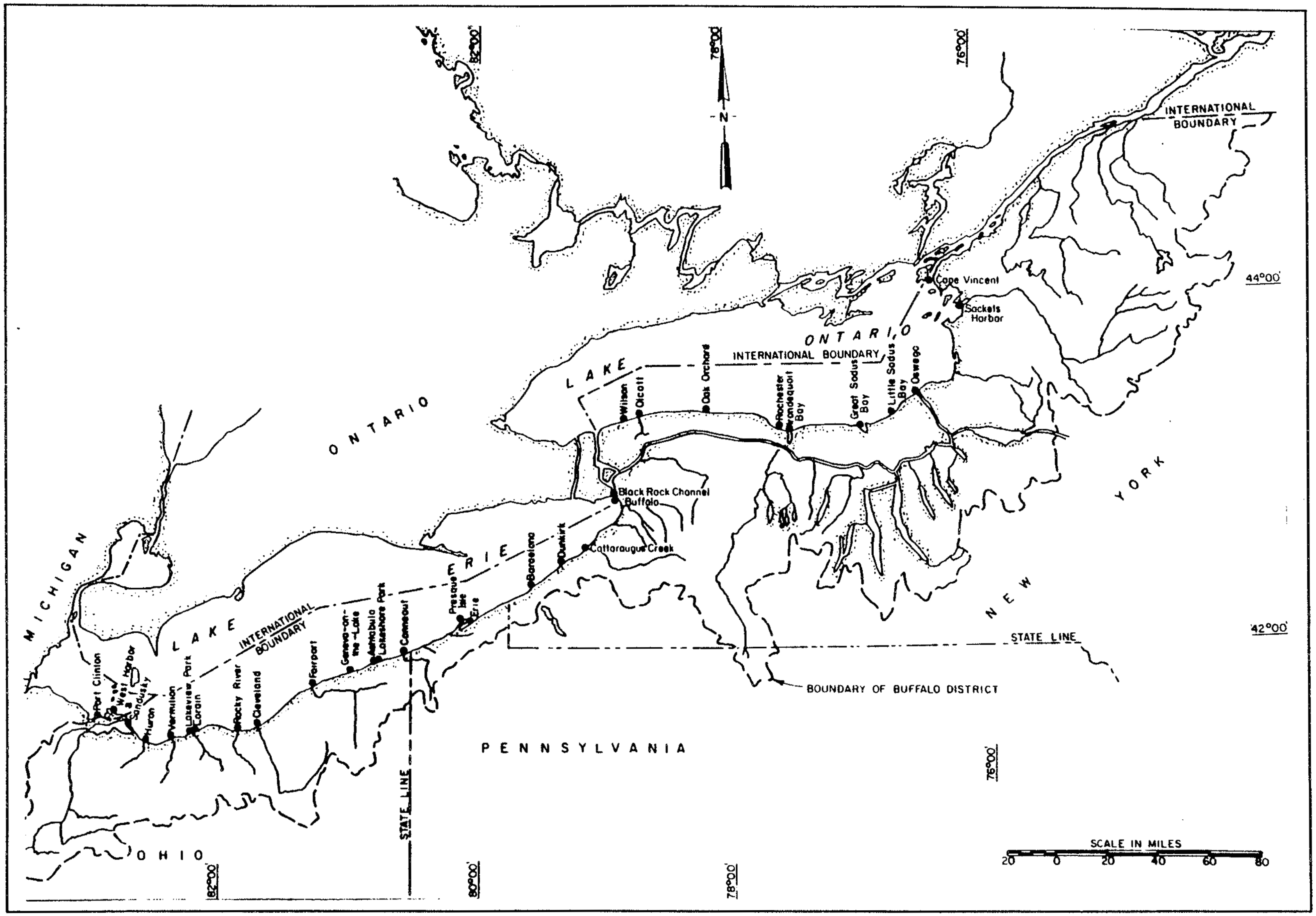

Figure 41. Location map of North Central Division's breakwater and jetty projects

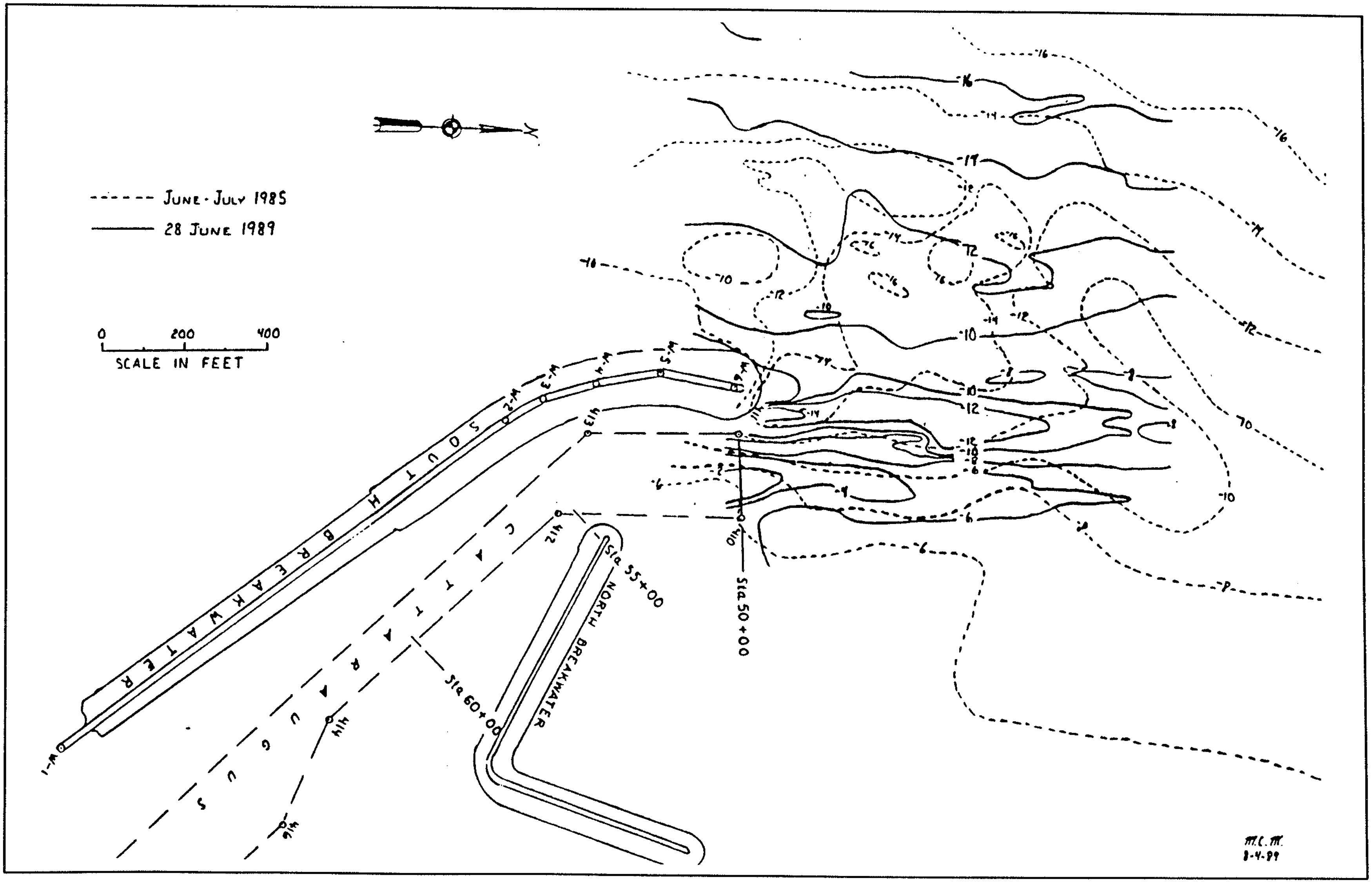

Figure 42. Cattaraugus Harbor, New York, site location map

During the scour hole episode at Cattaraugus Harbor, the lake was about 1.5 ft above average. It is thought that the scour was a temporary feature resulting from construction of the breakwater, possibly caused by wave reflection from the structure. The high lake levels may have allowed more wave energy closer to shore, also contributing to the scour. The scour was not thought to be related to storm activity.

Irondequoit Bay, New York

The entrance channel to Irondequoit Bay, New York, on Lake Ontario was completed in 1986. The location of this entrance is also shown in Figure 41. The highest lake level after the time of construction was about 2 ft above average, and breaking waves with heights of 12 ft are typical for the depths at the head of the structure.

Post-construction scour, similar to what occurred at Cattaraugus Harbor, developed at the tip of the west breakwater as shown on Figure 43, only it was more severe, with maximum depths 19 ft below the bottom level of the surrounding area.

The scour hole caused sufficient concern that it was filled in December 1987, prior to the winter storm season. The rock material used to fill the hole was quarry scrap with sizes up to 1,500 lb. Subsequent to the rock filling, the rest of the scour hole filled naturally with sand from the littoral system to the point that the scour hole can be considered negligible. As with Cattaraugus Harbor's scour hole, the scour at Irondequoit was most likely a transient effect resulting from construction of the breakwater. Over time, these holes seem to heal themselves with sand available from the littoral drift. The scour holes do not appear to be storm-related, but scour may be linked to the higher water levels present at the time of construction.

Lake Michigan

Lake Michigan has numerous small harbors, many of them built in the early 1900's. Typically these harbors have about a 14-ft draft if they handle commercial traffic, and an 8- to 10-ft draft if they are recreational harbors. Although rubble-mound structures are used, caisson-type breakwaters are common. These structures have vertical sidewalls made of sheetpile or timber cribs, and they are highly reflective to incident waves.

Scour problems occur at Lake Michigan harbor structures, generally around the area of the breakwater head. Figure 44 is a sketch showing a harbor layout with areas susceptible to scour.

Depth of these scour holes usually ranges between 3 and 6 ft below the normal bottom. However, it is possible to have scour holes form that are as

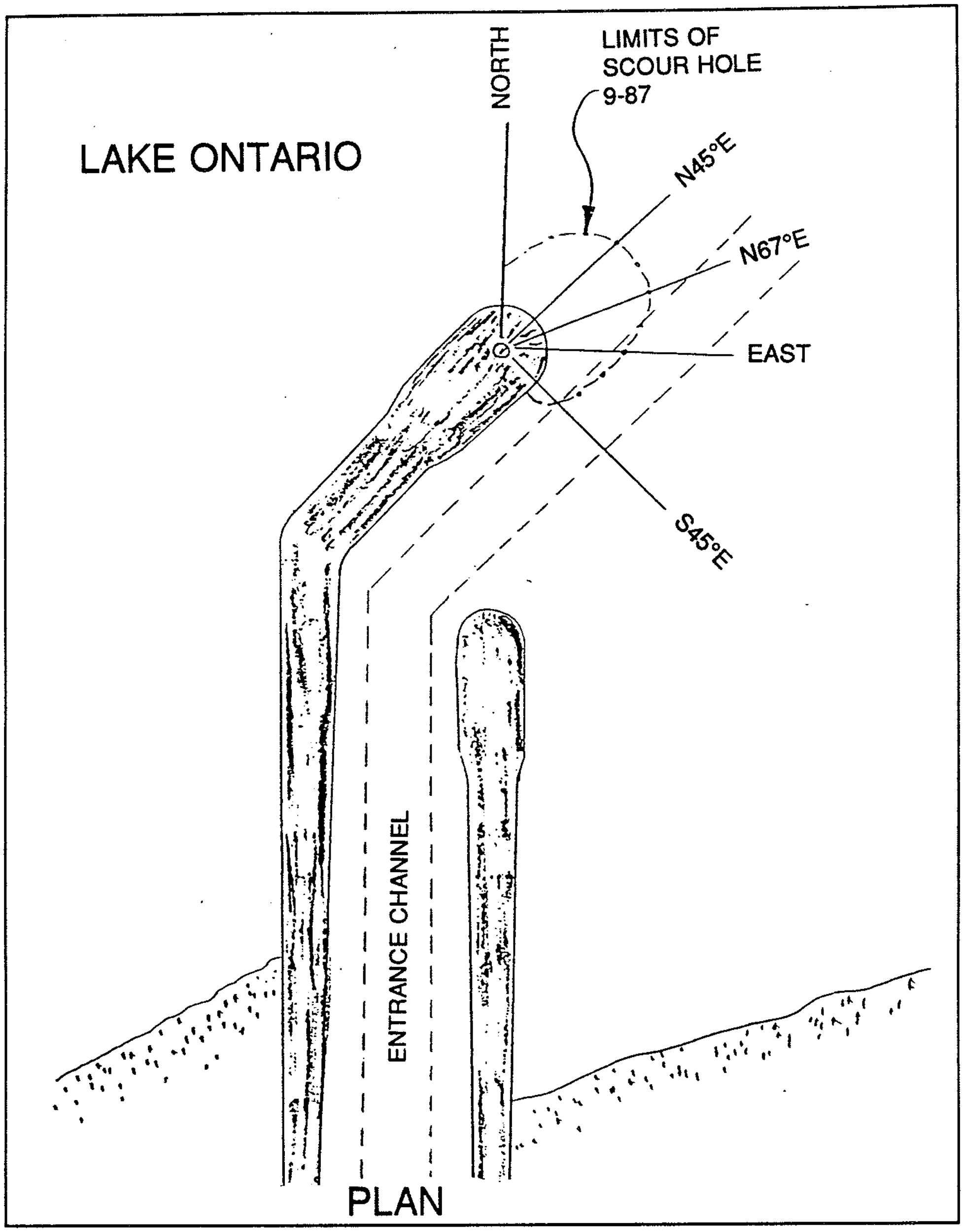

Figure 43. Irondequoit Bay, New York, site location map

much as 30 ft deep, and the Muskegon Harbor, Michigan jetty was cited during the 1991 workshop as having such a scour hole formation.

Scour holes also form on the upstream ends of pile-driven structures due to flow separation as the water moves past the pile structure. These types of problems are solved by adding stone toe protection where scour is likely to occur.

Rehabilitation of sheet-pile structures on Lake Michigan usually doesn't give consideration to scour potential, thus effective design guidance would be

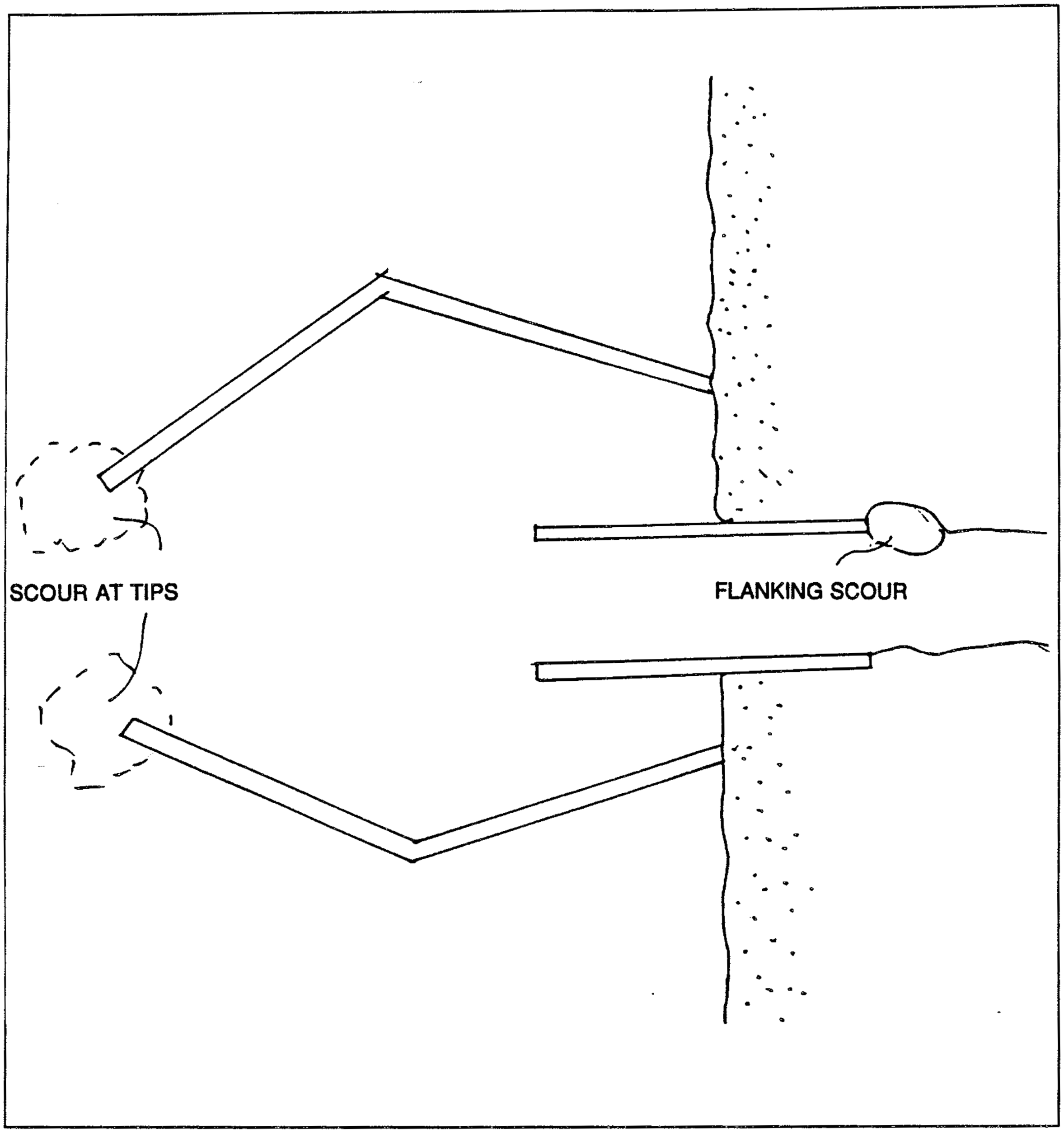

Figure 44. Scour problems at Lake Michigan harbors

welcomed by field engineers responsible for designing and/or rehabilitating sheet-pile structures.

Winter ice was discounted as a possible source of scour holes around structures. However, in deeper water it was thought that ice ridges might be a potential problem.

3 Summary

A review of structure, scour hole, and process data from the case studies is presented in Table 3. This table is divided into three main sections: (a) jetty, covering year of construction, type, and distance between jetty tips; (b) scour hole, covering location of the scour hole relative to the jetty (in many cases there are several scour hole locations per project), and maximum reported depth of the hole; and (c) coastal processes, covering adjacent bottom depth, type of material (and size if known), current speed, and net transport direction. A fourth section attempts to classify the major mechanism(s) causing or participating in the scour development. Three potential causes are identified: (a) waves - including wave/structure interaction (Shinnecock Inlet) and breaking waves agitating and removing sediment from the hole (Cattaraugus Creek), (b) current, including longshore currents (Suislaw) and current/structure interaction (Indian River Inlet), and (c) thalweg. Thalweg, although current driven, differs from a current classification in cases where there is natural channel migration and meandering, such as Little River Inlet.

These categories are meant to be very general, serving only to identify major processes that might be at work and have contributed to development of the scour hole and, ultimately, to a structure's failure. It is possible, and in some cases highly likely, that a structure's failure was a function of more than one of these causes. Wave-induced scour includes the transport of material by currents induced by waves either directly, such as orbital velocities, or indirectly, such as by currents generated by wave setup. Current scour is caused by tidal currents capable of transporting material, such as experienced at Moriches Inlet, New York. This can also include currents generated by storm flooding and river flow. Thalweg migration describes the apparently natural migration or meandering of a channel within an inlet. During the course of its natural evolution, an inlet may be stabilized with jetties, but the natural channel continues to adjust regardless of attempts to maintain a navigation channel, such as Little River Inlet, North Carolina.

For scour hole development to occur there must be currents of sufficient magnitude to move sediment. Figure 45 presents velocity versus particle size, and identifies when erosion and deposition are expected (Reineck and Singh 1980). Most of the case studies presented have fine to medium sands (0.01 mm to 0.3 mm); thus, a current magnitude of less than 20 cm/sec (approximately 0.7 ft/sec) can initiate sediment transport and erosion. Projects

Table 3
Scour Hole Data Summary

Project Name	Jetty			Scour Hole			Coastal Process Data				Contributing Process
	Constructed	Type	Width	Location	Diameter	Depth	Adjacent Bottom Depth	Bottom Mtl	Current Speed ft/s	Transport Dir	Wave/Current/ Thalweg
Moriches	mid-1950's	Rubble	750 ft	W Jetty Tip	200 ft	55 ft	6-10 ft	Sand	8.4	W	C/T
Shinnecock	1952-1954	Rubble	815 ft	W Jetty Tip	250 ft	70 ft	6-10 ft	Sand	5.4	W	C/T
Fire Island	1941	Rubble	Single Jetty	Base				Sand 0.3-.35			
Indian River	1938	Rubble	500 ft	N Jetty Tip		100 ft	40 ft	Sand Clay 0.2-0.3	7-8	N	C
Ocean City	mid 1930's	Rubble	1100 ft	S Jetty Tip				Sand			C
Oregon Inlet	1989	Rubble	Groin	Groin		25 ft	12 ft	Sand		S	C
Little River	1983	Rubble		E Tip W Tip W Channel		30 ft 20 ft 25 ft	6 ft 6 ft	Sand		V V	C C T
St. Johns	None	Rubble		Channel Bend	500 ft	65 ft	10-20-ft				
Ponce de Leon	1968	Rubble		N Jetty Tip	200 ft	35 ft	10-15 ft	F/M Sand	2-3	W	T
Panama City	1934	Rubble	1500 ft	W Jetty Tip		50 ft	35 ft	F/M Sand	2.5-3.5 f/s	W	T
East Pass	1967	Rubble	1000 ft	Tip of Spur W Jetty	200 ft	55 ft 45 ft	25 ft 20 ft	Sand	4.5/2.8	V	T/W C

(Continued)

Table 3 (Concluded)

Project Name	Jetty			Scour Hole			Coastal Process Data				Contributing Process
	Constructed	Type	Width	Location	Diameter	Depth	Adjacent Bottom Depth	Bottom Mtl	Current Speed ft/s	Transport Dir	Wave/Current/ Thalweg
Morro Bay		Rubble	900 ft	Tip N Jetty	100 ft	30 ft	20 ft				W
Humboldt	1889	Rubble	2800 ft	Tip Channel Rip	N-250-yd 100 yds	65 ft 60 ft	50 ft 35 ft 15 ft	Mid- Fine Sand	8	V	C C/T W/C
Suislaw	1910	Rubble		Rip Bend	20 ft		20 ft			S	W/C C
Yaquina	1895	Rubble	900 ft	Tip N				Sand			W
Tillamook	N-1917 S-1971	Rubble	1000 ft	S Tip N Tip		61 ft	35 ft	Med Sand			W/C W/C
Columbia	1895	Rubble		N Jetty Tip N Jetty Tip S Jetty Spur		50 ft 80 ft 95 ft 103 ft	25 ft	Med Sand			W
Grays Harbor	1898	Rubble	6500 ft	S		70t			4		C
Cattaraugus	1983	Rubble	200 ft	BW Tip	800 ft	16 ft	10 ft	Sand Gravel		SW	W
Irondequoit	1986	Rubble	100 ft	BW Tip		19 ft					
Lake Michigan											

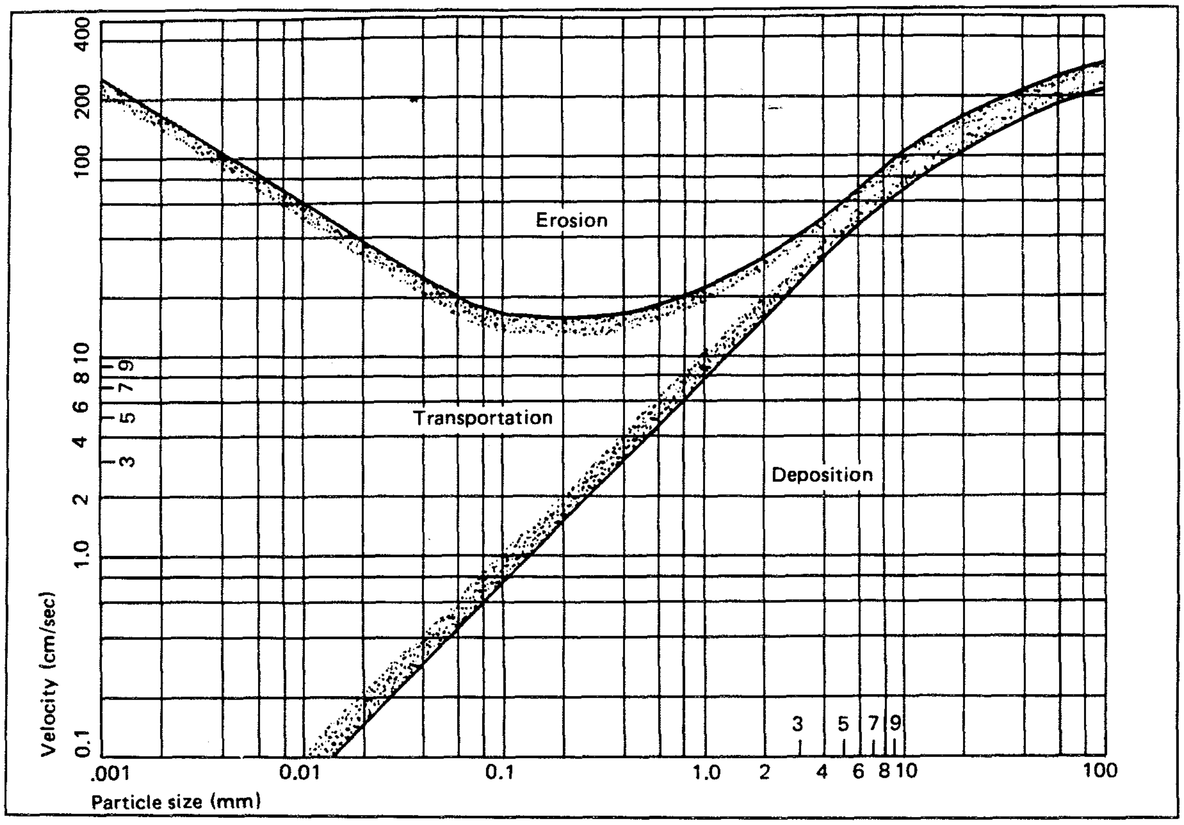

Figure 45. Sediment transport regimes as a function of velocity

like Indian River Inlet, Delaware, and Shinnecock Inlet, New York, have velocities greater than 200 cm/sec (6.5 ft/sec).

Before a structure damaged by scour can be repaired, the scour hole problem must be mitigated. This requires an understanding of the processes involved in its formation. The scour hole at Ocean City Inlet, Maryland, was filled with dredged material and capped with rubble. The scour hole at Moriches Inlet, New York, was filled with dredged material without a rubble cap. The scour hole at Indian River Inlet, Delaware, must be mitigated before repairs of the jetty can begin. However, in all these cases, there is no predictive capability to determine if a proposed mitigation or repair will provide a long-term solution. As seen in the case studies, there can be different time scales associated with scour hole formation, ranging from short episodic events (Cattaraugus Creek, New York), to medium time scales (Indian River Inlet, Delaware), to chronic, long-term problems (Yaquina, Oregon).

What appears to be a remedy at one location may turn out to be a short-term solution or, worse, cause scour to occur elsewhere. Only through monitoring of projects experiencing scour hole formation, and research of the processes involved, can progress be made in understanding scour hole development and predicting scour extent.

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13. ABSTRACT *(Maximum 200 words)*

This report is an expanded version of an earlier unpublished report that documented case studies of scour hole problems experienced by Corps of Engineers' District and Division offices. Most of the case studies contained herein were originally presented by Corps personnel at a workshop held in May 1991 in Vicksburg, Mississippi. Additional case studies not discussed at the workshop have been added to this report.

Scour hole problems at 21 specific sites are detailed in the report, with the vast majority of problems occurring in the vicinity of coastal structures at improved navigation entrances. Possible causes for scour hole development are given for each case, and characteristic hydrodynamic and morphological characteristics of the problem area are given.

Swift tidal currents interacting with coastal structures appear to be the most predominant factor in the development of scour holes. In these cases, incident waves serve to mobilize sediment so that it can be swept away by the currents. However, there were reported instances of scour holes that appeared after storms, and in some cases were infilled by sediment over time. Scour during construction of coastal structures has resulted in cost overruns despite efforts to control the scour.

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